Rocket Propulsion

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Lecture No. #13

Divergence Loss in Conical Nozzles and the Bell Nozzles

Well good morning. In today's class, we continue with nozzles. First, I will review what we have done so far and then, we will see whether there are any gaps anything which has happened in nozzle development which I have not covered and those things we will cover. Having said that what did we do about nozzles. We told ourselves it is something like a bend, and we first learnt how to calculate the jet velocity right. How did we calculate? We said I have a chamber which is at a pressure p c. Suppose, at the exit I have pressure pe; I can calculate the jet velocity 0.1 then, we told ourselves look here I want V J to be as high as possible and to be able to get a high value, I need this vent or opening to be in the form of a convergent divergent shape and we also put a condition that the minimum area which we called as a throat should have a mach number equal to 1.

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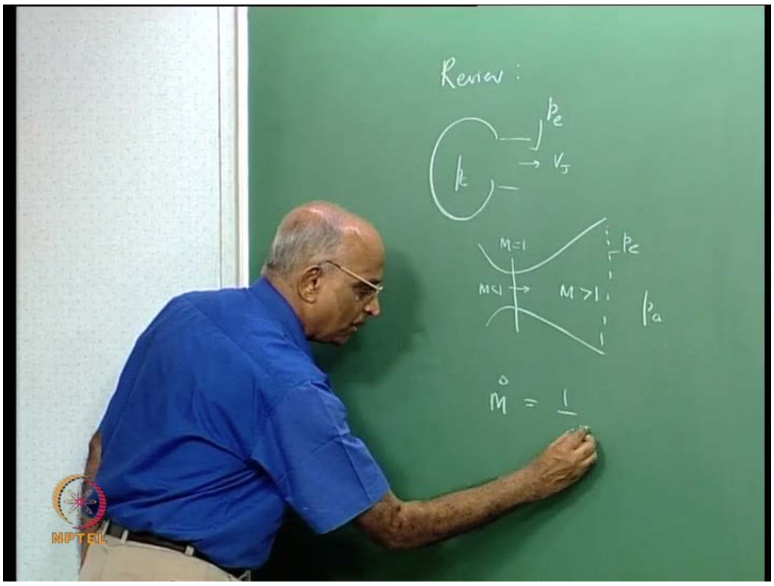

We call this as a delevel nozzle or the convergent divergent nozzle. In the convergent part, the mach number was less than 1; in the divergent the mach number was greater than 1 right. After having done this, we said at the exit I have exit pressure which is pe; the ambient pressure is pa and if the exit pressure is not match to the ambient pressure, I could have something like short timings in the processer either due to under expansion or due to over expansion. After this, we also took a look at what is the flow through the nozzle. In fact, we got an equation of M dot is equal to 1 over C star into p c into At was the flow, and we got an expression say M dot by At was equal to if I write this as a chamber pressure p c into 1 over C star here. C star had units of meter per second and we were able to correlate the pressure built in the chamber. In the chamber, what is the pressure built as a function of mass flow rate; we called this as a transfer function or C as the characteristic velocity of a rocket. Let us take one example just to clarify things. Suppose, I have a rocket let us say; let us now presume that I know something; I put propellant in it; the massive propellant I have in the rocket is let us say M p.

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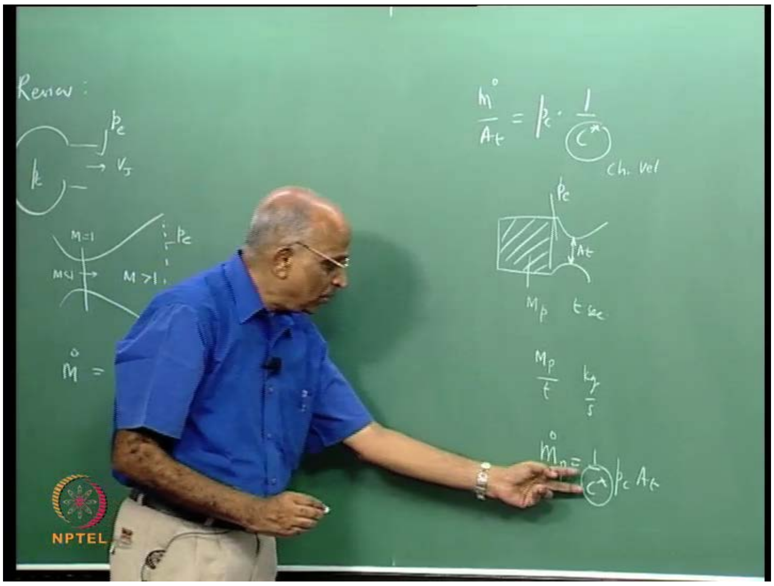

Let the rocket fire steadily for a period of t seconds then, I know that the mass flow rate for the nozzle is equal to M p divided by t; let us say M p is in kilograms; this is kilogram per second. If the pressure built in the rock in the chamber is p c and I after all I give a particular throat At, I can directly say that M p by t is equal to M dot p is equal to 1 over C star into the chamber pressure into At, I can determine this value of C star. If I go and do an experiment and determine the value of C star and then, I start comparing the value of C star which I actually measure to the C star which I ideal which we ideally derive, and how much was it? We told ourselves C star is equal to under root RTC by capital gamma; I find that, the ideal value may be a little more than the actual value because, some flow losses are taking place we called it as C star efficiency of a rocket or chamber. We also told ourselves, well I have divergence or I have rocket nozzle something like this and I can also write the thrust of a nozzle as equal to in terms of the chamber pressure; in terms of At and I can put it in terms of a co efficient. We derive the equation for this co efficient. We called this as C F ideal and we told ourselves look here, the thrust need not always be the same; that means, always I have pe here; I have the ambient pressure here. Always pe may not be equal to pa, but the thrust is a maximum in p is equal to pa; we called this ideal thrust coefficient as C F 0 when the exit pressure was equal to pa. Just same way I have a rocket

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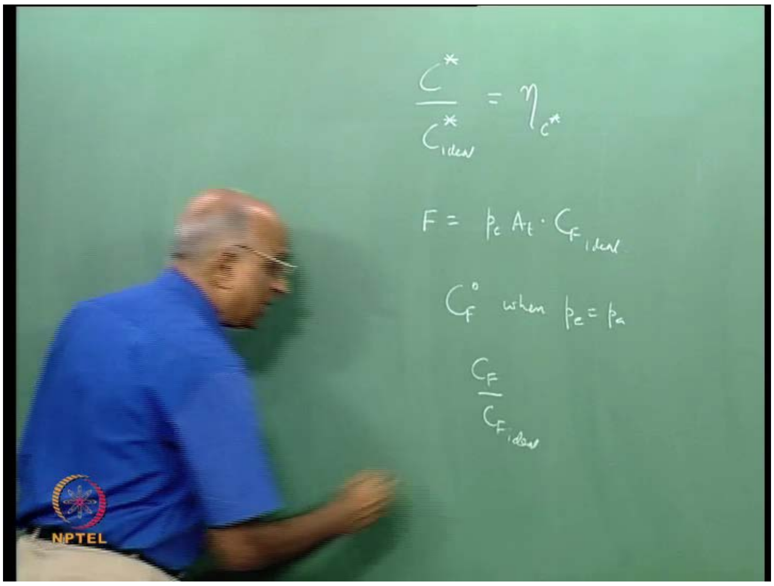

which is firing. I put some measurement here for a transducer; I measure what is the thrust what is did generated by rocket then, I go and measure the value of CF. I get the value of CF, which I calculate using the ideal value which we call as the thrust correction factor eta f. I think this is all what we did. We also did something which was important. We told ourselves instead of specifying the exit pressure and the chamber pressure, I can also specify a rocket in terms of a nozzle; in terms of the exit area Ae divided by the throat area which is no represented because, this is what mach number is always 1, we called it as Ae by At.

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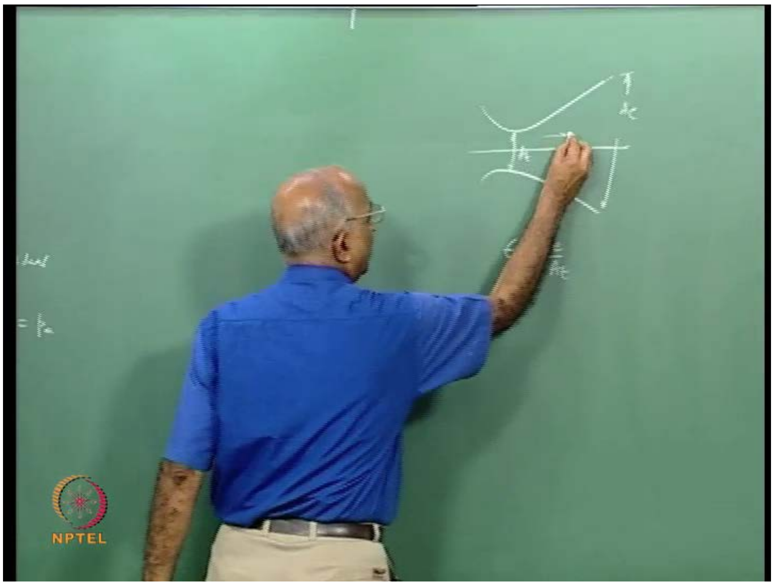

Right. Are there any questions on what we have done so far? Mind you all that we have done is for an ideal case, an adiabatic nozzle. And one dimensional flow you always said that flow is going straight like this right and all the mass flow rate is contributing to the thrust and expansion. Are there any questions so far? This is this is all what we have done in nozzle yes.

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Yes, let us lets k look. We… Your question is, how do we… Let me put your question on the board itself; it is something important.

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Why do we go for C star efficiency? The question asked is, why do we compare or club C star efficiency with thrust coefficient and call this is as the specific impulse. This is your question. Let us first clarify C star efficiency is something which tells how much chamber pressure is developed when I give a certain mass flow rate through the nozzle. The nozzle is identified by the throat area. In other words, the transfer function between mass per unit flow rate through the nozzle or mass flux through the nozzle at the throat to the chamber pressure gives me the value of the C star because, we had the expression p c is equal to 1 over no; let us put it down M star M by At. We could get the chamber pressure for a given mass flux at the throat and this is your transfer function. What does it tell us? What does this expression tells us? And we also had the expression C star gave me something like under root RT C by the by the value of capital gamma because of function under root gamma 2 over gamma plus 1 to the power gamma minus 1 gamma plus 1 divide by gamma minus 1. What does it really tell? It tells, supposing I have a mass flow rate through the nozzle mass flux through the nozzle,

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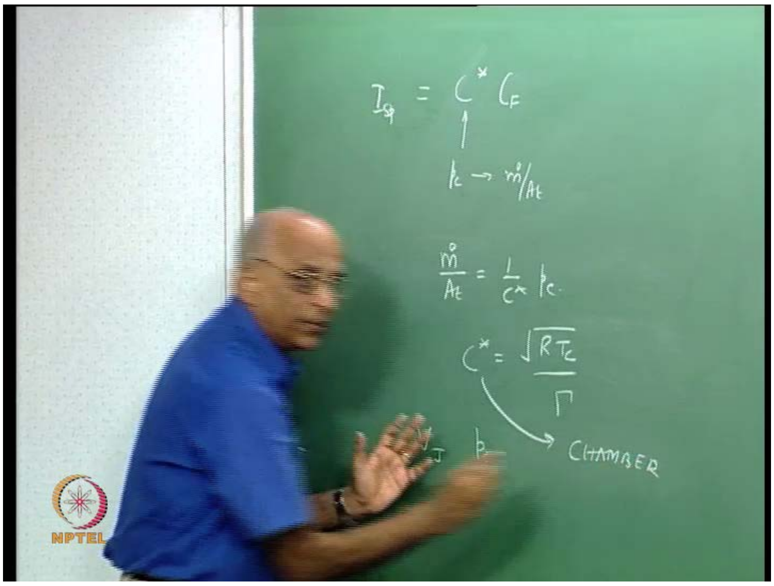

what is the value of chamber pressure I get and what is what is it we have been telling ourselves all along? To get a high value of V J, I need a high value of chamber pressure. Therefore, this C star tells you the capacity of whatever you have in the chamber to generate a high pressure. Therefore, C star is not a function of nozzle performance, but more like what how a chamber can build up high pressure. All what it tells you is let us take one or two small examples. Let us take an example of a rocket which burns; see we have still not done propellant that will be what we will do in the next series of classes.

Suppose, I have a tank containing let us say liquid kerosene I call it as kerosene. I have another tank containing oxygen; I take both these liquids; I take liquid oxygen allowed to kerosene over here. I take both of them into a chamber, and what is it I have to do? I have to push these things in and I have to generate a high value of p c and to be able generate a high value of p c, I also plug in some amount of total quantity of M kerosene plus liquid oxygen I put it here; I allow it to burn and when it burn and when it burns, I generate a value of p c. Therefore, C star tells me the capacity of propellants to generate

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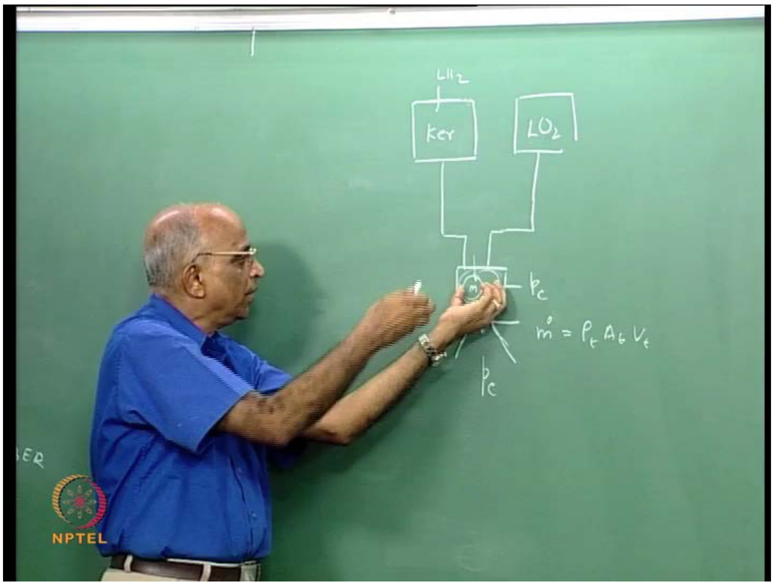

a high value of chamber pressure p c; that means, it is a chamber only. We are not doing, we have not done anything with respect to this because, C star we only look at the nozzle flow; we told ourselves well M dot is equal to rho t At into Vt. Therefore, we did not never really looked at the divergent part of it, we looked only up to this place. Therefore, C star is representative of the chamber to be able to generate high pressure gases when some mass is flowing. If instead of having kerosene and oxygen suppose, I have say liquid hydrogen and liquid oxygen may be the C star could be higher. Therefore, I would prefer this to this and C star therefore becomes a capacity of the chamber for a given propellant to generate high pressure gases.

Like normally, the value of C star is around 2000 to 3500 a lower performing rocket or propellant which are not that good will give me a lower value. Propellants which are extremely competitive, extremely energetic will give me higher value that is C star. Now, when I look at C F, what is C F? We define C F as equal to thrust is equal to CF into p c into At. In other words, if I have terminated the rocket at the throat itself; let us qualify this through another example. If I have a rocket nozzle and I terminate it at the throat where mark number is equal to 1 and now, I tell myself I have chamber pressure p c and now for all practical purposes, now I do a diagram over here in which, I say that p c is acting on all this areas p c is also acting on this area over here the normal to this is equal to this p c is acting on these areas; pc is also acting on this area over here. The normal to this is equal to this; p c is acting on the head end over here; p c at the nozzle end is acting. Therefore, this and this gets cancel; this and this get cancel.

The ultimate thrust what I get is something this is unbalanced; this is p c. If p c is very much higher than p, I can neglect it and therefore, my thrust is equal to p c into At just an order of minority. Now, what I do is, I have the divergent part like this and now I find that the force has somewhat increased

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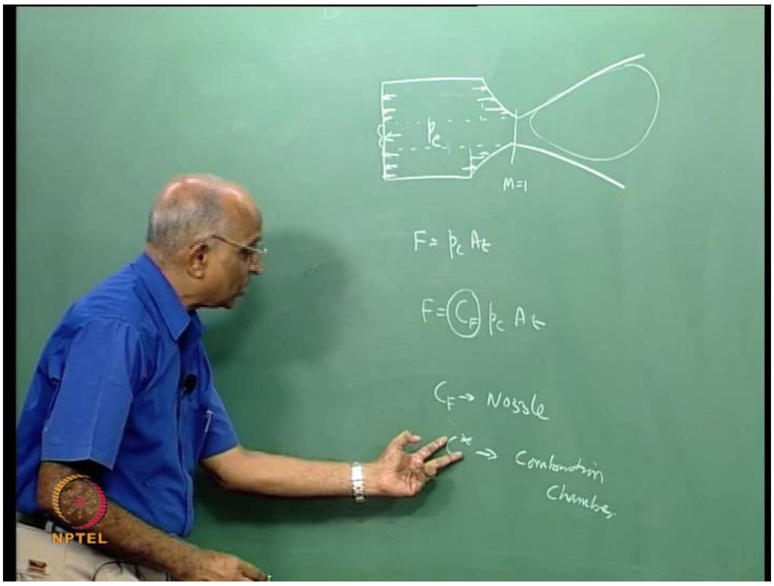

because of this expansion and therefore, I write F is equal to C F into p c into At. Therefore, C F is something like thrust magnification due to the divergent part of the nozzle and therefore, C F is a quality factor for nozzle. In fact, C F for most nozzles are between 1.2 to something like 3 or 4. You can work through some examples in the later part of this class. Therefore, I can tell you that C F is a quality factor for a nozzle; C star is a quality factor on the capacity to generate the pressure in the combustion chamber or in the chamber of a rocket, and the product we derived was the product of C F and C star is the net I sp. What is I sp? It is the total thrust divided by the mass flow rate.

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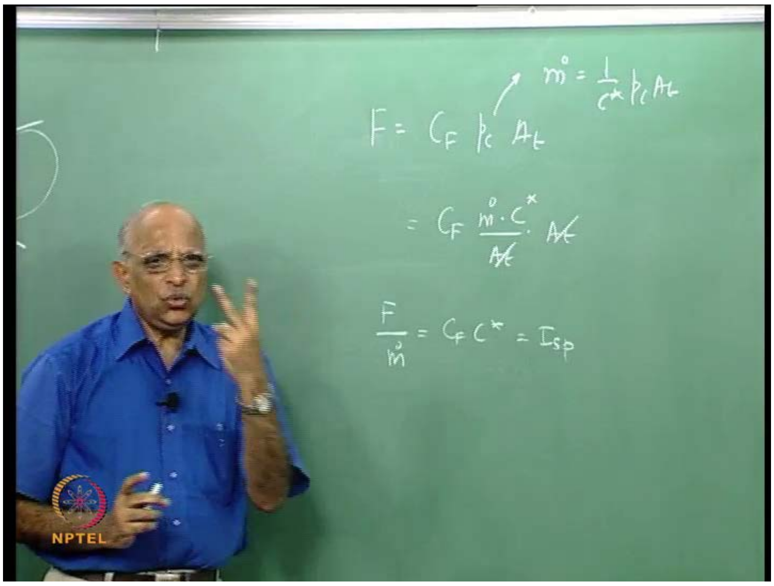

Let us put that down again because, we will expand on it a little bit in the next few minutes let us write it out. Force is equal to thrust is equal to C F p c At and what did we tell? Well, p c can be written as in terms of mass flow rate M dot is equal to 1 over C star into p c At and therefore p c At, I can write it as equal to M dot into C star divided by At into At; At At got cancelled and I have thrust or force divided by M dot is equal to C F into C star, and what do we get? Force M dot is equal to mass of propellant into time; F into time is impulse per unit mass of propellant was what we called as specific impulse of a rocket.

Therefore, the specific impulse of a rocket has two things in it; the capacity of chamber to generate high pressure and high temperature gases and how you expand the gases to get high velocity. Therefore, let us keep this terminology very clear. I have nozzle factor, chamber factor which gives me the net I sp of a nozzle. I will dwell on this a little in detail in next couple of minutes, let me get started with it because, all of us are not clear about area ratio, but does this answer your specific question, why C star? Why C F and what is the relation? How I got the specific impulse? Let us do one example; let me take the example of let us say a particular nozzle which operates let us say in vacuum, and let me take another nozzle which operates on the ground; let us say at Chennai which is at sea level; let us say, I have a nozzle this a chamber which generates high pressure. I have the exit; the exit pressure is equal to say pe. At sea level the ambient pressure is equal to pa at sea level it is equal to 100 kPa which is equal to 0.1 mPa right. Now, I want you to tell me what is the relation between let us say I sp. I want I spat sea level condition; I say I sp let me put it a little more clearly specific impulse at sea level. How do I write it? I write it as equal to m dot V J plus I have pe minus pa into what? ae momentum thrust plus the exit pressure minus pa into the exit area where ae is the exit area of the nozzle. Mind you we derive this, and we said we had control volume and therefore, we found a pressure thrust was there please check

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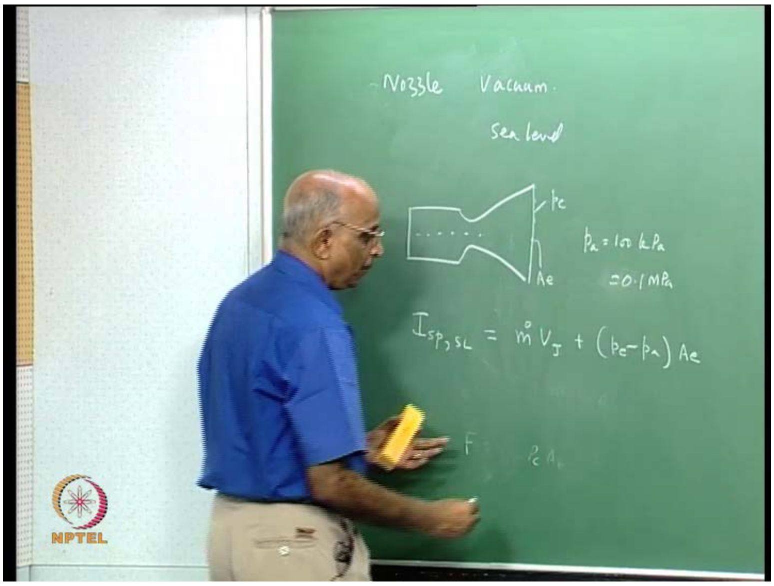

this again right. Can I go forward? Now, I want to be able to say if I say, I am looking at the same nozzle, if instead of operating on the ground sea level, if it is going to operate in vacuum, what is going to be the difference? Let us say the nozzle now operates in the vacuum, the same nozzle, the same area ratio this is the value I have pe; I have ae; the chamber pressure let us say p c. If it is going yes

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I sp sea level.

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Divided by m dot very good.

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No, let let let let us put it this way; let us redo it. F is equal to m dot V J. Therefore, specific impulse is equal to V J plus pe minus pa into ae divided by M dot; that means, I have more than the jet velocity; I have some contribution from this (( )). Now, I want to find out what is the specific impulse at sea level let us rewrite it. Specific impulse at sea level is therefore equal to V J plus I have pe minus pc no pc minus pa pe minus pa divided by m dot is a value into the value of ae at sea level.

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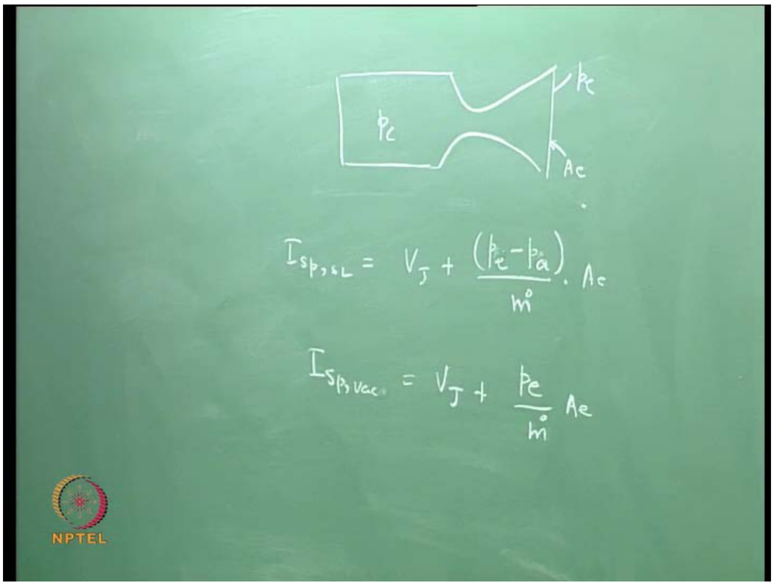

Now, what would be the value of specific impulse is the same nozzle functions in vacuum; I call it as vacuum specific impulse. Vacuum is equal to what would be the value? pa goes to 0 it is vacuum therefore, I have V J plus pe divided by m dot into ae. In other words, the same nozzle when it is fired in vacuum gives me a higher thrust because, minus pa is missing over here. Can I relate these two? Let us say I sp at vacuum; I find therefore, the specific impulse of a nozzle the specific impulse of a given rocket operating in vacuum is greater than when it operates on the ground. In other words, the specific impulse corresponding to operation vacuum is greater than when the same rocket operates at sea level conditions. Now, I want you to give me a slightly let us lets expand on this and find a relationship between the two. Therefore, I tell I sp at vacuum is equal to V J plus pe, what is the value of m dot? m dot is equal to 1 over C star into pc At yes in terms of C star, and I have the value of ae here; ae by At is the nozzle ratio which is equal to V J plus I have C star into pe by pc into E ratio. That is the nozzle area ratio over here. In other words, compared to a nozzle which gave me V J plus this value here, I get a much higher value and if this particular nozzle at sea level was such that I have optimum expansion namely pe was equal to pa, the I sp at sea level would have been just V J alone.

All what I am telling is, if the nozzle was such that that the exit pressure was same as the ambient pressure for which we told ourselves the C F is the maximum, we would have got the value I sp is equal to V J alone whereas, the same nozzle when I fly in vacuum, I get an additional contribution coming over here. Therefore, now the question comes how do I specify the specific impulse. If I tell if I say my rocket is flying in vacuum, I get a higher value of specific impulse. If it is tested on ground, I get a different value. Therefore, I must be clear in my terminology and therefore, two types of specific impulses are given; one is I sp corresponding to C F and the second is I sp corresponding to vacuum. Therefore, whenever we say a rocket somebody may give I sp at sea level, but we must be careful what he is specifying.

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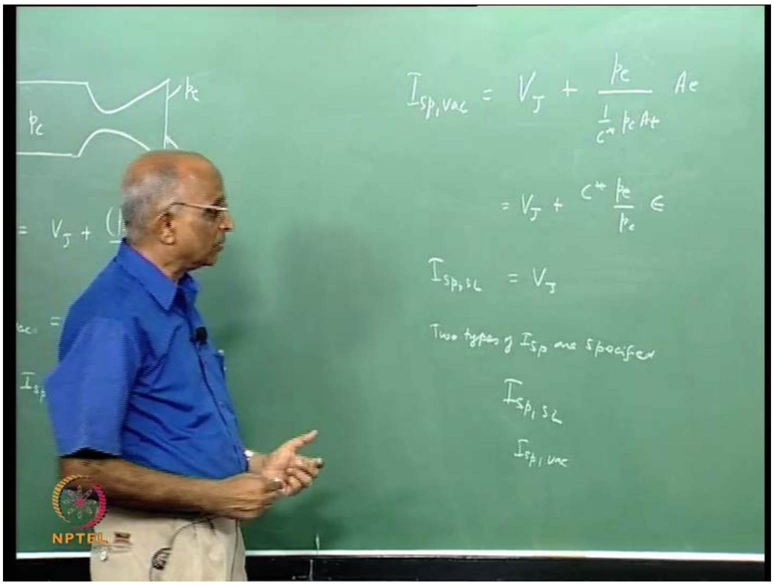

He is specifying C F which is the lower value whereas, somebody may be specify with respect to vacuum. Therefore, there are two ways of specifying the specific impulse whether a vacuum specific impulse or sea level specific impulse but then, there is another problem. If I have a higher value of chamber pressure, I get a higher value of expansion ratio and I can get a higher value of the specific impulse. Therefore, I also need some terminology which says a standard and the standard chosen is we specify specific impulse for pc equal to 7 mPa or 70 bar pressure; that means, specific impulse is normally specified when the chamber pressure as a standard is equal to 70 bar; the sea level

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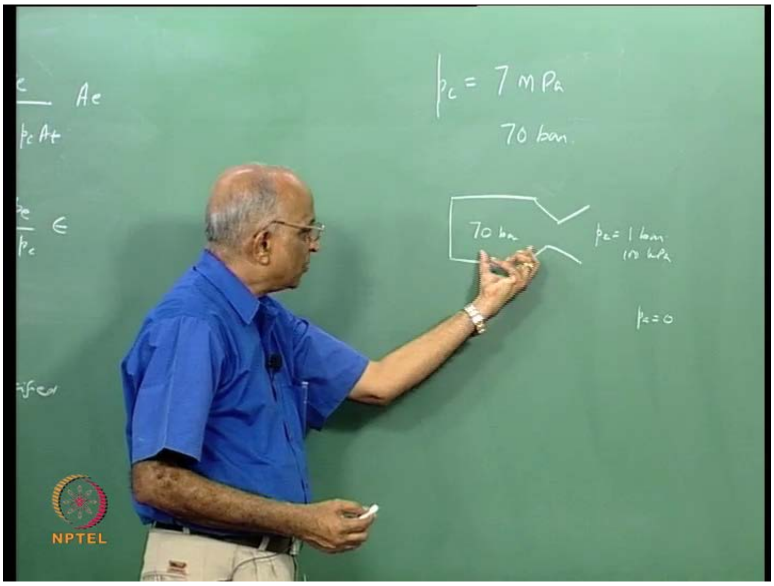

when the ambient pressure is equal to 1 bar or 100 kPa pressure whereas, when I talk in terms of vacuum well, I am saying that pa is equal to 0 bar vacuum, but I still keep 70 over here; that means, there are some standards because, rocket can fire at different pressures, but if we to compare something, we need some standard and that standard is a chamber pressure of 70 and an ambient pressure of 1 bar for sea level value I sp and if I consider vacuum it is there, but something to remember is well, the vacuum specific impulse is higher than the sea level specific impulse which is essentially V J when the exit pressure is equal to ambient pressure. I think this is all what we have done so far right. Are there any other questions on what we have done? If not, let me go further. See so far, we have been talking of only one dimensional flow right. We told ourselves well, I need a divergent part and I know my divergent part looks like this.

I have the convergent part, but I am really not bothered about convergent because, anyway at throat I have mark number is equal to 1; I have a chamber over here p c. Now, my divergent part you know something like it is diverging out, and if I look at the flow which is taking place, the gas which is flowing near to the wall will have a divergent direction along the wall which is flowing along the axis, will have flow along the axis.

Therefore, how can I how long I justify in assuming one dimensional flow it is really not correct, I have to make some corrections for may be the radial flow or for the divergence in the flow correct. There is a simple way; that means, all my thrust is not going in this direction; a component of thrust is going in this direction; it gets balanced out and only my effective thrust in this direction which is what pushing me is going to decrease. How do I get that value? May be let us address that in the next few minutes let us let us look at that, we look at that divergent center line.

Well, there is a actual flow over here; let us assume that the half divergent angle is alpha. Now, the flow near the wall will be alpha may be you know I have to take some approximation may be if I consider on an average, the flow may be alpha by 2 because here, it is alpha along the center line of symmetry it is actual; may be the average value of the flow or on an average the entire flow we can say goes through alpha by 2. I can do it rigorously, but this will this is sufficient for me to give an answer. In other words, on an average the flow leaves at a at an angle equal to alpha by 2. Is it ok? Now, I tell myself well, what is thrust? Let us assume that the nozzle is adapted; that means, ambient pressure is equal to pc here; F is equal to m dot into V J over here. What is the mass which flows along the axis now? It is equal to m dot into Cos alpha by 2, that is the actual mass flow rate because, on an average some goes at alpha, some goes at 0; the mean z is alpha by 2.

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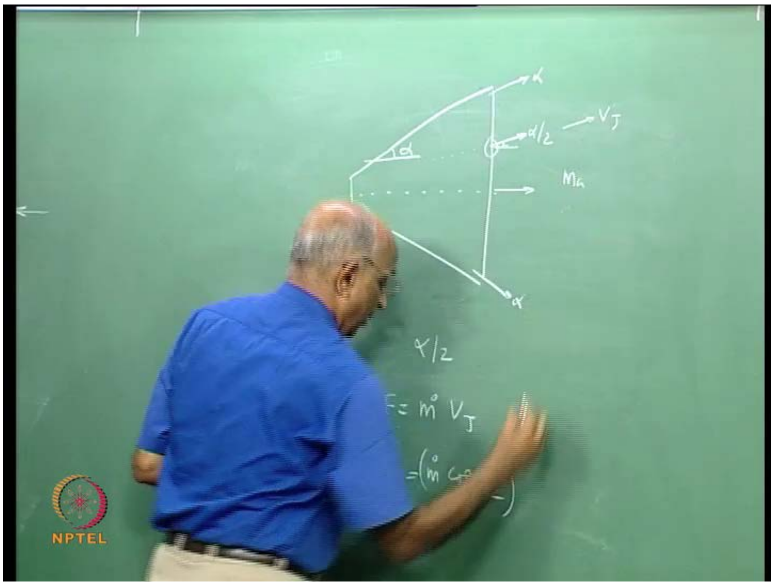

The average mass is Cos alpha by 2; V J is again corresponding to this over here is equal to V J Cos alpha by 2. Therefore, the thrust due to the divergence being at an angle alpha will therefore be F is equal to m dot V J Cos square alpha by 2; please be with me. Is it all right? All what did we told was flow is not all actual. Flow towards the wall is alpha; on an average the flow is alpha by 2 and therefore, the mass component along the axis is equal to m dot into Cos alpha by 2. The velocity on an average tactual velocity is equal to V J Cos alpha by 2. Therefore, the product of m dot Cos alpha by 2 V J Cos alpha by 2, this make Cos square alpha by 2. Now, I want to simplify this expression therefore, we use the term Cos 2 theta is equal to 2 Cos square theta minus 1 or I have Cos square theta is equal to 1 plus Cos 2 theta divided by 2 and therefore, I can write Cos square alpha by 2 is equal to 1 plus Cos alpha divided by 2. This at trigonometric manipulation because, I can express it in terms of the divergence angle half divergence angle of the nozzle. Mind you the total divergence is 2 alpha; I said alpha is equal to half divergence angle over here.

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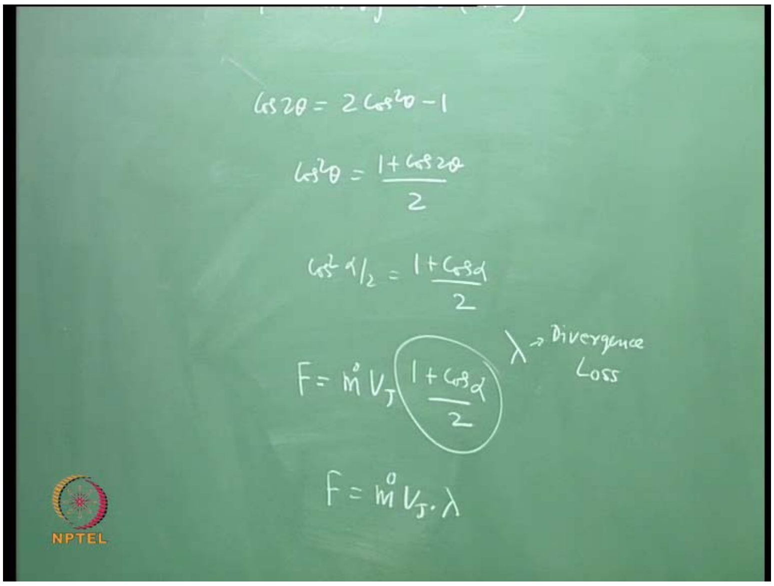

Therefore now, I get thrust of a nozzle F is equal to m dot V J into 1 plus Cos alpha by 2, and this is the loss due to the divergence and therefore, this is denoted by the word lambda, by the letter lambda and we say lambda corresponds to divergence loss or F is equal to m dot V J into lambda. Well, lambda is something we say loss due to divergence, but I am really looking at a loss you know; see actually, I am just multiplying it by a factor. Therefore, if I have to have a loss, the loss should be something different. See, we say lambda is due to non availability. What is non available? What is non available is delta let us say, what is not available? What is not available? The thrust not available is equal to 1 minus lambda. In other words, this tells me the fraction by of the availability which we call as divergence loss factor, and if I want to put it explicitly in terms of something that trust is not available, it is equal to 1 minus lambda. Therefore, I have defined two terms and what are the two terms for a for the actual divergence effects? We define lambda is the divergence loss factor or rather I have to multiply the value of m dot V J by lambda to be able to give me the thrust.

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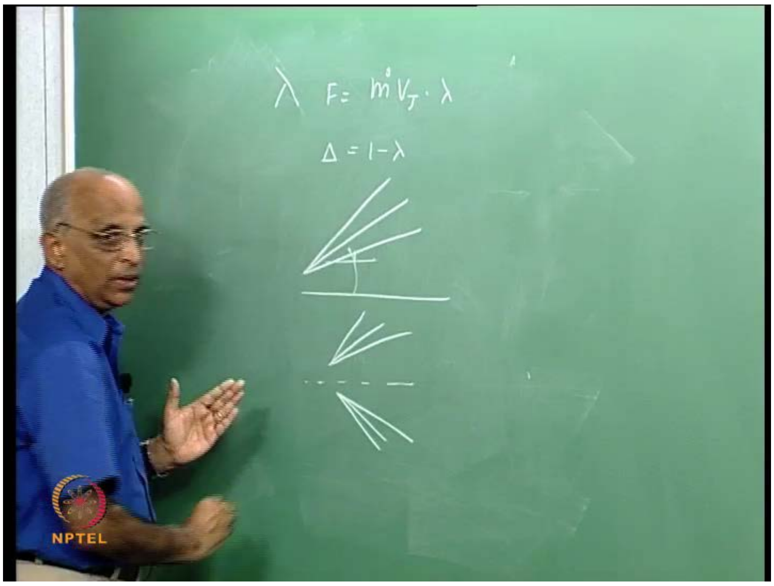

What is not available? The thrust, if everything was actually would be m dot V J therefore, 1 minus lambda is not available. Therefore, I said capital delta related to the available lambda over here. Now, why am I doing all this; I would like to still have a nozzle in which I do not have too not much of this loss coming. Therefore, let let let us put some numbers on it; let us put some numbers which will help us to clarify and let us say alpha of a nozzle could it be 0; it is not possible because, I have a parallel nozzle. It could be 5 degrees alpha; it could be 10; it could be 15; it could be 20; it could be 25 let us say 30. In other words, I am looking at different nozzles for which let us say divergence angle half divergence angle varies from 0 degree in which case I have total effect, but this is not diverging therefore, this is really not a case to be considered, but let us include that or I have 5 degrees, 10 degrees and so on; 5 degree divergence and so on; I am vary divergent angle.

In other words, I am looking at divergence of nozzles with different angles as it well. I want to find out if I have these nozzles, what are the typical losses I have. Therefore, I like to put the value of lambda for each of the angles, and also I would like to find out what is the real loss; that means, this is a divergence loss coefficient and this is the loss which I have in the nozzle. I worked out these values and let me quickly go through it, and it is quite easy to do it; you just find out the value of Cos alpha. In other words, when alpha is 0, Cos alpha is 1; therefore, the value of 1 plus Cos alpha by 2 is 1; that means, the entire thrust is available and the loss coefficient is 0 or in terms of percentage it is 0 percent.

When I have the value of alpha equal to 5, the value of lambda we said is 1 plus Cos alpha by 2; Cos alpha is around 0.99 something and the value of lambda comes out to be 0.998, and if I have 1 minus lambda, it is equal to 0.12 percentage; that means, 0.0012 it should have been actually 78 or 880 over here yeah 12 correct 0.0012 which gives 0.12 percentage. If I have the angle as 10 degrees, it is equal to 0.9924 and the loss which comes out to be 0.76 percent. Let us put few more values for 15 degrees, the value is 0.9830 1 plus Cos alpha by 2 and the loss is 1.7 percent. If it is 20 degrees 0.9699 1 minus lambda gives me value of around 3 percent that is 0.97. If it is 25, it is 0.9537; I will qualify these numbers and the loss is 4.63 percent or 0.0463. Well, last value I will put for 30 degrees 0.933 and this comes out to be 6.7 percent. If I were to put one more angle let us say 35 degrees, the value is 0.9066 and the value is something like a 9.04 percent. What is it I am doing? I am considering the divergent angle of the nozzles to vary from 5 degrees to 35 degrees for each of the values, I get the divergence coefficient and also I am putting the loss in percentage. You find when I go for 5 degree, I am losing just 0.12 percent thrust; for 10 degree I am losing 0.76 percent thrust; when I come to 15, I have lost already 1.7 percent thrust; when I go to 20 I am quite higher, I have lost all those 3 percent of the thrust; when it goes to 25 it becomes 4, 6 and all that.

In other words, it does not become meaningful to have any divergence angle greater than 20 degrees. In fact, I were to compare this and this

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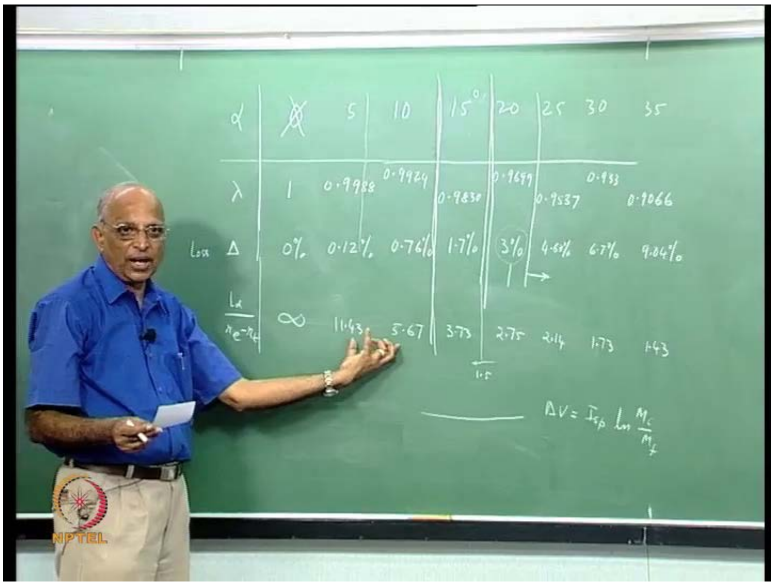

I find that, this is something like 1.0 here. The value is 1.75 times more; loss is 1.7 times more than if alpha were equal to 15 degrees. In other words, if the half divergent value was 20 degrees, the loss is quite heavy here; it is something like 1.175 times more than this particular value; that is 3 divided by 1.7 is almost like 3 quarter and that is that is 1.75 times more than this value. Therefore, you know the general practice therefore is let us let us adapt some value around 15 such that the loss is somewhat small. What loss? The divergence loss, but that is not the only reason. Let us try to put one more number on to it. Let us say I have a nozzle, I find that

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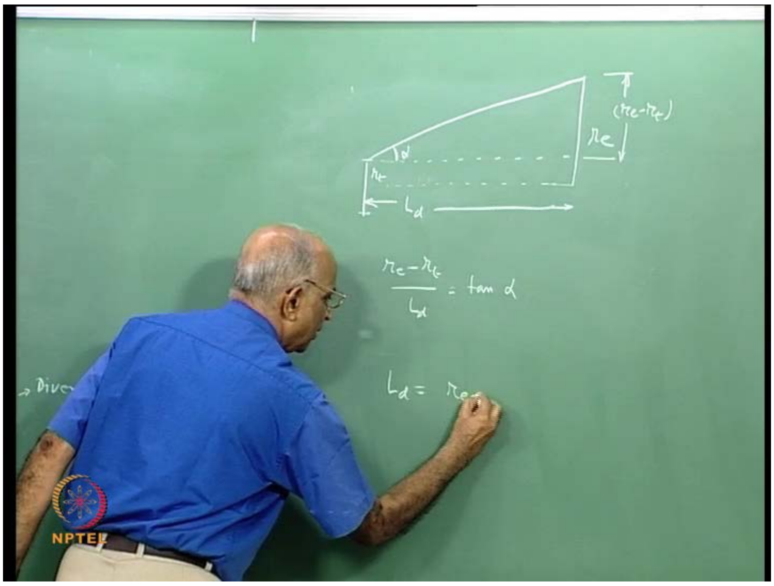

If I a very small angle of 5 degrees or even 1 degree, my loss is almost going to be negligible. Therefore, why not have such a small angle. Let us let us see, what is the implication of it? Let us say, I have nozzle center line; I have the throat; the throat radius is rt; the exit value is re and what is alpha? alpha is a value of this angle alpha.

In other words, the value of re minus rt which is this value divided by the length of the divergent L d is equal to tangent of alpha or the divergent length L d is equal to re minus rt of the tangent of the value of alpha. Is it all right? All what we are saying is, if I have a small angle nozzle for the same exit diameter, I will have a much longer one. If my angle is 0 well, my length will be infinity. Therefore, let us put the same thing down over here into this plot; what will we find? Well, I just put the length of the divergent for a particular case let us say and since I do not know rc and rt to come in the picture I say, L d divided by rc; r at the exit re minus radius at the throat. I find for 0, the length of the nozzle is infinity.

If I have something like 5 degrees, it becomes 11.43 the particular ratio. If it 10 degrees, it is 5.67. If it is 15 degrees, it is 3.73. If it is 20 degrees, it is 2.75; 25 it is 2.14; 30 degrees it is 1.73 and if it is 35, it is 1.43. What is it we are telling? The length of the nozzle is very large if the angle is very small and the nozzle length reduces, but if compare these things around 15 degree if I take; if I compare 3.73 with 2.75 well then, change is not as rapid as it is for smaller values. In fact, we find that it is something like 2.75 is something like 1.7 times only and it becomes even smaller. Therefore, since the nozzle length as it becomes longer and longer, the mass of the nozzle becomes larger and we also told ourselves delta v, the ideal velocity of the rocket is equal to you have I sp or V J lon of initial mass to final mass of the rocket. The mass of the rocket will go up as the length of the nozzle increases and therefore, it is not good for me to go for very narrow nozzles angles because, the length of the nozzle becomes hard; the weight of the nozzles go up and therefore, the general practice is to choose a divergence angle around 15 degrees. Mind you it is just based on the premise that, I do not lose any further; I do not lose too much of thrust here, but at the same I do not lose too much of thrust; I have lost only 1.7 percent and there and also my nozzle weight does not go up drastically as it is if I go for smaller angle. Therefore, all what I will tell is based on this divergence analysis, we can tell ourselves that a conical nozzle will normally have a semi divergence angle of 15 degrees. We will not go for smaller angles because in that case, the nozzle becomes long and weight goes up; we will not go for larger values of angle because, if we go for larger angles, we will lose more by the thrust as it well. Therefore, the optimum for a conical nozzle is generally kept at 15 degrees semi divergent angle.

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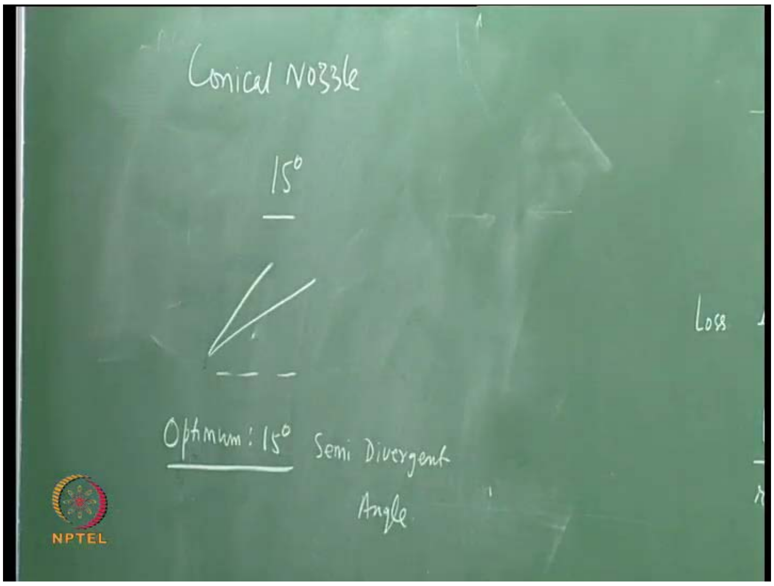

Does it make sense? does it meaning? Now, if this part is clear I just have a few more things to tell in a nozzle. The question is, why did we address this divergence problem in such a critical way like for instance. We told ourselves well, your nozzle is something like this divergent and you are interested in this angle being alpha; you do not want to lose thrust. What prevents us from having a nozzle which I can bring it back like this; I can initially expand it out and bring it like this. What am I talking? Let me make myself a little more clear. We have the throat here; I have a conical nozzle. If I have the divergence angle alpha and the divergence angle at the exit is important and if I have, if I can somehow reduce

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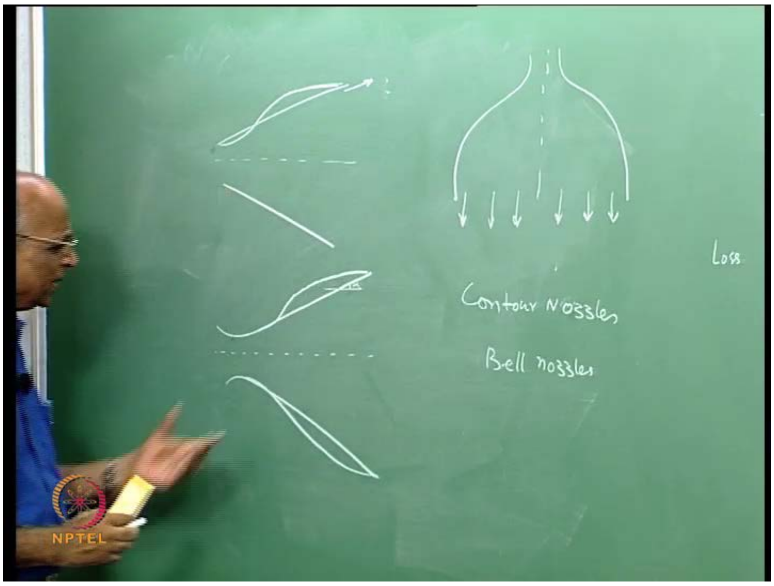

this divergence angle over here and in the initial stages what I do is, I expand it like this and bring it back like this; that means, I expand it out and bring it like this or the shape looks something like a bell; the shape of the nozzle looks like a bell here; I am sorry the figure is not. All right, this is the center line; how does a bell look like? Like this. Initially, I expand it out; I decrease the divergence angle such that the flow goes out actually.

In other words, I have a contour for the shape and these are known as contour nozzles or simply stated bell nozzles. I think I have to spent a couple of minutes on this, let us try to find out what exactly is the role of this? Why did I say initially you expand out the gases? Let us let us plot out the pressure distribution in the nozzle because, we now know how to do it. We told ourselves the pressure at the throat is equal to 2 over gamma plus 1 divided by we had an expression gamma by gamma minus 1 let let let us let us do that chamber center line. We have the nozzle convergent; I have a conical nozzle. Let us say the angle is still meaningful let us say around 15 degrees, I have I do one dimensional analysis; this is the throat. I plot the value of pressure in the nozzle as a function of distance over here. This is from the chamber; this is at the throat t and you have the divergence over here at the exit at the exit over here.

Now, what will the pressure be from the chamber pressure which pressure keeps falling; Let us say this is the chamber pressure value at the throat it is you know, how to calculate 2 over gamma plus 1 into gamma by gamma minus 1 if the pressure keeps falling like this and this is the exit value of the pressure. This is for a conical nozzle. All what I am trying to say is in this part, the pressure is still quite high therefore, over here may be I slightly what I do is, I expand the gases little bit more because, the pressure is high, the flow cannot separate; it has to follow the wall and then, I reclaim it and bring it back here. In other words, over here I expand the gases at higher pressure and then, I bring it out over here.

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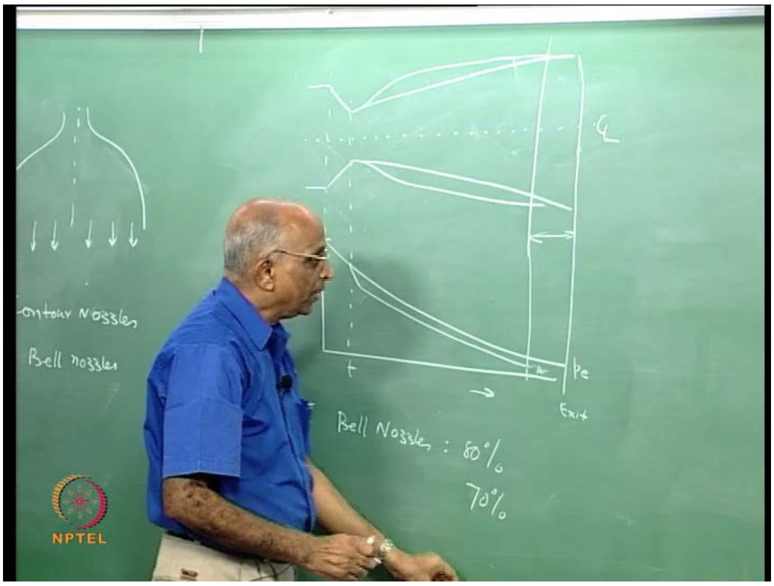

In which case it could be possible for me to even reduce the length of the nozzle and therefore, these bell nozzles are specified in terms of let say 80 percent bell or they say 70 percent bell, what do we mean? A bell nozzle whose length is 80 percent of a conical nozzle is all what is required. I can terminate this over here because, here itself I got the value of p and therefore, I am able to use a conical nozzle or a contour nozzle much more effectively than a bell nozzle than a conical nozzle. In other words,

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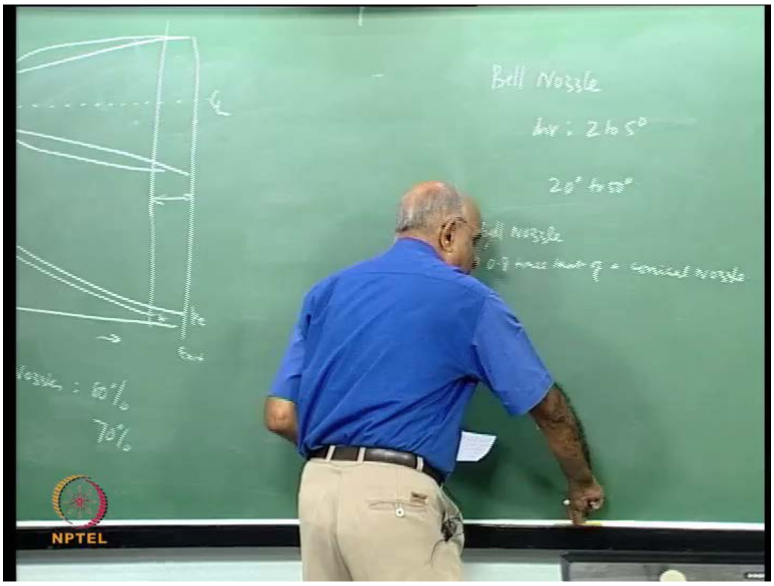

a bell nozzle, I can give a divergence angle between let us say 2 degrees to something like 5 degrees. Initially, I expand it rapidly; here I give a large value may be 20 degrees to 15 degrees and in the process, I can make the nozzle a little more stubby and I tell that the length of the bell nozzle could be a fraction of this and this is what we called as a bell nozzle. 80 percent bell nozzle means, the length of the bell is 0.8 times that of a conical nozzle. What do we do in a bell nozzle? We immediately expand downstream of the throat; allow the divergence to be smaller such that I lose less nature of the divergence loss. In fact, one paper which we all must read was is by I will give you that paper here; it is very important.

It was first put forward in rocket dime I think and this particular person who worked on it is an Indian by name G V Rao, G V R Rao it is known bell nozzle is also known as Rao's nozzle; it is known as exhaust nozzle contour for optimum thrust.

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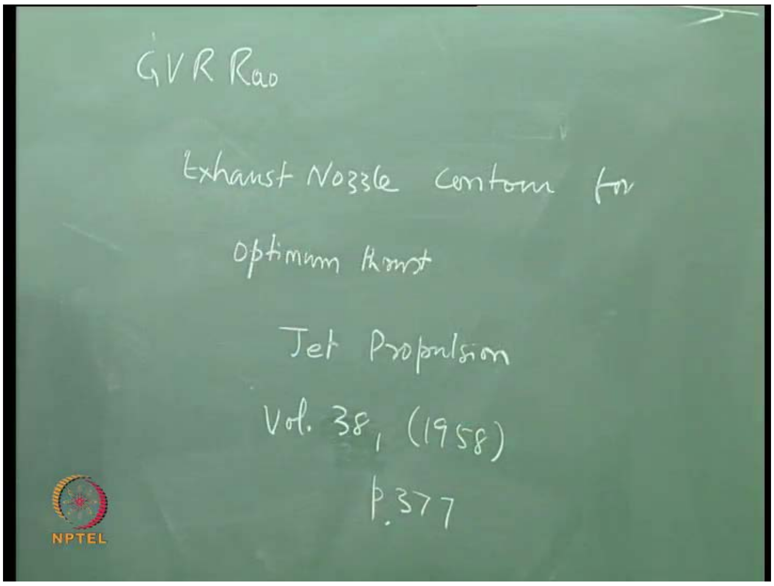

This came in a journal known as jet propulsion which preceded the a journal volume number 138 no volume 38 I am sorry 1958; the page is 377 to I think 381. Please if you have sometime, please go through this. You know, all what is done is if you want to work out in detail what is happening in a bell nozzle is, you expand the gas rapidly; you have something like expansion and then, you have compression. It compresses the flow and comes over here with the result. I can afford to have a shorter nozzle compared to a conical nozzle which is a bell nozzles and most rockets make use of the bell nozzles, and if I have a bell, nozzle none of the earlier criterion like flow separation and all are possible because, I am having higher pressure gradient along the wall. Therefore, whenever we talk of Somerfield criterion saying exit pressure is 0.4 times the ambient; it is more applicable for conical nozzle and not for bell nozzle. I think this is all about nozzles; conical nozzle may be the contour nozzle. I want to spend another few minutes on different types of nozzles. Can we have different types of nozzle

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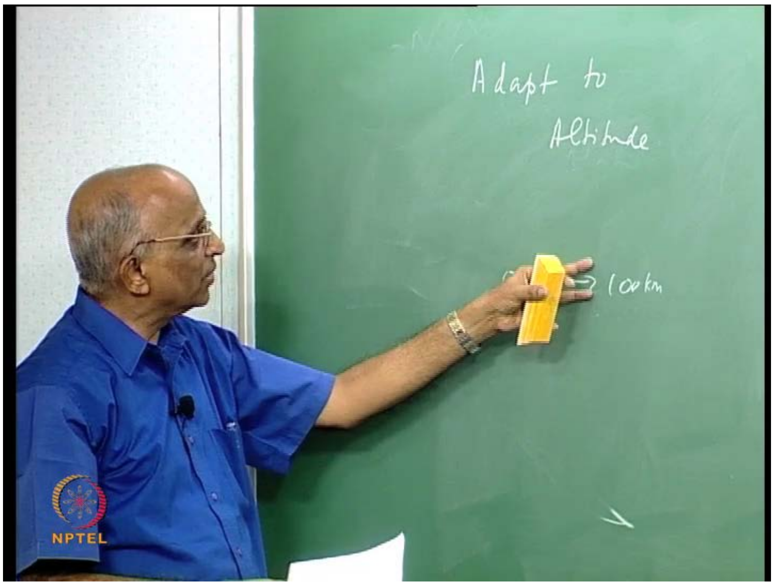

something like which I would like to say is, is it possible to have a different type of nozzle all together. A nozzle we say has to adapt to altitude; that means, can I make it to adapt to different altitudes start from 0 kilometers and keep going up to 10 kilometers or 100 kilometers for the same nozzle and may be some of these things I will do in the next class; may be just spent 5 to 10 minutes on different types of nozzles and work out one or two small problems. Well, thank you then I think that is enough.