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NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

Aerospace Propulsion

Rocket Nozzles – Real Effects II

Lecture 22

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The last class we have seen what are the non isentropic factors that cause losses and we identified three of them the momentum lost due to friction and the constriction of the flow passage these are not going to be very large it said that heat transfer to the wall is a major factor.

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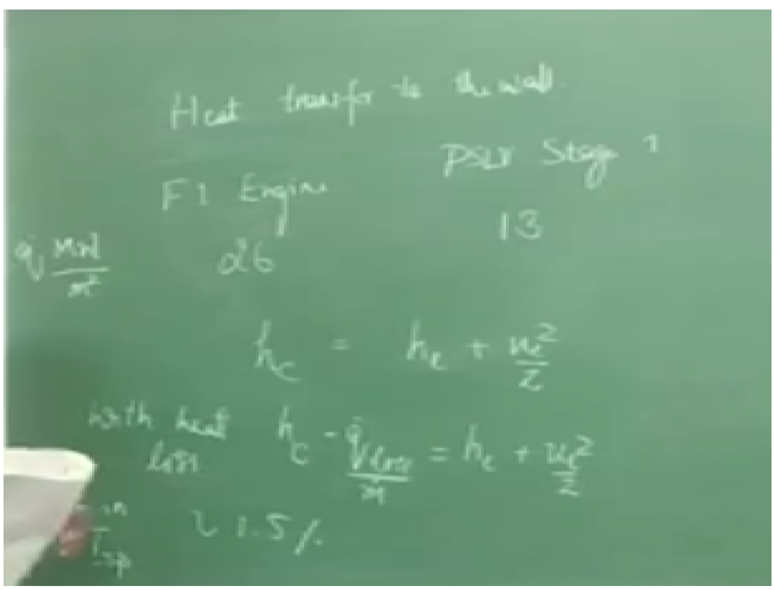

If you look at large motors the first two that is momentum loss due, to friction and constriction of the flow passage will be smaller but this component will be a major one f1 engine for example f1 engine, f1 engine was the engine used on the mission that went to took man first time to move right Saturn 4, so f1 engine it is a liquid engine and if you compare our own PSLV stage one and if you look at the overall heat flux Q. MW/m^2 the f1 engine has something like 26 MW/m^2 this is the heat transfer to the walls okay and this is somewhere around 30.

So it is a very large heat transfer to the wall now there are two things here one if you want to maintain if you have good material that is a advantage here because then you can allow the walls to be at a higher temperature and still operate the engine okay but if you if your material science is inferior then you like to settle at a lower temperature which means you lose more heat to the watts okay and this in turn impacts the specific impulse if you look at the energy equation that we had for the nozzle we had without loss we had written something like this he+ right.

Now if there is a loss then we have to account for it like this right so if you notice this has a - sign so therefore you will not be able to get the ue that is required ue in other terms is nothing but ISP so you will have a reduced ue okay typically it is of the order of something like loss in ISP is around 1.5 % because of heat loss to the worlds this loss is around 1.5 % of the ISP okay so if you if you do something like regenerative cooling most of it you can recover okay we will discuss about it when we discuss about cooling techniques a little later in the course.

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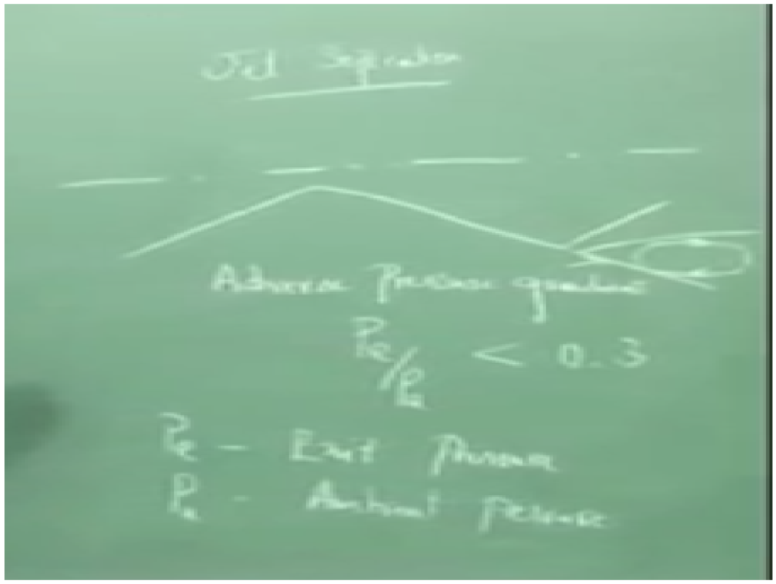

Now the next non isentropic the next the other thing that causes non isentropic behavior is jet separation if you take one half of the CD nozzle now if you remember when we talked about under expanded and over expanded flow right there is a particular criterion known as some field criterion by which you can say that if Pe / Pa is less than somewhere around 0.3 Pe is the exit pressure and PA is the ambient pressure up to this the flow somehow manages to adjust itself to the surroundings by having shocks and expansion fans and shocks on the outside right.

But what happens when it crosses this is the oblique shock moves it okay and you could have an oblique shock setting in the supersonic portion here itself and then what happens after the oblique shock is it is a strong enough shock the flow will tend to separate because the Mach number will reduce from here to here it will become subsonic right once it becomes subsonic that is considering the oblique shock is strong enough.

Then once it becomes subsonic this is like a diffuser and therefore pressure will increase right and this has an adverse pressure gradient so you will be having something like adverse pressure gradient in this portion in this portion and therefore the flow tends to separate so you could have flow separation taking place here and there could be a recirculation bubble sitting there what it does in a conical nozzle is it acts as though the nozzle is cut off right here okay.

So it is just like you are using a smaller nozzle right if you remember in the previous class we looked at what happens to the performance of a contoured nozzle as well as a conical nozzle and we said that the conical nozzle has a better performance of the under of design conditions right if it is designed for a higher altitude and we use it at a lower altitude.

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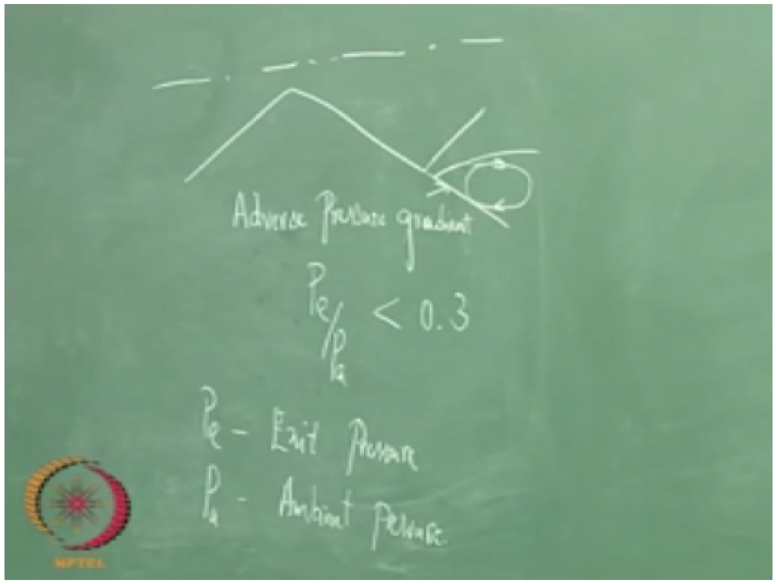

If you remember the craft this is F / F actual by F I do so if you have a nozzle design for a condition here somewhere around 14km a bell nozzle would go like this okay this is right so if you look at this in a contour nozzle or in a conical nozzle it acts as though you are cutting off the nozzle at this level and further there will be no use of this divergent portion right so it is acting like a nozzle being cut off here and the shock tends to become stronger and stronger depending when what the ambient pressure is okay.

Why does not the same happen in a bell nozzle they trouble with bell nozzle is if you look at the contour we warned the angle at the exit near the exit to be smaller right and what happens is it is not very clear as to where this flow separation will take place it could be on one side in one area I mean it could be at a different place in another area which means there will be a tremendous sight forces that will come on the nozzle right it may not be symmetric because the angle is very shallow.

If you look at it we would want the angle to be somewhere between 2 to 10^0 right it is very shallow and it is almost flat so depending on which place this flow separation takes place and that need not be symmetric across the nozzle so what happens is you will have enormous right forces and that is why you will not be able to derive any benefit out of it right that is one problem and also because it is it is very shallow it tries to accommodate it even further right the angle is very shallow only you have a very high angle right at the beginning and then the angle is very shallow in a contour nozzle right.

So it trained to accommodate it and only when the flow separation happens here which is at a much lower altitude then it becomes like a nozzle being cut off dead right so that is why it is off design performance as a lot worse than a conical nozzle right which is why if you look at most missiles or launch vehicles the lower stages will have a conical nozzle primarily because it is going through the atmosphere and the expansion's ratio that is available pressure ratios are smaller but the higher altitude nozzles they will have a much larger expansion ratio and it is beneficial if you go for a contoured nozzle there okay we will come back to this jet separation a little later when we are trying to look at how do we control a rocket motor right.

If you have a launch vehicle or a missile you would want to take it in some particular path so you should have some kind of thrust vectoring that is to be allowed for right to do the thrust vectoring you do something called secondary injection okay SITVC we will discuss that a little later in the course this is where this is what comes into use there now we have talked about non isentropic flows let us now talk about losses due to two phase flow.

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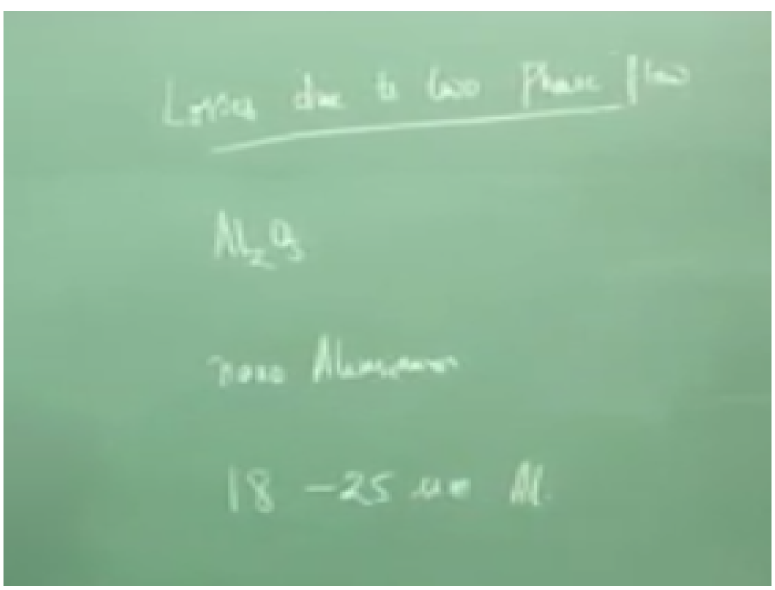

This is most predominant in solid rockets not so much in liquid rockets also in solid rockets which use something known as a composite propellant now these propellants are rich in aluminum they have something like 18% of aluminum that is loaded in order to increase the specific impulse okay now aluminum when it is oxidized it becomes alumina Al_2O_3 right now alumina it has a melting or a boiling temperature of around 2000, 300 Kelvin so in the nozzle during expansion process there could be if you are using a high area ratio and also right it could reach a temperature in the nozzle where an the temperatures are below this right.

So then it will start becoming a liquid now the trouble with this is the liquid does not expand gases can expand in the nozzle but liquids cannot expand right so because this is not expanding it is actually causing a drag on the rest of the flow so due to which the ISP's will drop because of this drag and it increases if you increase the aluminum loading if you increase the aluminum loading for some reason there are missile applications that will allow only something like 4 to 6% aluminum loading there are more strategic missile applications or the launch vehicle applications which have something like 18 %.

So it will be a lot smaller and applications which have lower % of aluminum and a lot higher in applications that have higher % of aluminum and it is also known that this has some relationship to the kind of particle size distribution that you give to the aluminum in the propellant let us say you have a very coarse aluminum particle it is noticed that this loss will be much more than in the case of very fine particles okay if you have a fine particle this is something like this aluminum is known to agglomerate as it goes through the combustion process right in the rocket motor.

Now if it is a large particle size you all know from fluid mechanics that if you have a large particle in a flow the drag caused by it is much more than if you have a fine particle only right so if you have a fine particle the drag is less if you have a large particle the drag is more so people have noticed that there is some relationship to the particle size that you input into the propellant okay and that is why people have all also been talking of something known as nano aluminum that is if you have a smaller very fine particle size typically in solid propellants what you use is something between 18 to 25 micron aluminum.

Now if you replace this with an aluminum whose particle sizes in nanometers right then they have noticed that this kind of losses is smaller okay there is also one more problem that sometimes is there in if you use aluminum in propellant solid propellants that is if you have a nozzle that can be flexed flex nozzles it is noticed that there is a slag accumulation because of this molten aluminum tends to accumulate and it causes a slag which could be of significant magnitude depending on how large that cavity is right.

So it also leads to an increase in weight which you would have probably not accounted for when you are designing everything this tends to increase the weight of the launch vehicle as it goes along in fact if you look at the Space Shuttle disaster one of the Space Shuttle disasters this lack prevented you know the hole in the motor tube from being seen up to a very high altitude and then because there was some aircraft that had traveled in that zone and this when this launch vehicle went into that zone there was air turbulence and because of which this lag got rid of and again that hole became much more prominent.

And the hot gases went and impinged on the hydrogen tank and that led to the subsequent explosion of the entire vehicle so now till now all the things that we have discussed starting from divergence loss to non isentropic flow behavior and losses due to two phase flow all of them if you see are decreasing the ISP from what we had calculated right they are going in one direction now the next thing that we are going to look at that is namely kinetic flow effects this is going to in essence increase the ISP.

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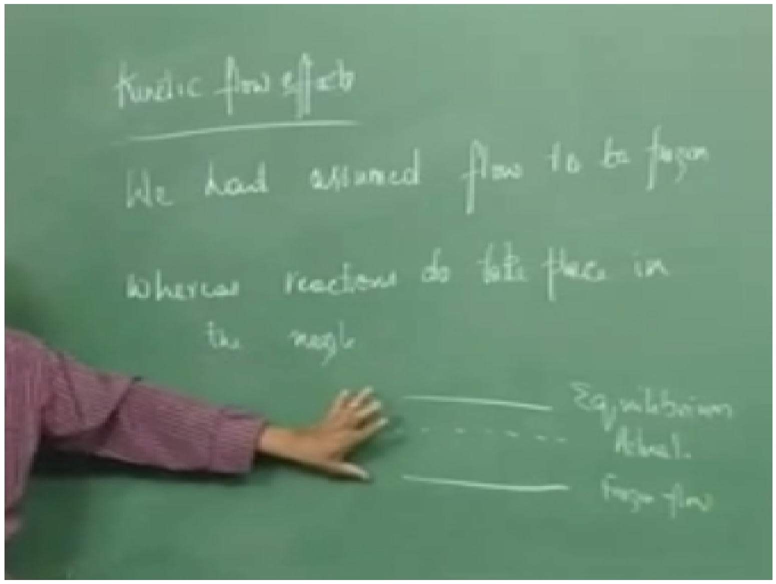

If you remember in our assumption if trying to derive the nozzle equations right we had made one assumption saying that the property's thermodynamic properties are constant across the nozzle like from the entry to the exit the thermodynamic properties will be the same which means that CP and γ are going to be the same in an actual case this is not so okay what happens is if you look at temperature and pressure right in the nozzle they are both decreasing and if you remember your high school chemistry wherein you learn something about exothermic reactions and endothermic reactions when they are favored when what is favored.

Right when are exothermic reactions favored when temperatures are lower right, so actually if you see in the nozzle the temperatures are getting reduced and therefore some more exothermic reactions to take place in the nozzle right so because of which you will get a slight improvement in ISP so that is what we has been noticed we had assumed the flow to be frozen lettuce reactions do take place in the nozzle because temperatures and pressures are decreasing so there is a certain amount of exothermic reactions that will take place.

Now in a sense we are not able to kind of make out what is the extent of these reactions okay there are two ways that one can get a solution one is if we can get the exact solution right if not the next best case is try and find out the bounds okay if you have a condition wherein you cannot estimate how much is the extent of reaction there is a possibility of doing this in one sense that if you assume the flow equilibria at each and every section of the nozzle okay then you will get a certain improvement and performance right.

That is one bound the other bound is it does not have any time to equilibria and therefore there are no reactions that are taking place so essentially what we are saying is one is equilibrium and the other one is frozen flow the actual case might be somewhere in between these two right if you look at the nozzle the flow through the nozzle is a very high-speed flow okay it has very little time to equally played right some reactions have some residence times if the gas has that kind of residence times in that region they will react if not they will not react completely okay.

So which is why as I said the actual situation is somewhere in between equilibrium and that of frozen okay even if you there are computer programs that can do these calculations of specific impulse we look at it a little later in the course even if you do that we are only going to get these two bounds so the actual solution might lie somewhere in between these two bombs will not be able to get a closed-form solution for this okay.

So now we have learnt in some sense what is it that happens inside a nozzle right and we have got equations to get the performance of flow through a nozzle right and we have also seen what are the shortcomings of these equations right in one of the major shortcomings in the entire nozzle itself is that it is adaptability to altitude right we have noticed that as you have a rocket going through the atmosphere right the pressure varies from 1 to nearly 0 through the atmosphere and you find that even if you use Beller conical nozzle we are not able to kind of get the entire benefit that we could have got if the flow were to be optimally expanded at each and every altitude.

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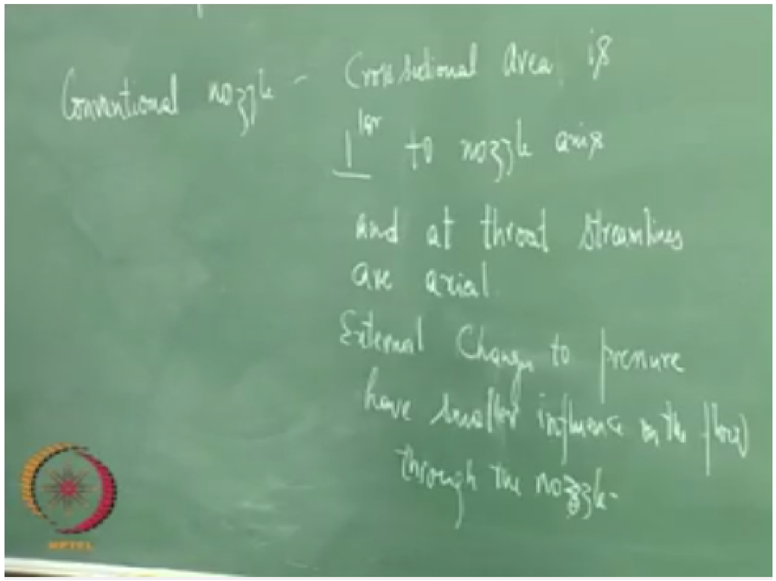

So the next section that we are looking at is something known as unconventional nozzles in this other thing we were primarily going to focus on an area where in we can look at how close we can have go towards achieving an adaptive nozzle we all know that adaptive nozzle is best because it will try to have the flow optimally expanded at each and every altitude and therefore you will get a better performance right.

Now if having studied all this conventional nozzles we find this that conventional nozzles because you have the flow being confined in the x in the divergent portion it can only sense what is happening on the outside after it comes out of the nozzle right and therefore it has to adjust to it in some way either outside or if the conditions become too severe as we had seen Pe / Pa being less than 0.3 then the shock moves into the supersonic portion of the nozzle.

So one of the things is can we look at having the nozzle experience ambient pressure conditions at least one of the jet boundaries experience the ambient conditions throughout the travel and that is what is the idea of an unconventional nozzle so if you look at conventional nozzle the cross-sectional area is perpendicular to nozzle axis and at throat streamlines are axial right and the other thing is external compression or expansion or to put it in other words external changes have smaller influence on them flow-through nozzle.

Now as I said the essential idea of unconventional nozzle is to have it in such a way that this condition is taken out okay that is it kind of feels the changes in the external conditions at least on one of the jet boundaries.

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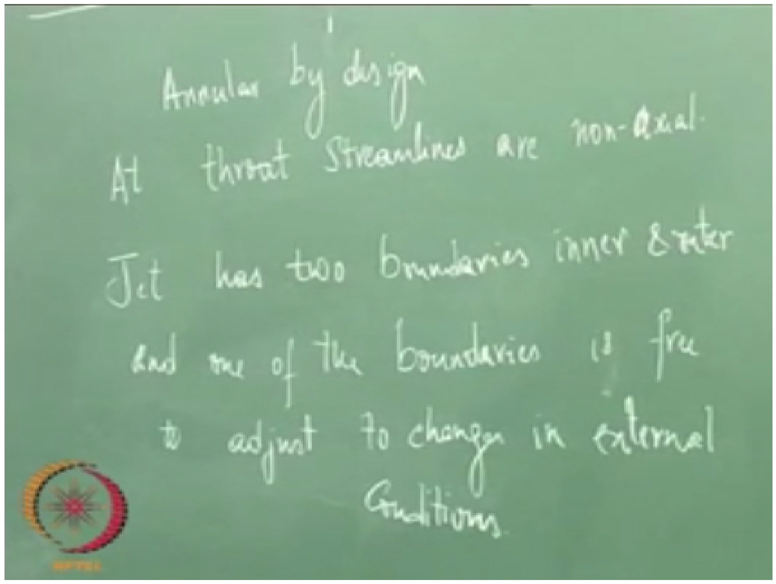

This is annular by design and at throat streamlines are non axial and the jet has two boundaries and one of them is inner and outer is free to adjust to changes in external conditions now how is this done let us look at the first design.

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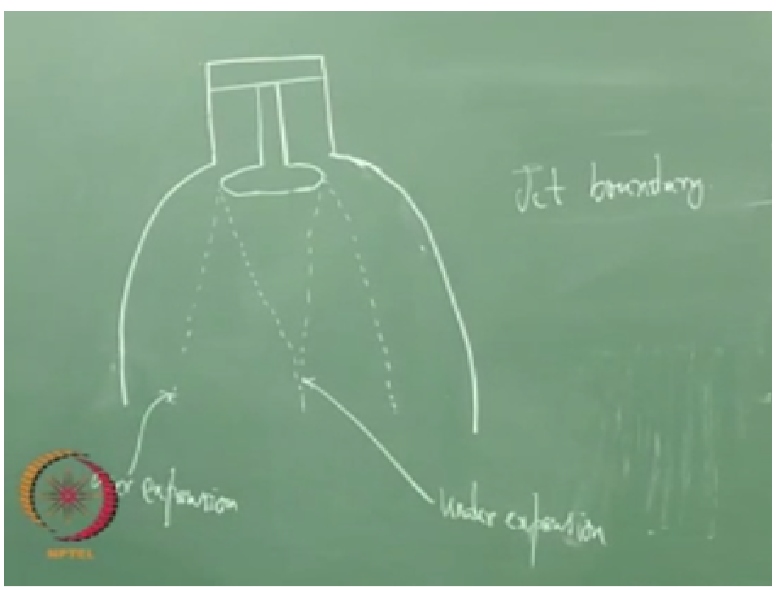

You have something known as an expansion deflection nozzle this is an expansion deflection nozzle if you see here the flow at the throat is non axial okay and that has a certain advantage if you look at how it senses the ambient pressure the external boundary is bounded right but the internal one can sense the ambient pressure and adjust itself so you will have you will have something for over-expansion this is for the under expansion okay so if the pressure is higher the flow tends to go along here if the pressure becomes lower then the flow tends to go in the other direction.

Okay so that it adjusts to what are the changes in the ambient conditions okay this is the jet boundary the internal jet boundary the flow is coming out through the throat on one side it is confined on the other side it is free to adjust itself depending on what is the ambient pressure so this is the jet boundary what I have shown in dotted line is the jet boundary okay now as opposed to this you could think of another kind of nozzle wherein in this case the internal boundary is the one that adjusts to the ambient pressure changes you could have the other one wherein the outside boundary adjusts to the changes in ambient pressure and that is known as the plug or a narrow spiked nozzle.

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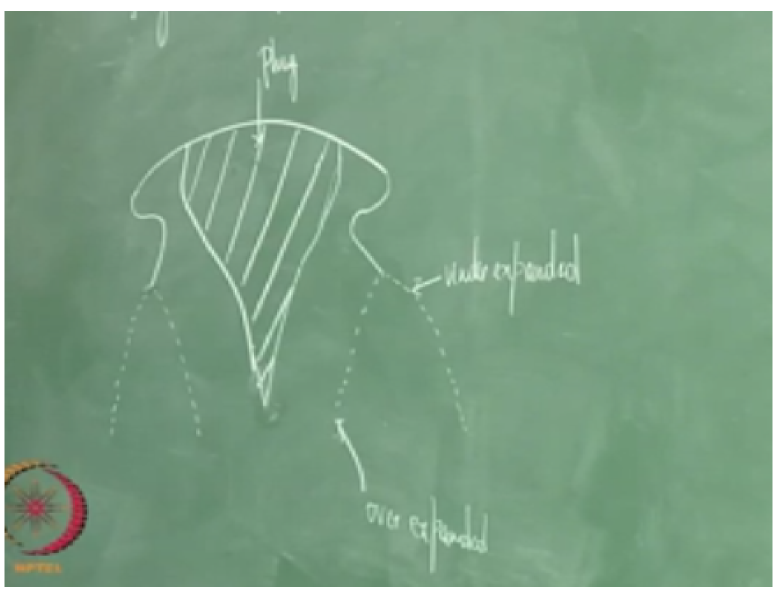

So this here is the central plug and in this case the external jet is free too since the changes in the ambient conditions and adjust itself right unlike the other one where in internal conditions internal jet boundary adjusted itself in this case the external jet boundary adjusts itself and if you look at the jet boundary for over expanded and under expanded it will be something like this is okay so in this sense this adjusts itself to changes in the ambient pressure and therefore you will not have the situation where in the flow after it comes out of the nozzle it has to either process itself through a series of oblique shocks.

And expansion fronts that situation is not does not arise here and therefore it is off design performance will also be very good compared to a conical nozzle or a bell nozzle okay and as a variant of this arrow spike or plug nozzle people have also come up with something that is even shorter that is you do not need to have this entire length and you can truncate it here which is known as truncated aero spike nozzle okay.

So it should be even more shorter in length and if we were to compare what is the length of the nozzle to the area ratio that we are looking at right you have conical nozzle bell nozzle and now the truncated aero spike nozzle which one do you think would be very small the truncated aero spike nozzle so let us look at some numbers for the same.

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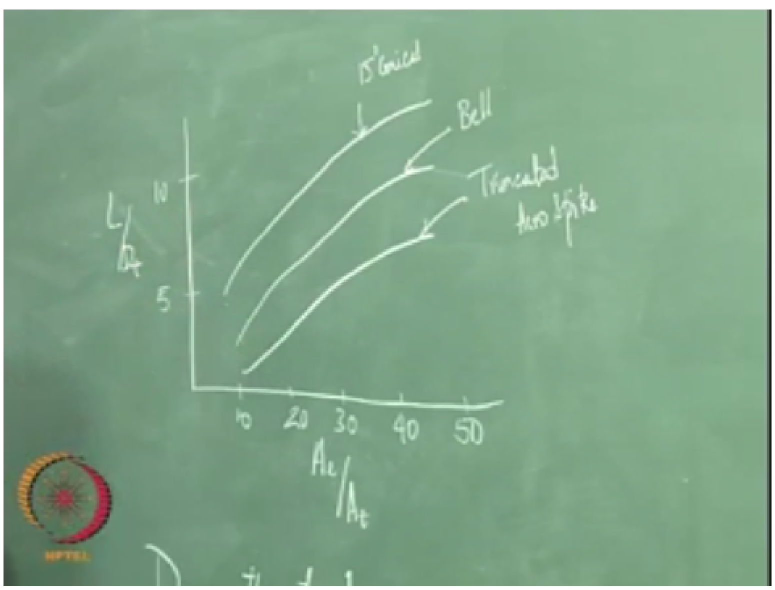

If we were to plot Ae / At versus length of the nozzle normalized by the throat diameter Dt here is and L is the length of the nozzle okay so you see here that to achieve the same area ratio the length of the truncated aero spike nozzle is very small compared to the length of a conical nozzle or a bell nozzle now this brings us to the question has this been used in any application well actually not really in any large application primarily because if you look at the changes that it requires you need to have both in the case of plug and the expansion diffusion nozzle you have something that is a large surface area that is there where the heat fluxes are highest at the throat okay.

So which means that your cooling requirement will be enormous and for a large burn time application this has been very difficult to achieve and moreover the other reason for this is we have still not looked at any case wherein we are going from for a single stage to orbit vehicle if you are looking at a single stage to orbit vehicle then use of any of this would be justified but if you are looking at different stages then whatever we are right now having in terms of having a conical nozzle at the lower stages and a contoured or a bell nozzle at higher altitudes suits just fine because it is operating within the narrow band if you are looking at bell nozzle or a conical nozzle.

And that is why we are currently having this in the days to come if people go in for a single stage to orbit vehicle which will be more reliable because you have tested the propulsion system on ground and there are no more changes to it that is the same propulsion system that takes you to orbit then probably one needs to consider this because then this would be useful because it is going to the entire atmosphere right until that time people have not talked about people are not likely to look at this very careful there is also another nozzle that has been coming up and literature recently that is something known as dual Bell nozzle okay.

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The idea is very simple here instead of having just one well have another change here something like this right and there is a change in slope at this point due to which depending on the pressure the flow will be attached to the first bail up to some altitude and then it will shift to the next bet okay and that people argue will increase the delivered specific impulse much higher than what we are having right now and that is being contemplated or being tried out in various organization we will stop here and continue in the next class thank you.

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