Rocket Propulsion

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Lecture No. # 31

Injectors, Cooling of Chambers and Mixture Ratio Distribution

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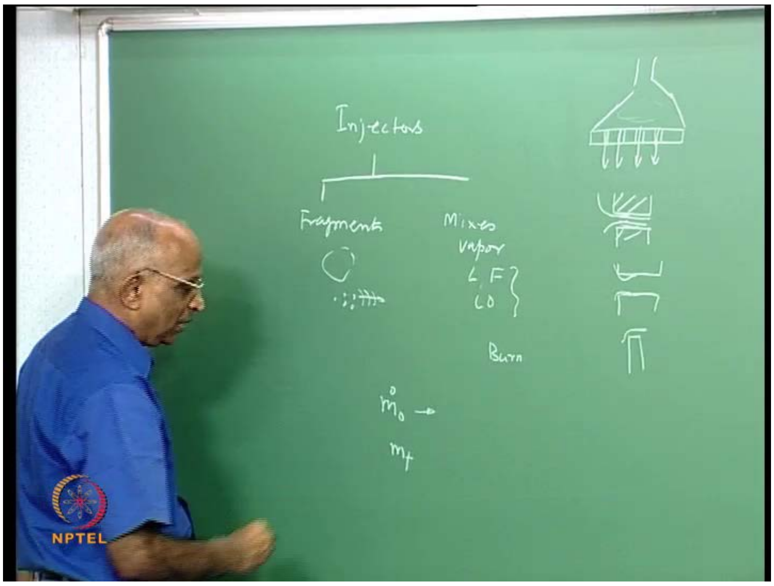

Well good morning. I think we will continue with the with discussion on liquid propellant rockets. And in the last class, we were looking at injectors, and what does an injector do? You take the liquid fuel and liquid oxidizer, break it up into particles, why do you have to break it up? So that the surface area increases, it will evaporate, mix the fuel and oxidizer vapor, and after mixing it burns. Therefore the purpose of injectors what we had told in the last class is maybe it fragments the liquid, then once it is fragmented; that means, the liquid is available, it makes it into fine drops or something such that the surface area increases, then there is something like an evaporation taking place. And then it mixes the vapor of the liquid and the of the liquid fuel and the liquid oxidizer, the vapor of the fuel and oxidizer are mixed; and then once they mix they chemically react and they burn in the combustion chamber.

In first half of today's class maybe I will finish the remaining portion of the injector, and what did we do in injector in the last class? We told we could have something like a shower head which we normally use for waving, which consists of a series of orifices holes, and then you have the water which comes from your tap into the shower head, and this is the manifold where water collects, and then the jets are passed through like this and this is what was a shower head. But, we had said that the flow of the water in the even in the shower head is such that if I have a hole like this; and if I have the metal in between over here; that means, the liquid comes and flows, it is not that flow is throughout it is happening, it could I could have something like a vena contracta wherein the flow comes and gets attached, or else if I have something like a small orifice that detach flow itself flows off like this.

And I could have different flows, and if it is cavitated again it detaches and flows. Therefore, the flow does not happen fully through the orifice. Therefore, how do we now calculate the flow of let us say the oxidizer? The flow of fuel through this particular shower head orifices, I spend time on the shower head, because it is central to the others and something which we can readily visualize. Therefore, let us say the mass of oxidizer I want to calculate.

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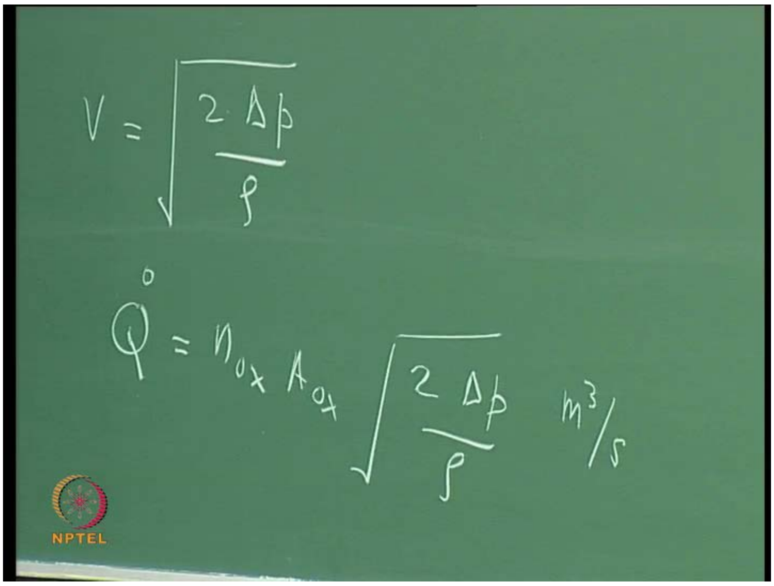

And therefore, what is want is I need to know the velocity of the flow, and we derived an expression using Bernoulli that velocity is equal to under root of 2 the pressure drop over here. Pressure at in the manifold minus the pressure in the combustion chamber, which we called as delta p divided by the density of the liquid, maybe density of the oxidizer density of the fuel.

Therefore, this was 2 delta p by rho, and to be able to get the quantity of flow which is taking place; you had let us say out of all these holes which you had n was n oxidizer was a number of holes for the oxidizer, and A oxidizer was the area of 1 oxidizer orifice into something like 2 delta p by rho is the quantity of flow taking place. And this will be let us say, if delta p is in Newton per meter square A oxidizer is in meter square, the number is here I could say it is so much meter cube by second. But mind you, we are still missing something what is that missing?

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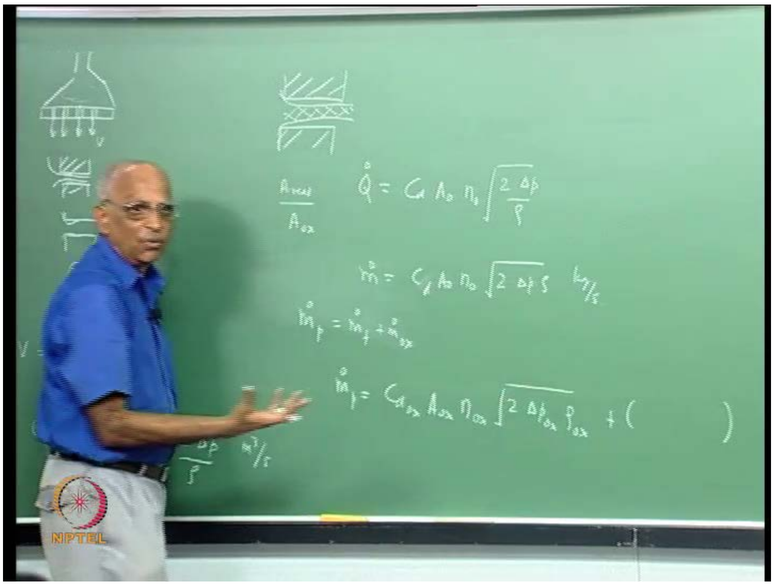

You know when we say flow is taking place through the orifice very often I did tell that suppose this is the hole here; this is the material here; flow gets detached here, and sometimes the flow goes gets detached like this. That means, this is the flow taking place let me section it something like this; this is the liquid which is flowing out. Something like a jet coming out like a jet of liquid coming out like this; and therefore, what is happening? The entire orifice is not fully flowing, and but still I have to base it on the real area here. Therefore, what will I find? The real area, apparent area, let us say the real area of flow is only this. The apparent area is the area of the orifice which if it is oxidizer we say is a oxidizer if it is fuel we say this.

And therefore, the cube which is flowing through the orifice is much lower than what I have calculated, not only this even when the flow gets attached let us say I have the orifice like this; I have a vena contract a and it gets attached. There is some frictional drop here the flow may not be linearly going like this. It may go at an angle and therefore, I still have loses and therefore, the loses due to the apparently lower value of the real area of flow to the… But, we are basing the area on the total orifice area. And therefore, I say that the Q actual which is flowing I put it terms of a coefficient which I call as discharge coefficient C d into something like a of the orifice into the value n of the number of holes I have what I get into under root 2 into delta p by rho, or rather this is the rate of flow in meter cube per second. I convert it to mass flow rate and I get the mass flow rate as equal to m dot is equal to I multiply by the density I get C d into A 0 into number of orifices into under root 2 into delta p into rho so many kilograms per second.

Right this is all what we did in the last class. That is the flow through an orifice can be written in terms of corrected area of flow corrected pressures, the reduced flow due to the real nature of the liquid as a discharge coefficient into area of orifices number of orifices into what we are having. Therefore, now I say I want total propellant flow I can always calculate, because I know the I s p for the thrust I know the total propellant flow. I can apportion it into mass of fuel and mass of oxidizer. And therefore, I will put a number of oxidizer or holes for the oxidizer number of holes for the fuel and I can get the required flow what I want. And therefore, the total propellant flow will be equal to C d for the oxidizer orifices, area of the oxidizer orifices into the number of oxidizer orifices into something like 2 delta p across the oxidizer orifices into the density of the oxidizer.

And similarly, for fuel I write C d fuel A fuel n fuel and all that and I get the other term which is just I substitute oxidizer by the fuel, and what was the mixture ratio? Mixture ratio is this quantity divided by the other quantity and we know how to design a shower head, and this is what I show in this; I again repeat what I told in the last class.

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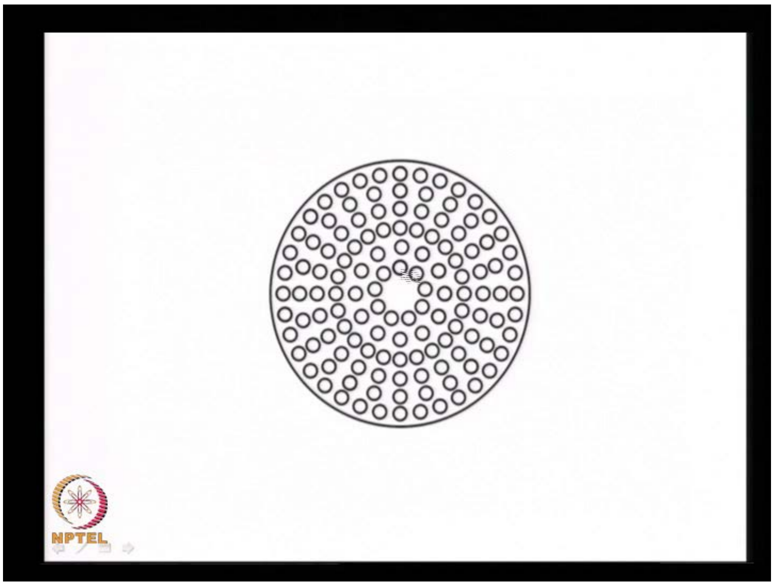

You have the number of holes and we saw the actual shower which we use to take bath, we compartmentalize it. We have a few oxidizer orifices or few fuel orifices.

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And then, what we have is something like let us say a shower you have jets of liquid going like this and you find that these are individual jets which are going, and they break into droplets and you have you have the shower head injector.

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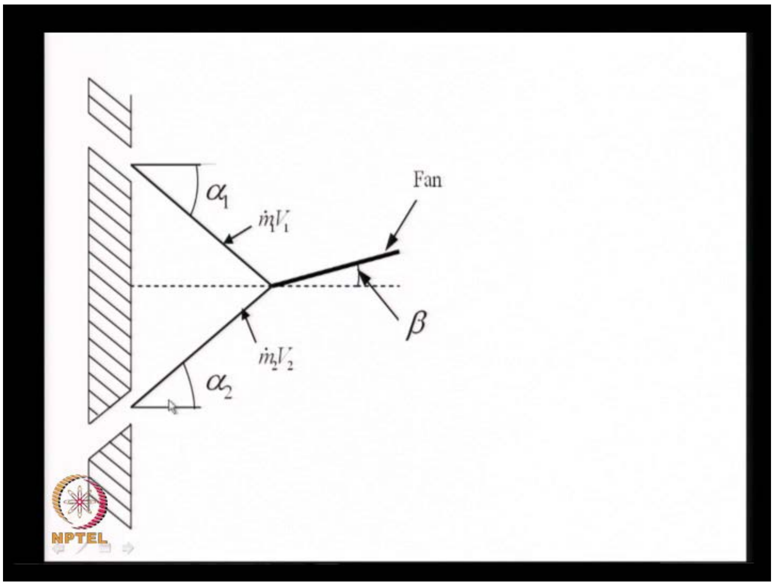

But, there is one problem with shower head; what I show is something different there, you know what I am saying is I have something like jets coming like this from the holes in the orifices and these become droplets.

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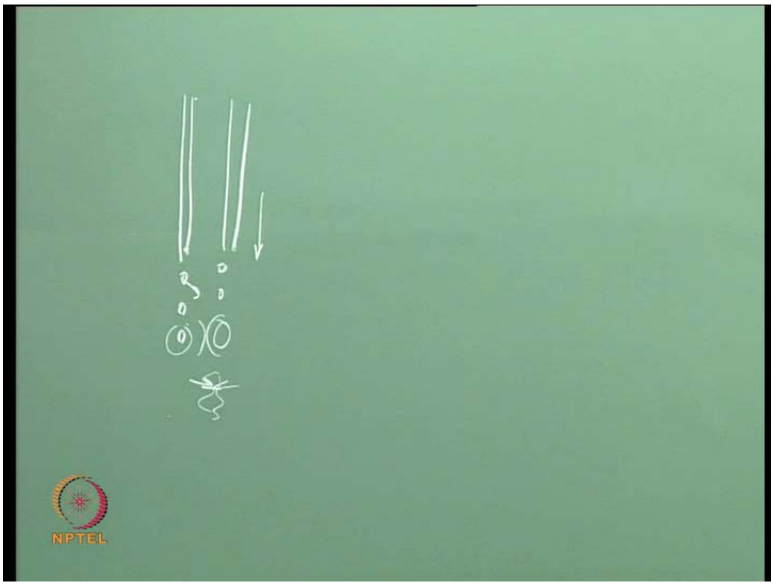

The direction of flow is like this. If I have one fuel jet and one oxidizer jet, I am not promoting the mixing, I am not giving it an angle such that the vapors can come and mix. Therefore, mixing is poor in a shower head injector, and how do I have to improve this? I need to have some strategies such that I can have maybe the fuel vapor which is formed by evaporation. I have the oxidizer vapor which is formed; I must maybe make it impinge on each other such that I get something like a mixing zone. If I can get a mixing then I will be better off. And therefore, I schematically show this you know I was thinking how to illustrate it, because it is a three dimensional problem. Let us say for the present I have this as the jet which is coming from a shower head, then I want, what I do is I take one of these jets over here. Let us say I I I I make two jets and what I do is I make the two jets impinge on each other at this particular point.

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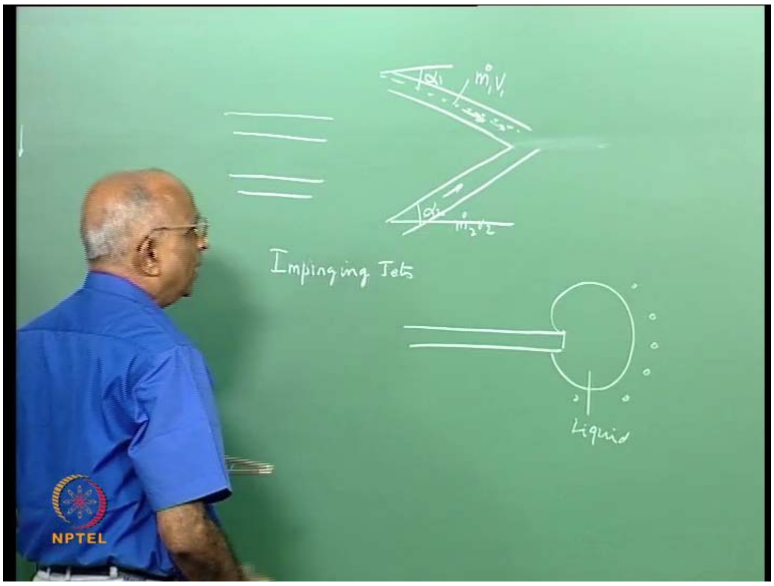

And when I make the jets impinge at this point, I have momentum rate of change of momentum, and what is there let us put together first. I have something like a jet coming over here; one liquid jet coming from one hole of the orifice. I say that the mass of flow is m dot here, let the velocity of the flow is m V. Therefore, the momentum or the rate of change of momentum along this is equal to m dot V into this, and all what I have done is I take another jet and I impinge it, this has something like let us say m 1 V 1; I have m dot 2 into V 2 which is impinging. And at the point where these two jets are impinging, let us say they impinge over here, I have something like a pressure which is built up at this contact point, the two jets are interacting and therefore, what we get is when the jets impinge I have high pressure. And therefore, at this particular point I get something like a high pressure and therefore, the liquid jets spread out; I get something like a sheet which is known as a fan.

Therefore, if I look at it the two jets are impinging and therefore, I get a fan like this maybe if I look at it in the plane of impingement like I have; maybe the plane of impingement is along this if you look along this particular direction along this, I just see one jet; the other jet which you are not seeing because it is hidden I get a plane over here. Let us try to draw it such that it is clear. I have two jets just like I told you; I have a jet coming over here; I have a jet coming over here, the two jets are impinging, and therefore, I get a fan like this. If I were to draw it in the plan view I am looking from the top I see only one jet, because the other jet is behind and I get something like a fan over here, and this is the fan which is a liquid sheet which is found.

Therefore, if I instead of using single jets in a shower head I have lot of jets like this, what I do is I make these jets impinge on each other; I make two jets impinge on each other. And therefore, I form a thin liquid sheet which then breaks into droplets, and this is what we say is instead of having something like a shower head over here, I talk start talking in terms of impinging jets.

And now you know, I can make this final jet in any direction I want, how do I do it? Let us consider a small example. Let us say the angle of this with respect to the horizontal is alpha 1, the angle of the second one with respect to the horizontal is alpha 2. Let me draw it distinctly on the other side of the board.

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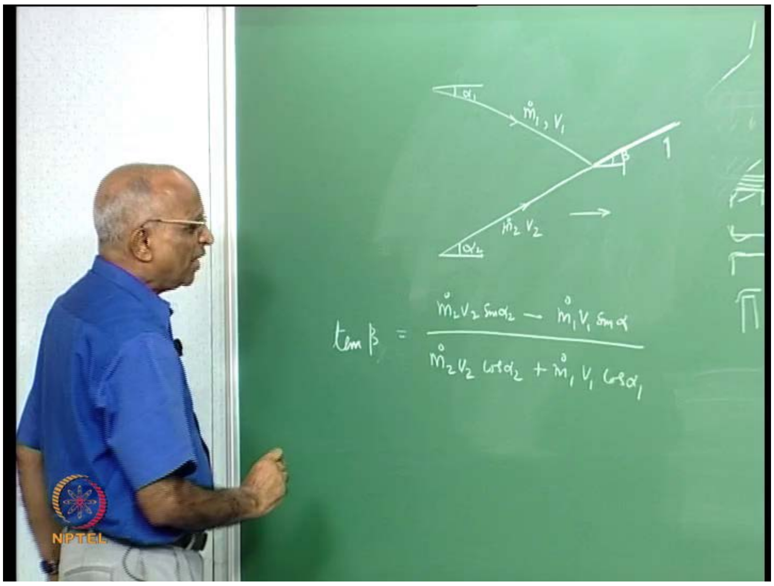

I have one jet coming over here, the angle with the horizontal is alpha 1; let the mass be m 1 let its velocity be V 1. I have another jet which impinges over here, let the angle be alpha 2; let the mass be m 2 and the velocity be V 2. Rather than the mass we consider mass flow rate m 1 dot and m 2 dot.

Now, depending on the momentum rate of change of momentum I get a force here, and I can make this jet in any angle I want, how do I do that? That means, the resultant jet or the resultant fan or a sheet which is formed and the sheet I said the two are impinging I get a pressure; I get something like a sheet over here. It could be at any angle what I want, and this angle beta will depend on the momentum and these angles. Supposing, I want to determine this angle, I tell myself well this is moving like this. The rate of change of momentum is in this direction, the rate of change of momentum in the axial direction is equal to m 2 dot V 2 I have cos alpha 2, this is also in the same direction. Therefore, I have plus m dot 1 V 1 cos alpha 1, and what is the vertical component over here? If I were to write the vertical component on top, I get m dot 2 into V 2 into sin alpha 2 the vertical component minus this is in the downward direction m dot 1 V 1 sin alpha 1 and this must be equal to your tangent of your beta here.

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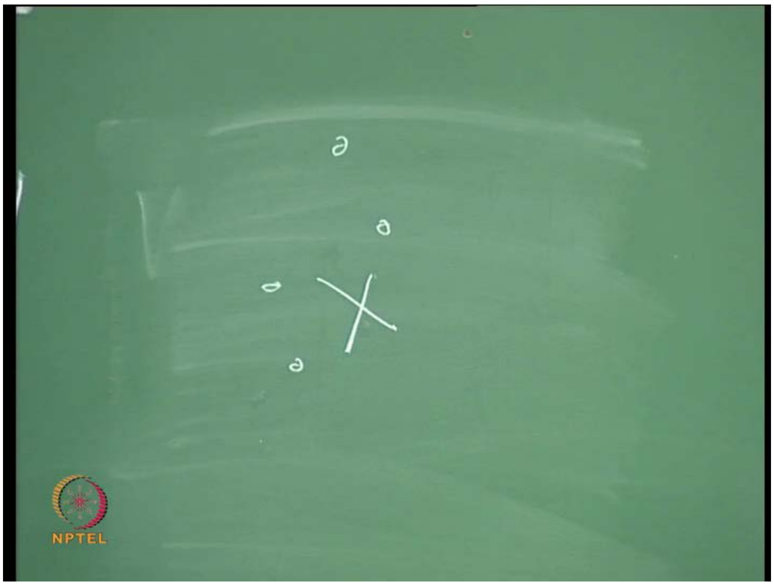

Therefore, depending on the angle what I choose, the momentum what I get I can get any angle beta what I want. And therefore, if I have something like these holes like this; I have another set of hole like this. By changing the angle I can make one spray fan like this; the other spray fan like this and I can mix them better. And therefore, this is the principle of impinging jets or impinging jet injectors. And therefore, let me again go through this all what I said was yes I have one jet over here; the other jet over here; this is the final fan, and this angle I can choose and therefore, my mixing in such type of injectors will be much better.

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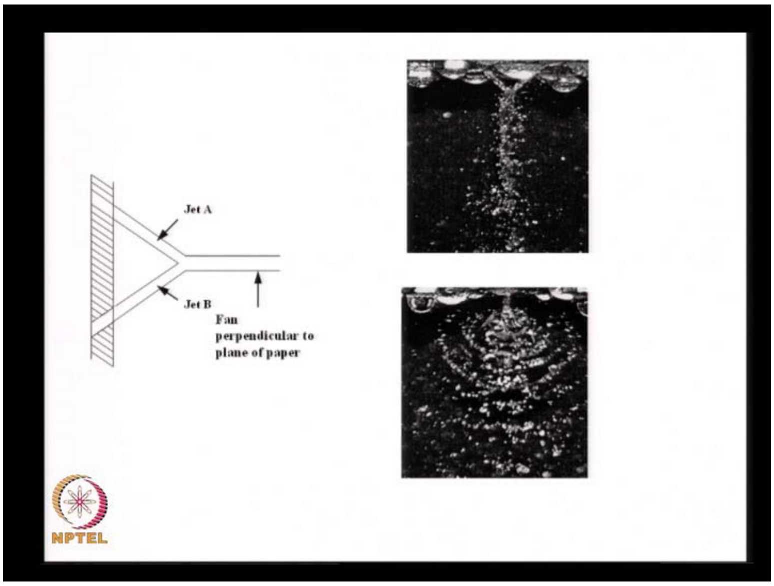

Let us take one or two experiments which we did on this injectors. Well, I have one jet here; the other jet here, equivalent to saying yes one jet comes here; the other jet comes over here. I have the fan which is formed along this, and how does the fan look? When I take these two jets which are coming over here; that means, the two jets are impinging, I have a local point and therefore, I get something like a fan over here. The fan is typically in this particular shape over here, and when I look at this particular fan over here the two, it is in the plane of the paper and therefore, I get droplets like this. When I look at a single one, I get a fan like this; and I get a series of droplets like this, and this is the principle of impinging jets which I used for injection.

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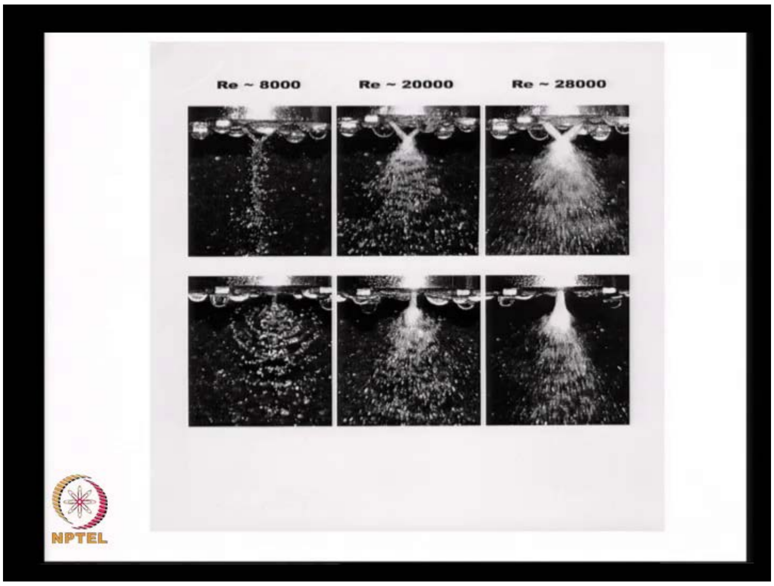

I show this at low Reynolds number when the jets are clean, when the jets are smooth I get neat fan like this; it forms a fan over here, and disintegrates into droplets. I go into the very turbulent regime there it is not so smooth, but still I get fine droplets. But, I told you about cavitation flow wherein the separates there are disturbances in the liquid, I do not get a good one. Therefore, we have to choose a proper Reynolds number or a proper weber number make sure that you get good droplets. This is the principle of impinging jet injectors. Therefore, now I can go a little faster and I can now tell myself well, injectors can be classified into some simple schemes, and what are the simple ones we can talk of?

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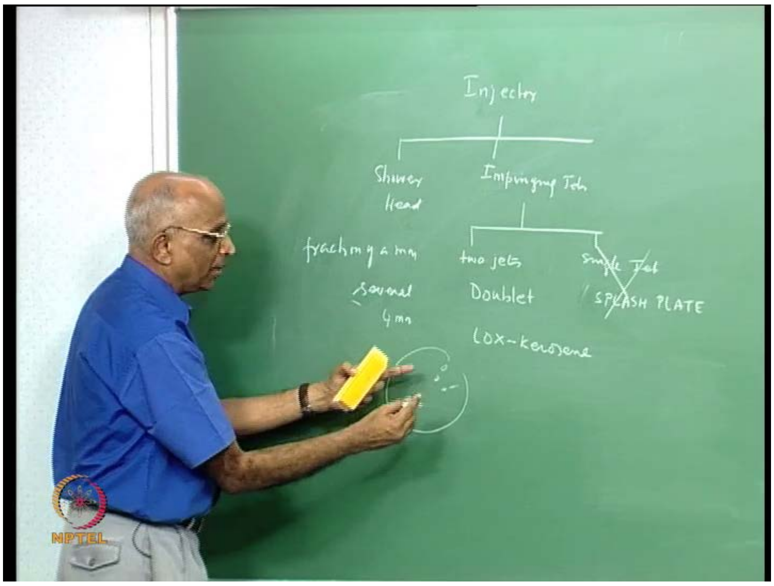

We can say injector we know the requirement could either be the simple shower head injector, but we said shower head is not very good because mixing is poor and therefore, it is not very widely used. Instead of using a single series of straight jets, I can have something like impinging jets and in both these cases what is it we use? We use the pressure of the liquid in breaking up the liquid into droplets and these are also known as pressure induced atomization what we get, we will just say impinging jets. Therefore, impinging jet could either be two jets impinging on each other. When we say two jets we call it as doublet, because you have two of them; that means, I have one jet; I have another jet; I have a fan and this fan breaks into droplets over here.

I call it as doublet, but instead of having even I could do with a single jet. If I use a single jet how do I still break? Maybe in the combustion chamber I have the injector over here; I put something like a plate here a plate on which the jet impinges; I make its splash on this plate and what I get is droplets here and this is known as a splash plate injector. Splash plate was used originally by the Germans, but now they used it in their missiles it is not very efficient, because compared to doublet in which I can do anything what I want. I think the doublet is much more important, and doublet is used in lox kerosene. You remember I showed you the F 1 engine which is we said is a very high thrust engine; it uses doublets, and what is done is you chose or if it is dimensions in between fraction of an mm to several mm depending on the size of the engine, may be 4 mm 5 mm to that extend the orifices could be there, you put a lot of these orifices together and may be impinge them on one on each other and you call them as a doublet injector. Well, we will just see one more example.

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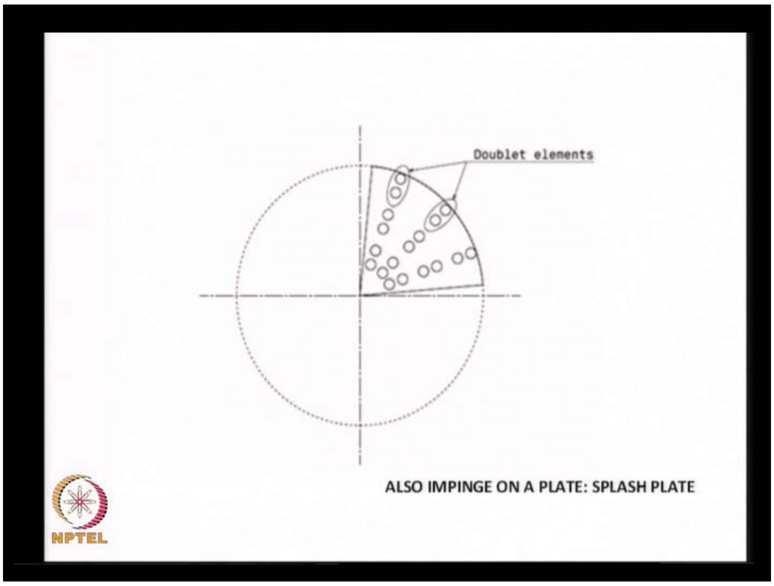

This is where we mount the doublets we put one on top of the other, one by the side of the other; create a fan over here, may be make this fan interact with this fan or may be make this fan interact with the other.

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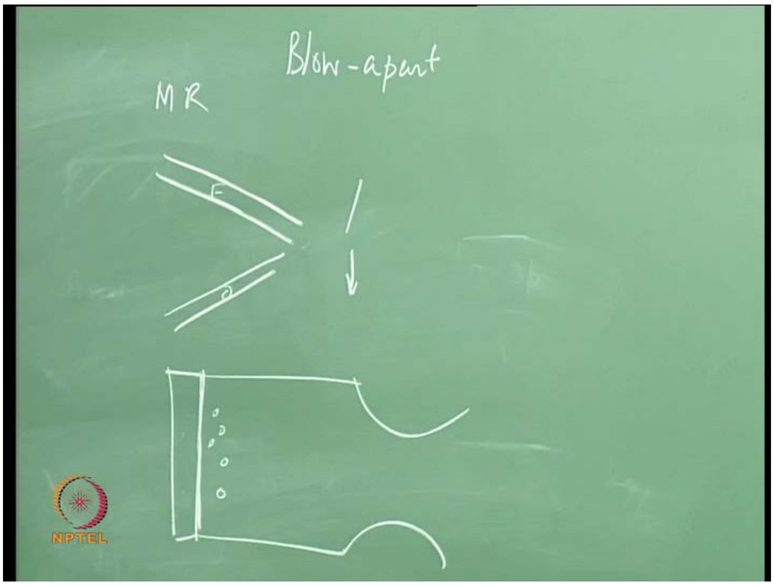

Well, this is the doublet injector, but instead of having two jets impinging, I can always say when I impinge two jets, if I vary my mixture ratio what happens is if I vary my mixture ratio and if I have had design the fan to go like this. If I vary my mixture ratio I may be varying the quantity of fuel with respect to the oxidizer and therefore, I will have a different type of a fan coming. Therefore, doublet is not good when the mixture ratio varies for a fixed mixture ratio for a fixed flow doublet is good enough. But then, we must also remember doublet is very efficient, because I can get whatever droplet I want, but at the injector head if atomization is taking place combustion is taking place the injector head of the rocket; let us say this is the combustion chamber; this is the injector. I have fine droplets here; combustion takes place here; injector gets heated. Therefore, the manifold must have a high velocity such that the injector remains cool.

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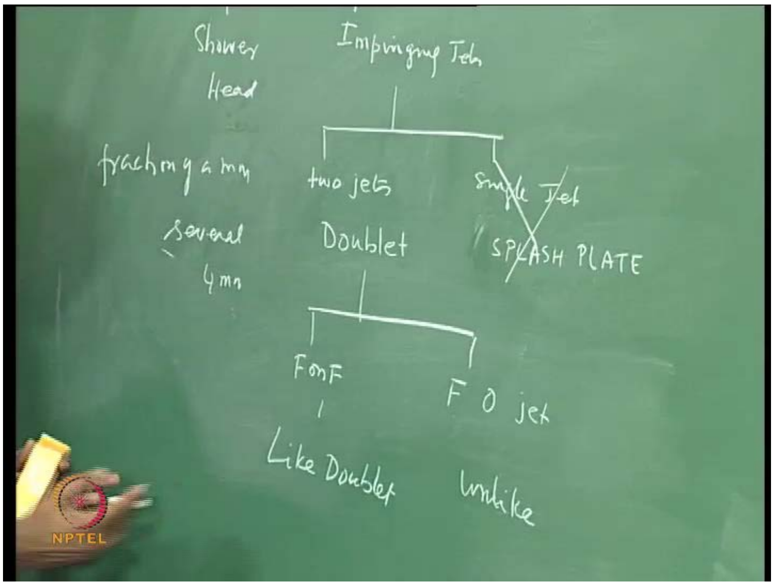

Therefore, we tell ourselves well impinging get could be doublet. In the doublet if I impinge fuel jet on fuel jet or I could also take fuel jet on oxidizer jet, I could have one of them, this is known as a like doublet. This is known as an unlike doublet, because I take unlike substances fuel and oxidizer and impinge them and what happens in a unlike? Supposing, I have a jet of fuel with a jet of oxidizer and because of chemical reactions which can occur I could have something like a blowing a part of this and therefore, I have some problems like blow apart because of chemical reactions. You know you have to control these things and still make an injector this is about doublet.

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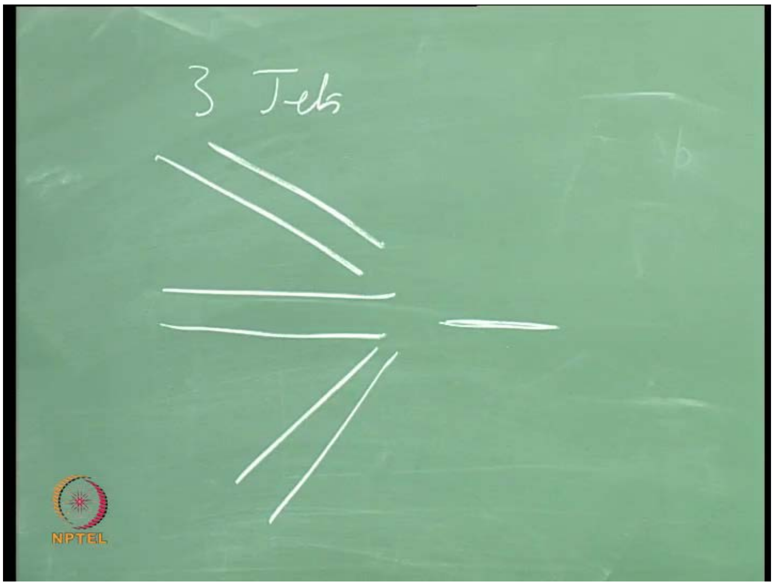

Instead of using two jets now I tell myself, well I have a mixture ratio problem in doublet. I can use three jets, what I do is have a central jet may be of oxidizer; I have fuel jets coming over here; and now I have a fan in this particular direction, and I can use three jets in which case the injector is known as triplet three jets.

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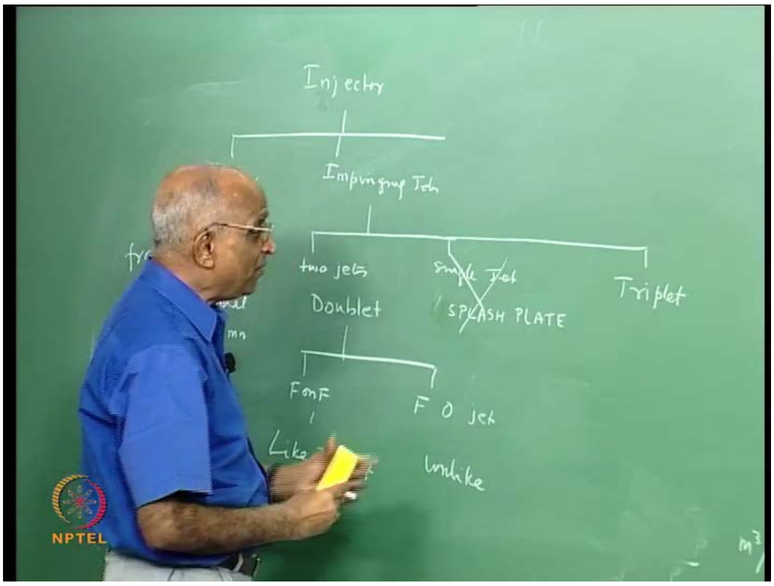

This is again very widely used in the industry, because I have a stable fan which is formed and let us take a configuration of a triplet.

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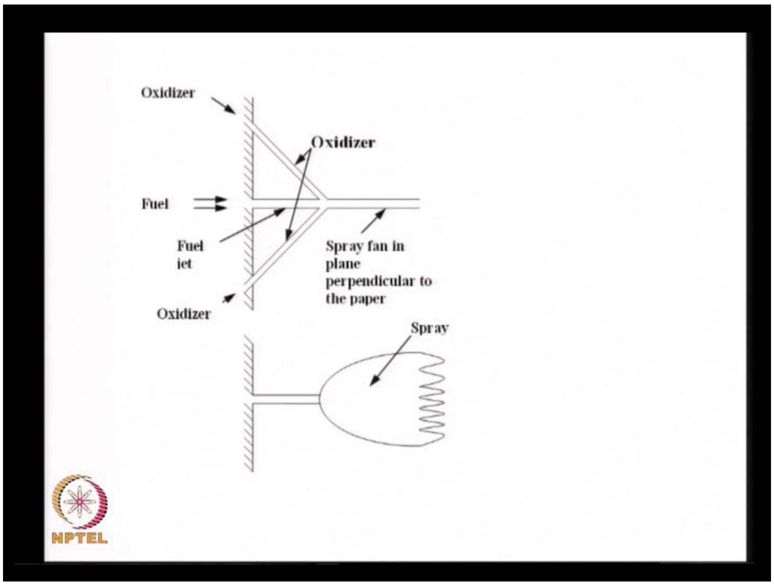

I have an oxidizer jet one, two, third jet, I form a fan. I look at it from the top, I get a spray fan and this is what is the triplet. The advantage of a triplet is when I change mixture ratio, I do not really I have the same quantity here same quantity here, and this is central. Therefore, the spray fan does not really change its angle and that is the advantage with triplets.

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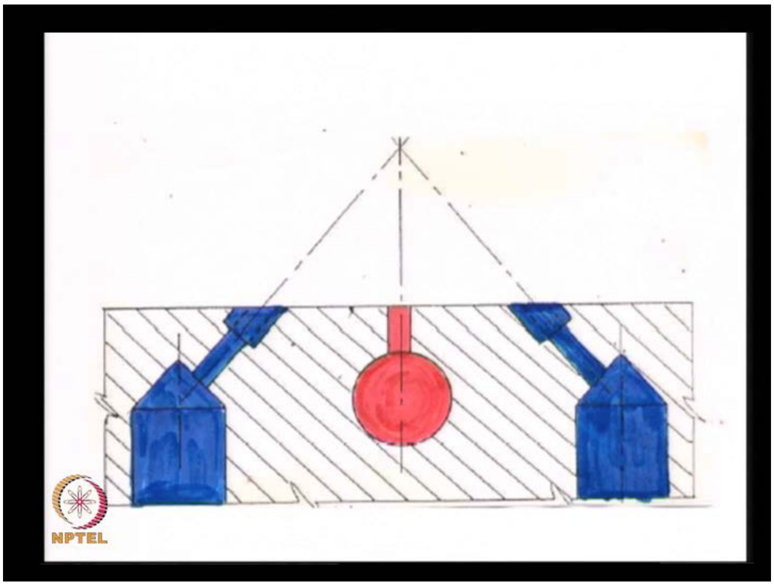

And I show an example of a triplet this is where you have may be a fuel jet coming in blue fuel jet coming in blue, the oxidizer jet coming in here; here you form a fan as it were it breaks into droplets in the combustion chamber.

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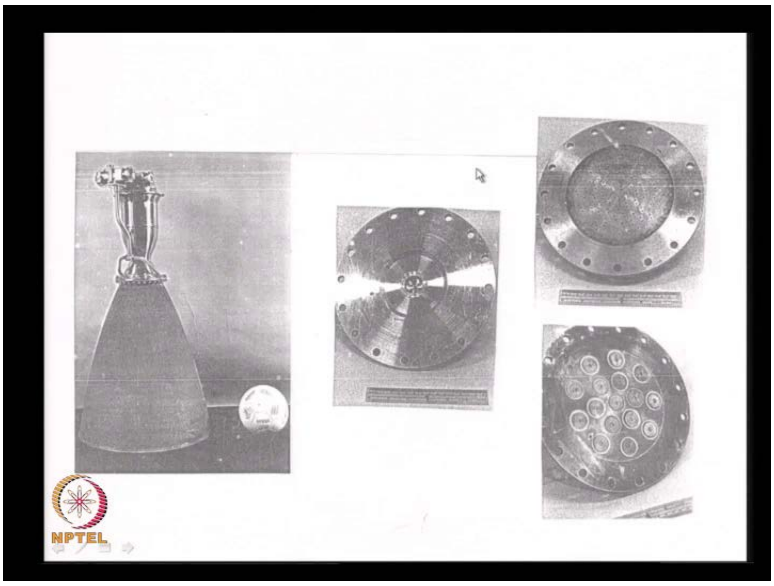

And experimentally, this shows let us disregard this, this is a particular engine which is a engine used as an upper stage. This is the injector, when I look at the injector here have a series of small holes three holes together three holes together which produce the triplet jets. We will disregard this and this, I will come back to this a little later.

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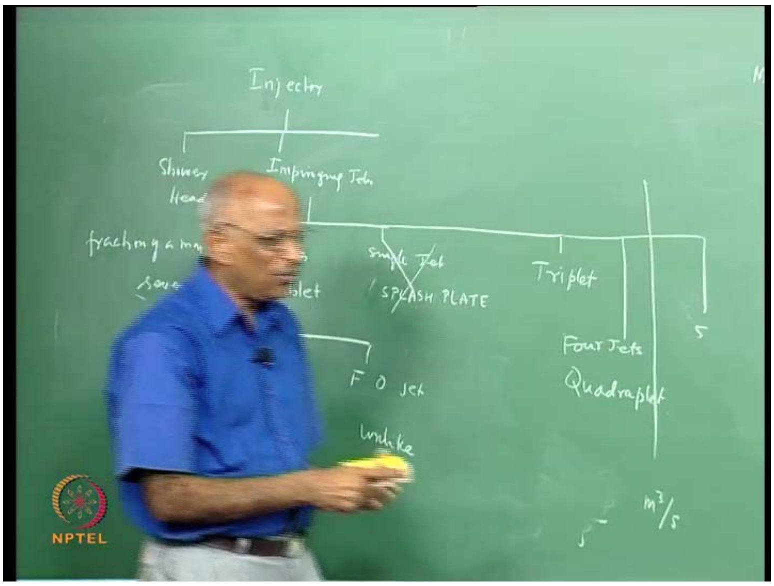

This is about triplet. I can also think instead of having triplet why not use four of them four jets. It has also been tried; it has been used; it is known as quadruplet. Its performance is not as good as the triplet, but it has been used and also I could use five jets, in which case it is known as the (( )) and so on. But, I think this stop over here; I have not seen anything use more than a quadruplet, but quadruplet as we say is not as sufficient as the triplet, because you do not really gain much and how does the quadruplet look like.

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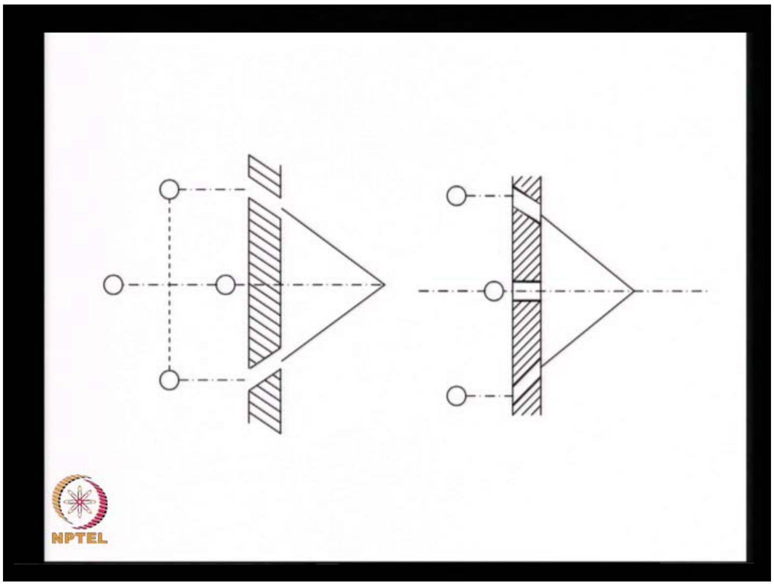

Let us take a figure over here. I have something like one hole here; one hole here; one hole here. The four jets come and impinge on each other you form a fan. In the case of five, you have one, two, three then, I have two more, and I have something like a five holes, one, two, three and again two more on this side; one one one somewhere here; one over here. All five jets mix and I will get this. Actually, what I should have shown is this is in a different plane I will have one central and then these two on a different plane. Let us sketch it out, you know we must be clear what little we study we must be clear.

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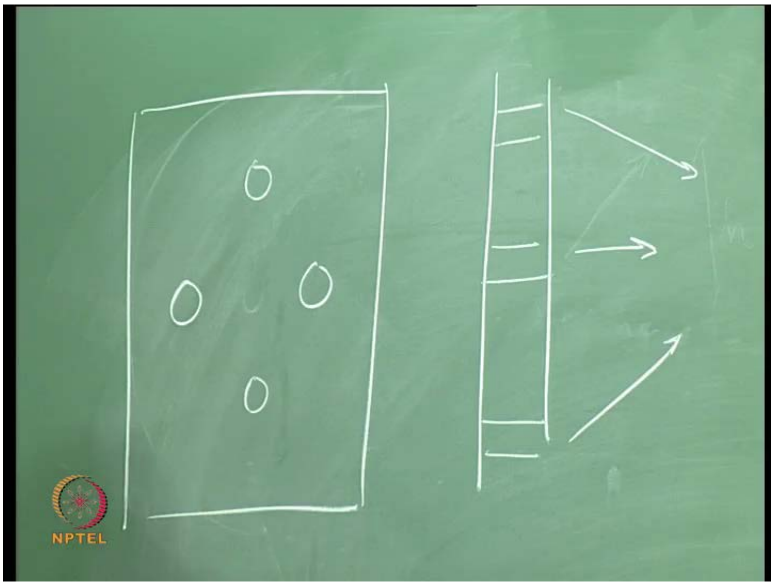

I show in that figure a hole here from which I get one jet, I have a hole here from which I get 1 jet. I also show one hole from which I get one jet. Now I take a view of this, this is the let us say the head is something like this. I just take a portion of the injector and therefore, this is one hole; this is one hole; this is one hole, I put two more holes over here and therefore, I get five of them coming and this is what constitutes (( )) or quadruplet means, I do not have this four jets combined impinge and this so on we have this.

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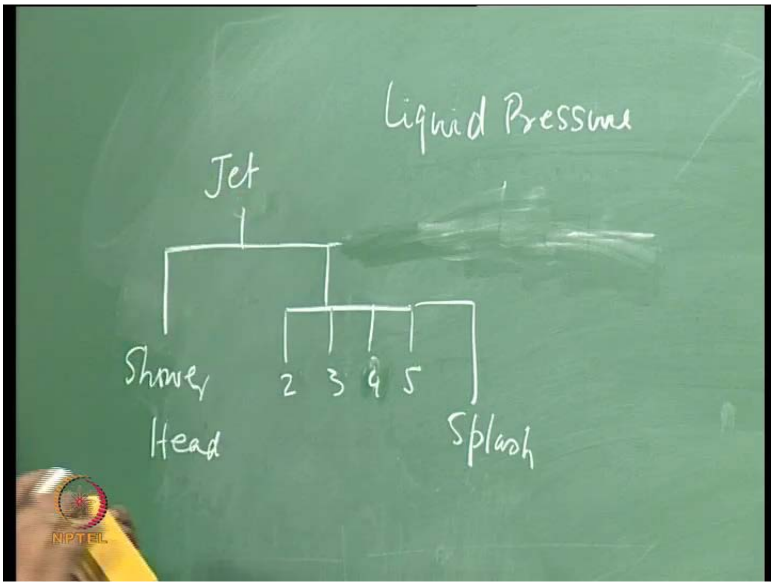

Therefore, injectors what we have studied so far use the liquid pressure and we had impinging jets, splash plate and an impinging jet we had the doublet, like doublet; unlike doublet, triplet may be quadruplet, pentlet; 2 may be 3, 4, 5 jets mixing or a splash plate and these things constitute what is a pressure, something similar to our shower head, but in the case of a shower head you do not get impingement here you get impingement.

Now, the question comes do we really need liquid jets as it is, in all these cases whatever we have studied what is it we have forming? We are forming first a liquid jet; something like a what I was trying to show is from the shower head you have something like a jet which comes either you impinge on a plate or you impinge against each other and form a fan.

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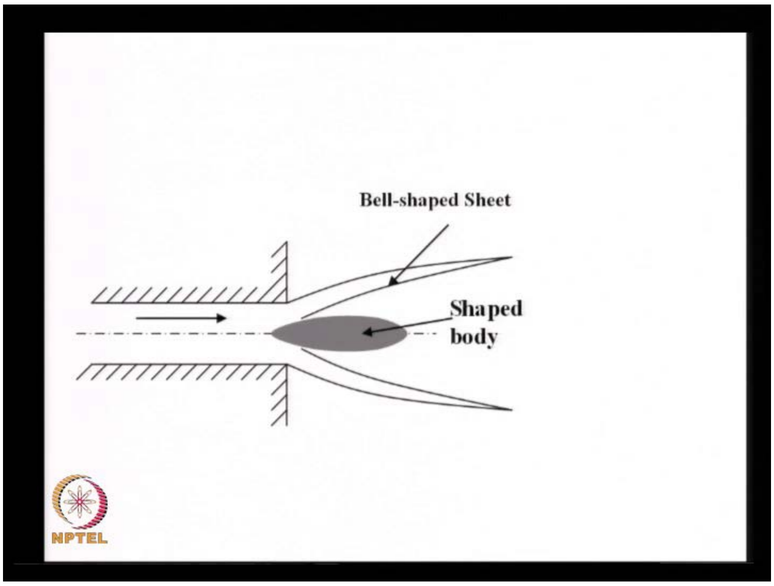

It is also possible for us to have another construction, wherein you allow the liquid to come from the orifice, you put a shape body here and when you put a shape body, the liquid gets diverted from something like a water bell. The water bell is something like a liquid sheet and this sheet breaks into droplets; that means, you convert the liquid which is flowing into a sheet rather than a jet, and you could have the same configurations what we talked of.

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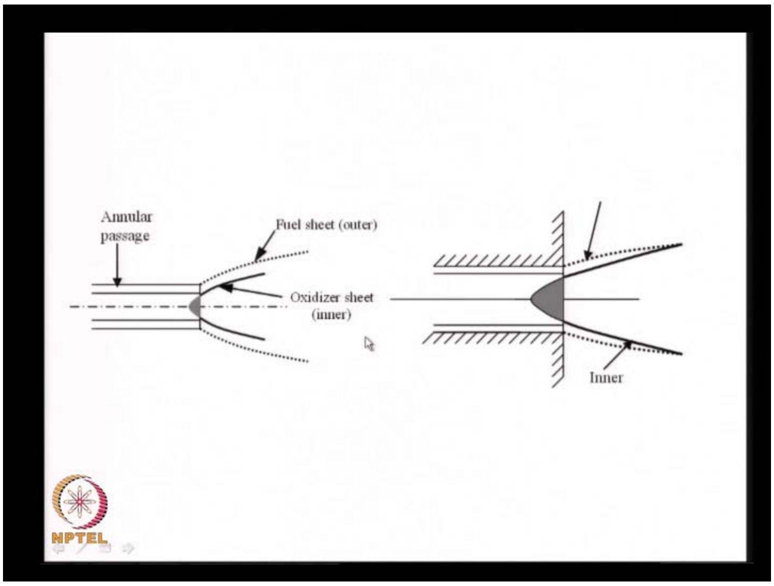

Maybe I put something like a shaped hole here; I have a liquid sheet here; I put an anular thing I get another sheet here; maybe I allow these things to break into droplets. I allow the two jets to impinge I could get an impinging sheet. I could have a sheet which breaks into droplets, and these are known as coaxial injectors because they are coaxial.

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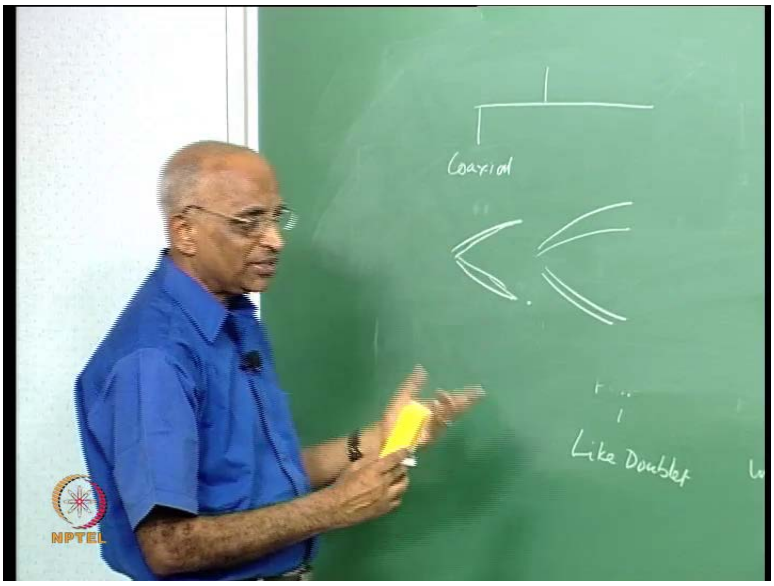

Let us say therefore, I could also think of having injectors, wherein instead of jets I have sheets, I have something like a coaxial configuration, wherein I have a sheet like this coming; maybe I have another sheet which impinges on it and breaks into droplets, or I have the central sheet like this; outer sheet like this and it keeps going like this. These are known as coaxial injectors, because I have I form sheets and these are coaxial with each other. Maybe we will take view of a of a of an injector which does this, you know here I have a coaxial injector; you have a series of elements which are coaxial; I have a central hole; I have another hole here; the sheets come out of this.

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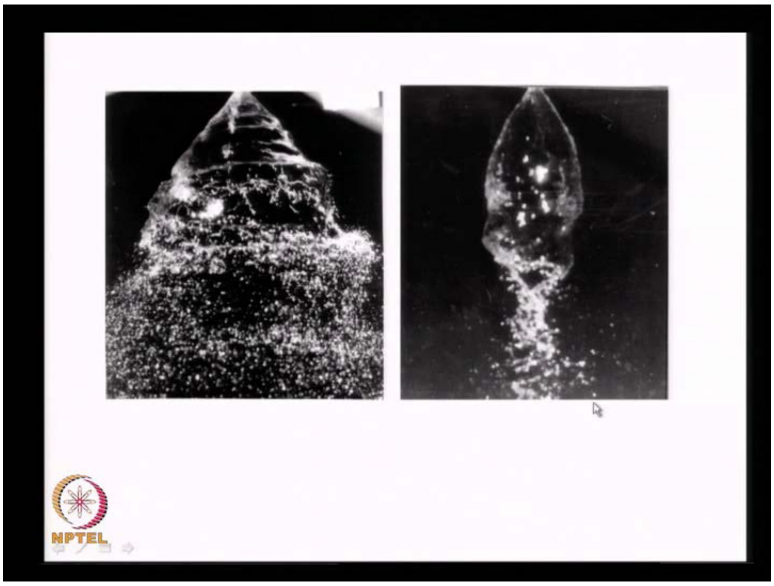

In other words, let us take a look at it. I have a sheet which comes out like this and this sheet breaks into droplets over here. Similarly, surrounding this I could have another sheet which comes like this breaks into droplets the droplet mixes and burns this is what we call as coaxial. But, if the pressure is not good and if I do not get a particular diverging geometry, I get something like a bulb or a tulip shape and this does not give good atomization. Therefore, in these cases it is necessary that I have something like a divergent and have a good shape to it and this is what we call as coaxial.

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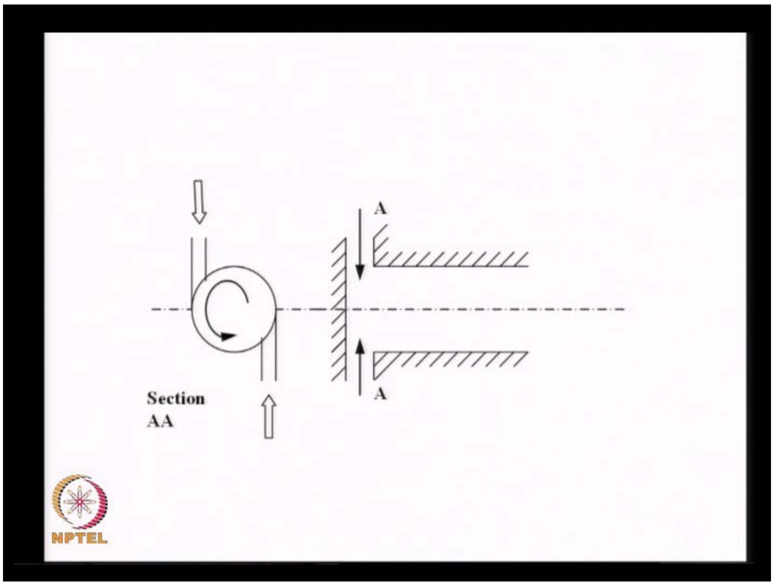

Having said that we could also in injectors I could instead of having the liquid come here I could rotate the liquid, how do I rotate the liquid? I admit it tangentially. Therefore, when I admit it tangentially here the liquid rotates and when a liquid rotates because of the centrifugal force the jet is thrown off.

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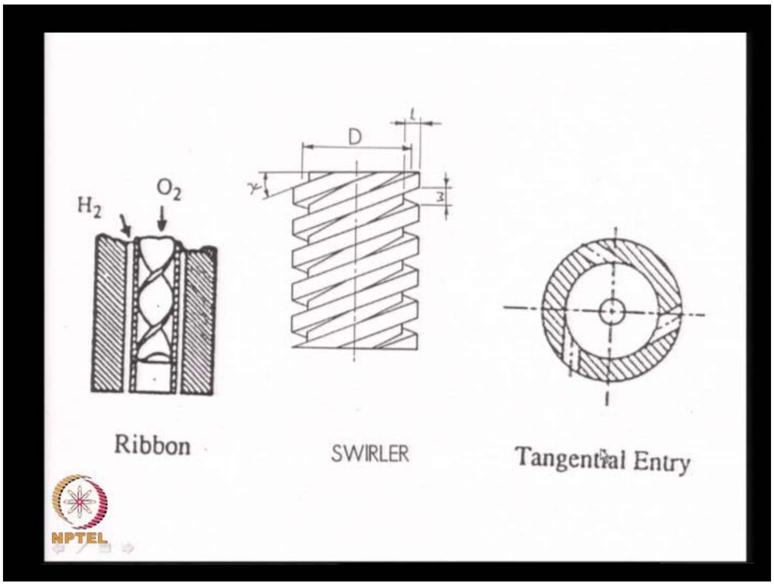

And therefore, I how do I rotate it? Either by tangentially entry over here. I put something like a spiral here, the liquid flows along the spiral and gets rotated, or I just put some ribbon or something on the surface and therefore, make the liquid rotate like this.

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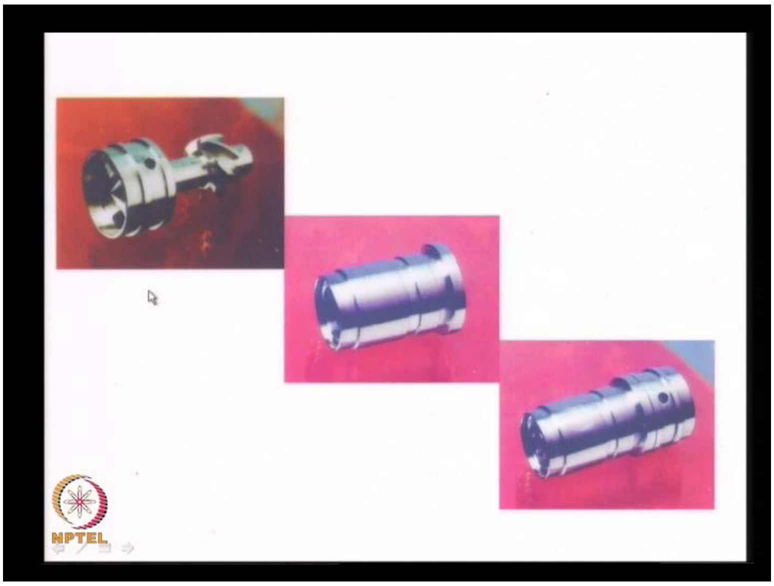

And when I do this what is it I get? Here again I show a something a how to rotate the liquid. I have a configuration I put this on the outer; I admit the liquid; I may be I make the liquid rotate and I inject it out.

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And then, instead of getting something like a jet which comes out like this into droplet.

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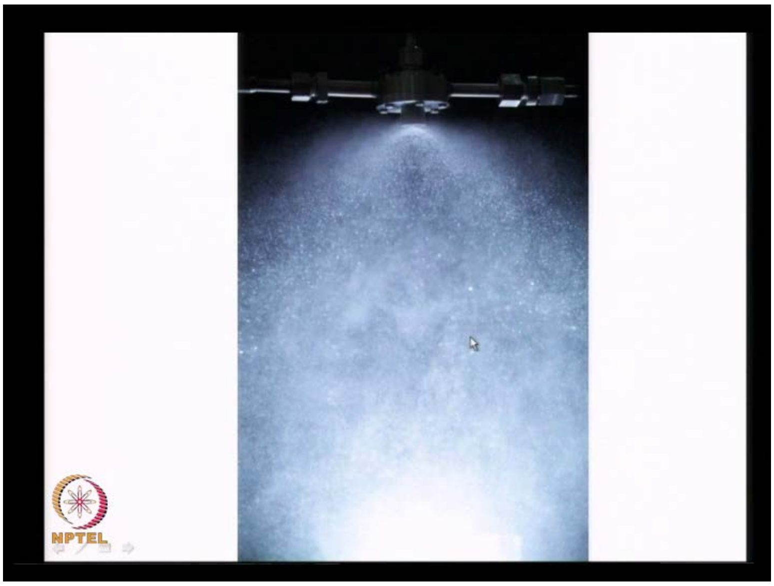

Now, I make it very fine over here and it has a much wider thing, and when I when I rotate a liquid, I say I swirl the liquid.

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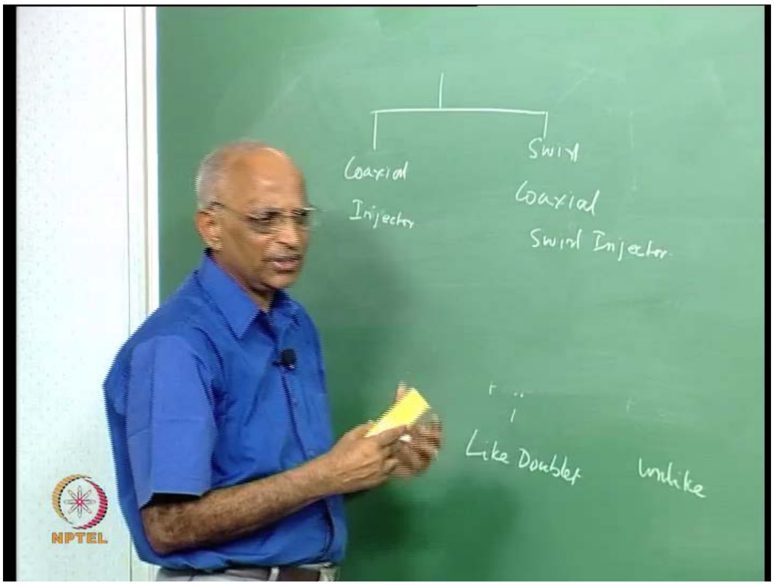

And therefore, such injectors are known as coaxial swirl injectors, whereas the earlier thing which I said was just a simple coaxial injector, all these things are used in practice. People who come from the gas turbine side rocket engineers or design engineers, who come from the gas turbine side are use to swirling, whereas the conventional rocket engineer is satisfied with a coaxial injector.

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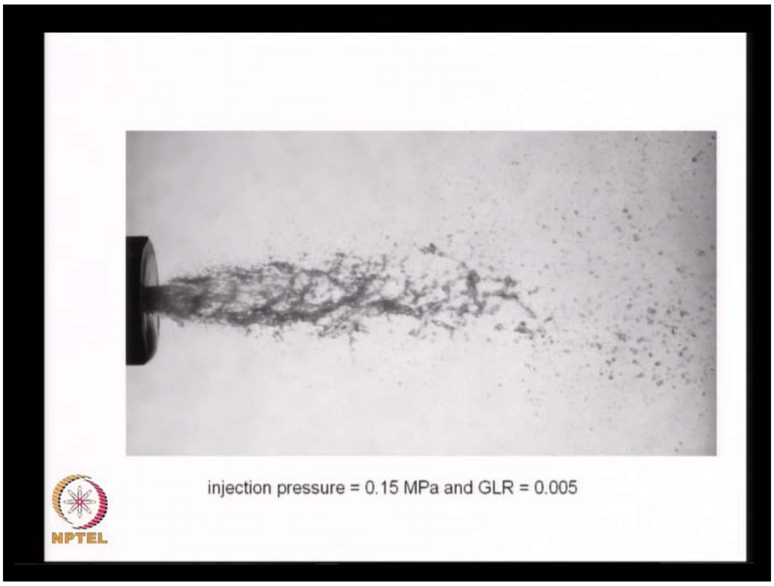

I think this is all about injectors, but I have still not completed the portion, because I can always think in terms of different things. You know this is some experiments which we did in our lab here at at IIT. You know what we do is instead of admitting the liquid, we put some gas in the liquid and again make it disintegrate into droplets and these are known as effervescent injectors, we are still working towards; there still not found application.

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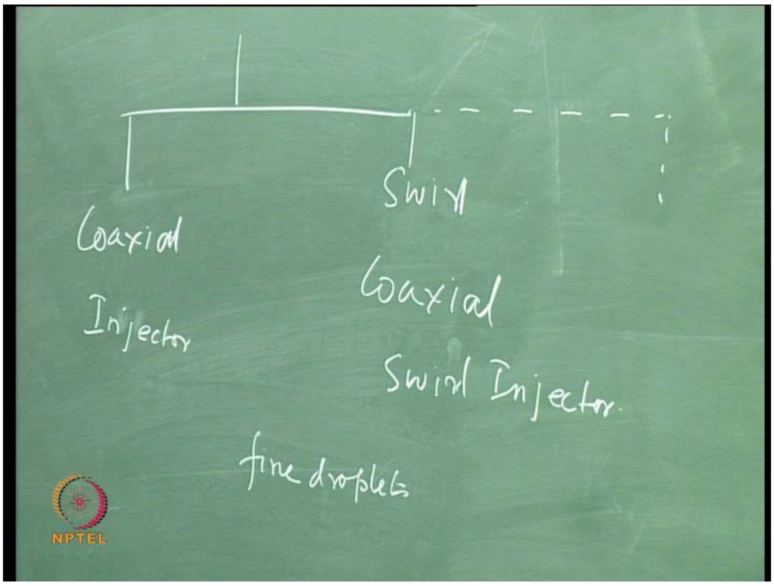

Therefore, I can keep on adding different types of injectors and all have a requirement and the requirement is I need fine droplets which can evaporate and burn, and also meter the required quantity of fuel and oxidizer.

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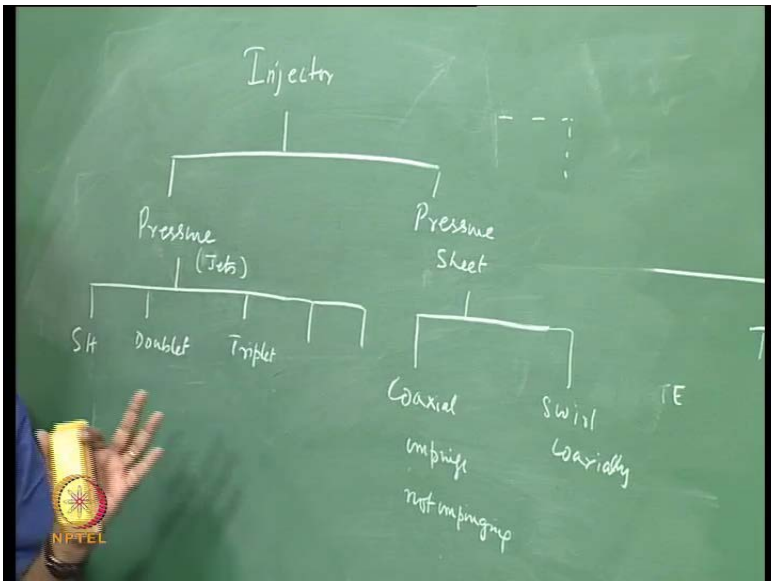

Now, I have a formal method of doing it pressure injectors or pressure atomizing injectors, these could be shower head; could be doublet. The doublet could be like or unlike. I could have triplet, quadruplet, pentlet; these are using liquid jets. I could use the same pressure to create a sheet and in the sheet I could have coaxial injector, wherein I could have the liquid oxidizer and liquid sheets impinge on each other or they may not impinge on each other; that is the second one not impinging, but just breaking into droplets, or I could also have swirl which is used co-axially. These are all about injectors which we use in liquid rockets.

But, having said that you would ask me well, in cryogenic rockets hydrogen is used. Hydrogen is a liquid only at very low temperatures and by the time hydrogen comes into the combustion chamber it could always be a gas.

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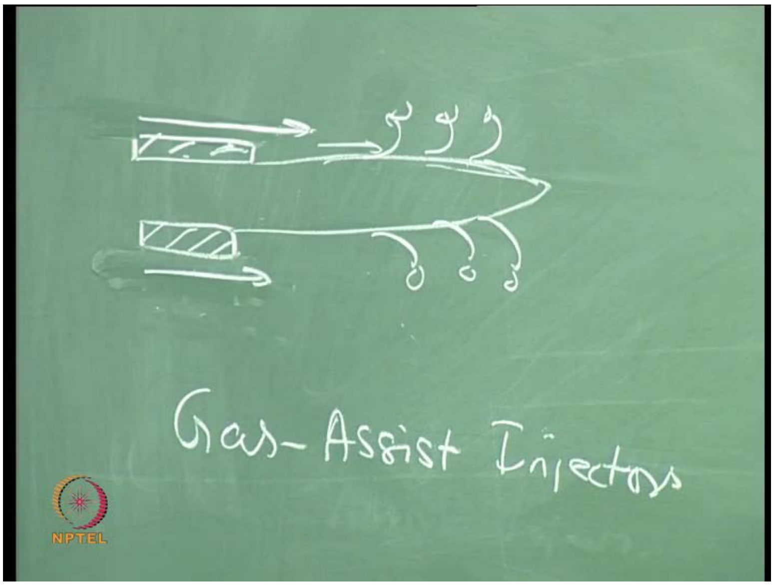

Also we talked of stage combustion cycle engine wherein products from the exhaust of the turbine are again as a hot gas. Can I use the hot gas for atomizing? In other words, I have a liquid jet, now let us make an orifice. I have the liquid jet which is coming like this may be it is coming over here; maybe what I do is on the outside of this; this is the metal portion. I allow the hydrogen jet or the gas from the turbine to come. I I I force the hot gas over the liquid surface, and when I force gas over liquid surface, it picks up the droplets because of the shear and I get the droplets coming over here, and this is known as these injectors are known as gas assist injector, because we use a gas for atomization these are known as gas assist. This gas assist could again be simple coaxial; I could rotate the liquid in which case I have swirl coaxial; I could rotate the gas I could have different configuration, but these are all the different ones.

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Let us quickly go through it because we we should have a an idea of what this is. See this shows the multiple elements in a coaxial you have liquid here; you have the other liquid here coming.

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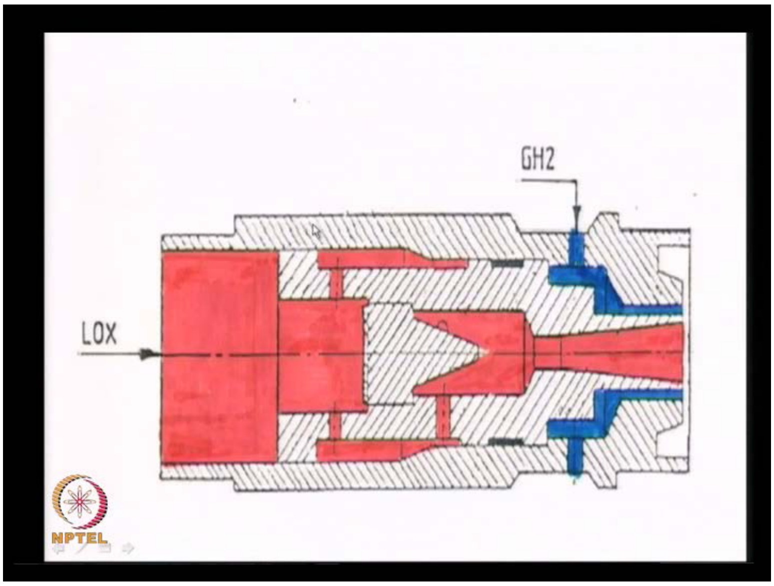

When we talk of gas assist, well I have gaseous hydrogen which is coming through the outside. I have the liquid oxygen which is coming over here; from here it gets communicated to the central channel it comes over here. Therefore, I have liquid oxygen jet over here guess flowing and it atomizes.

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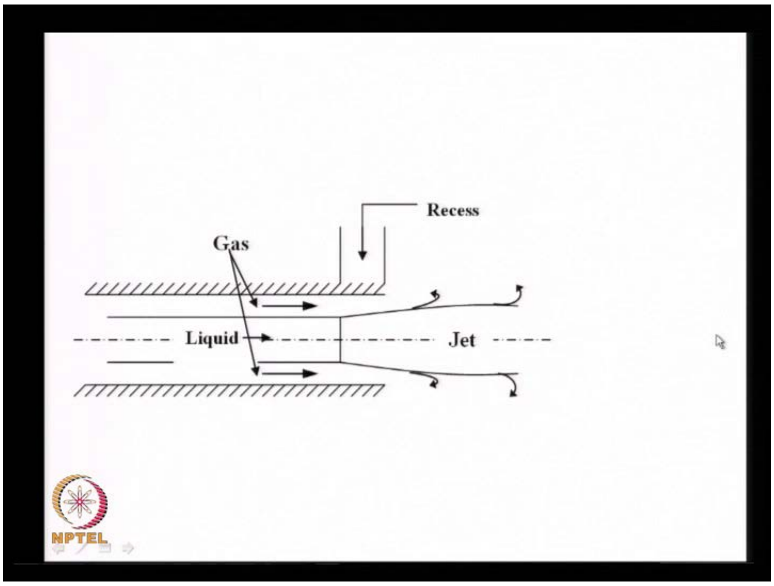

Well, when I have liquid flowing and I have gas coming on the outside, I allow the liquid to be within the orifices such that the gas does not expand. We say the gas must not relax such that I get the high velocity, and this distance between the outlet of the liquid orifices and the gaseous is what is known an as a recess. Recess essentially make sure that the gas velocity is available for atomization.

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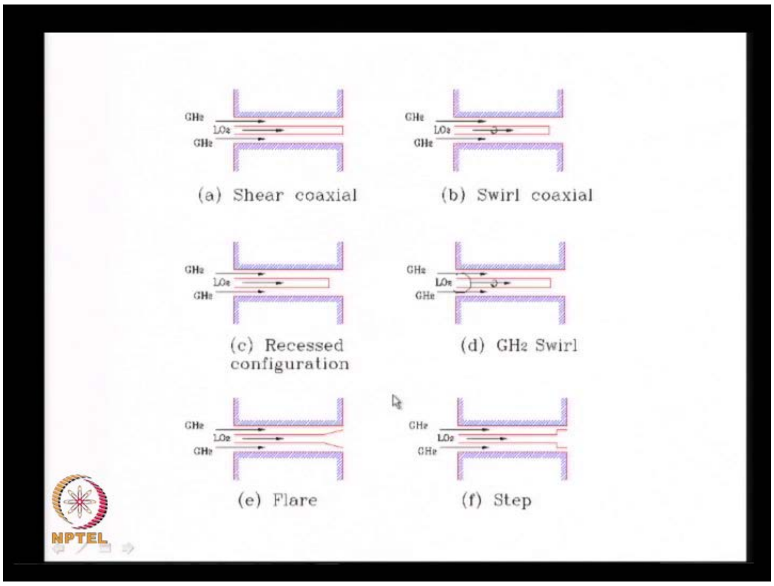

And therefore, I can talk in terms of shear coaxial, swirl coaxial; maybe I could have a recessed configuration; I could give rotation to the gaseous hydrogen; I could give rotation to the gaseous oxygen and therefore, I could also make the make the passages to flare or step and you can keep on doing in details, and injector by itself becomes up a major portion of the liquid propellant rocket.

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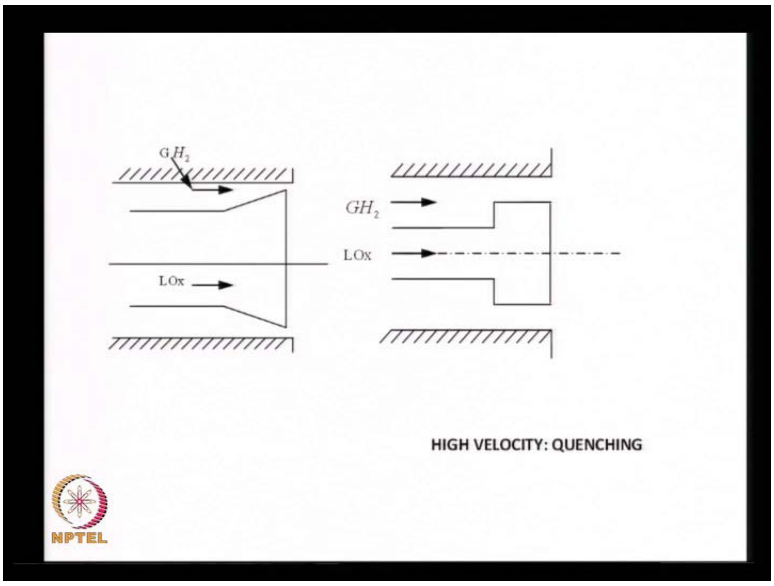

Namely, here I give flair here; I give an opening on the liquid oxygen; I reduce the velocity, why I reduce the velocity? If I give very high velocity, I cannot sustain a flame and therefore, this is what gets into injectors.

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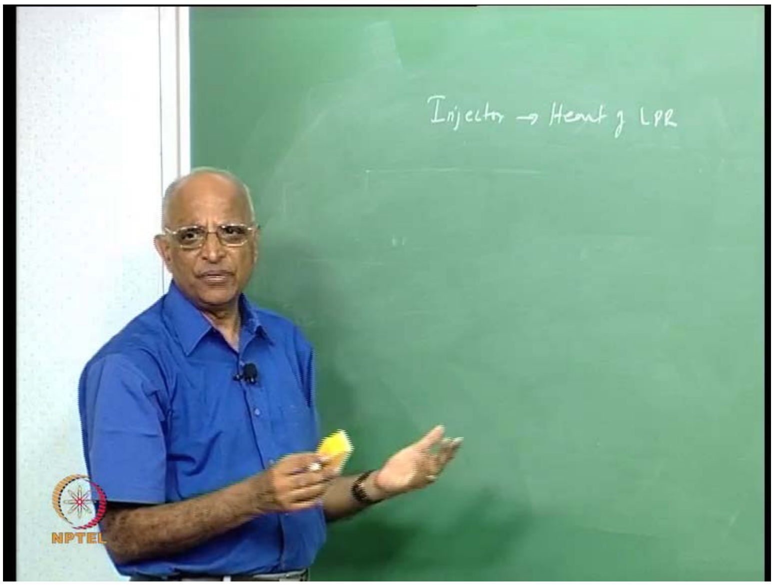

Therefore, injector design I would say is the heart of liquid propellant rockets, because this is what produces the droplets may be makes it evaporate and burn. I think I will stop with the injectors here; I will get back in to injectors when we talk of combustion instability and to a certain extent when we talk about efficiency of combustion.

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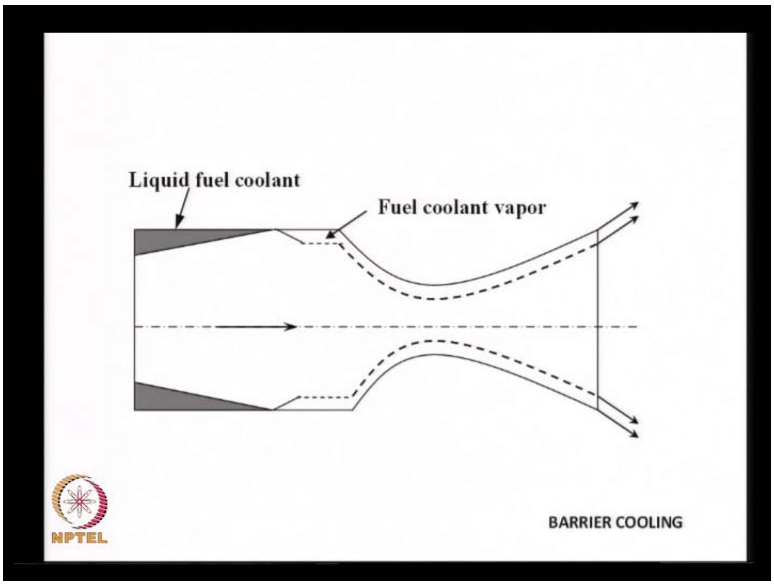

I think having said that let us go to the next topic and I thought at this point in time, let us look at something like cooling of liquid propellant rockets.

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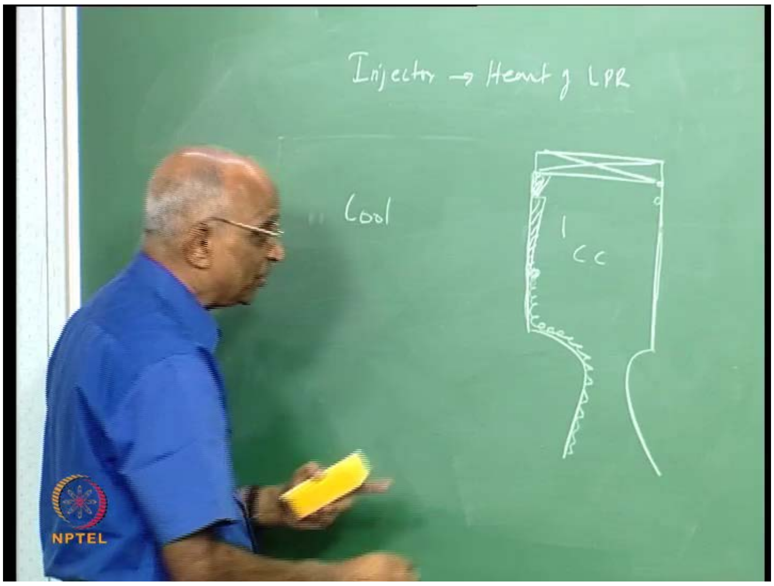

What is it I am talking? We have considered a combustion chamber over here. We said I have an injector over here. We consider different ways of injection, we also said how to calculate the mixture ratio and all that. Now, I have the combustion chamber here; hot gases are produced and it expands out over here. We told ourselves the mixture ratios are such that the temperatures in the combustion chamber are quite high of the order of we learnt how to calculate it, we found that it is of the order of 3000 to 3600 Kelvin. If it is so material which has to house the combustion chamber will burn of within seconds, because the gases are extremely hot.

Therefore, the question is how do I cool my combustion chamber? One of the ways is may be if I can admit some fuel near the valve; I admit the fuel near the valve, I give it some velocity, I rotate it such that I make sure it sticks to the valve. I have lot of liquid here and the length of the combustion chamber is small. Therefore, full turbulence cannot be developed and this liquid is entering by the gas and therefore, I have a thickness the liquid thickness decreases, and this liquid film keeps the combustion chamber cool then it vaporizes. When it vaporizes is still much cooler than the combustion gases and then these vapor can still further continue to cool and I have my combustion chamber which remains cool. In other words, I have a film of liquid which is injected and this method of cooling is what we call as film cooling.

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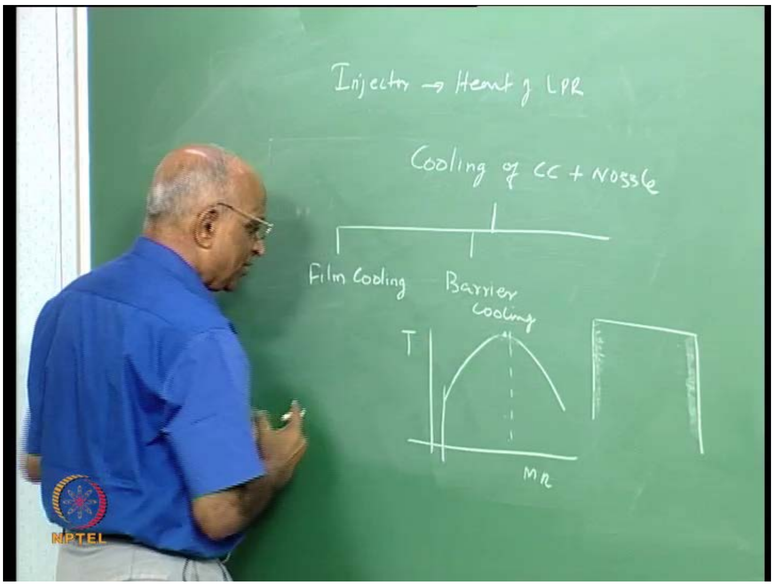

Right let us take an example, this is what I show over here. I have a liquid coolant being injected along the valve; hot gases are evaporating it; vapor is formed the vapor further cools the combustion chamber and nozzle and this is known as film cooling. See, instead of film cooling I could also make sure that maybe when I have the combustion chamber over here, I could make the vapor over here; maybe make this a little bit fuel rich. If it is fuel rich I know from my diagram of temperature versus mixture ratio. I know at near stoichiometry I get maximum flame temperature slightly less than this. If I can keep the gases over here at a very fuel rich, then I have low temperature over here I can keep it; that means, I have a barrier of fuel on this side and this method of cooling is what we call as barrier cooling.

To a certain extent the film cooling incorporates barrier cooling, because what is it we are doing? We have a barrier of the fuel vapor over here; maybe it also reacts to some extent, but it is still much cooler than the core gases and therefore, I keep the thing cool.

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How do you implement it in practice? Well, I show a figure here. I have something like co-axial injectors which are participating in combustion. I give a series of holes over here in which I admit the fuel; I direct it on the wall of the chamber and that is what is film cooling. This can be easily predicted; what we do is we calculate the heat transfer coefficients.

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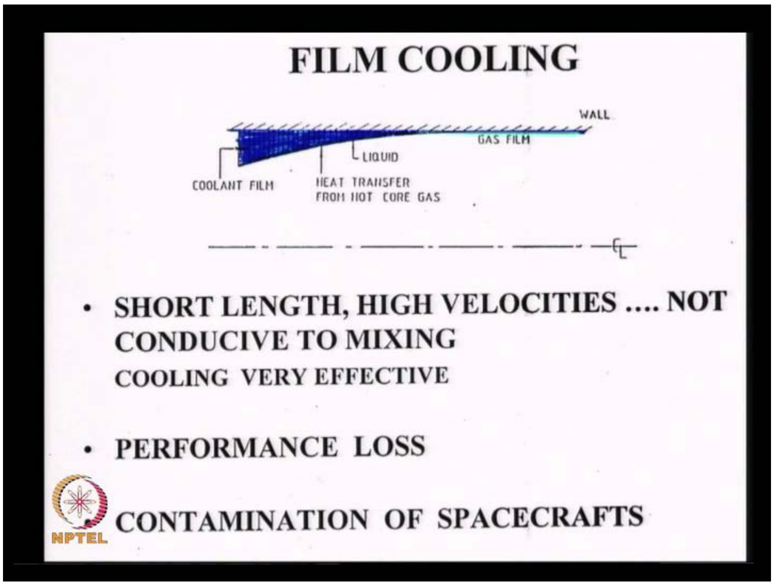

I have a film; I write the equation for the thickness initial thickness of the film. I know the heat transfer coefficient between the hot gases and the film. I can calculate the rate at which it evaporates. I know the heat transfer coefficient between the film and the wall. I do a composite thing. I can calculate the thickness and I can do the same thing for the gas film and do the calculation.

Therefore, film thickness is film cooling is what is used in rockets, and why it is very effective? The combustion chamber length is small, you do not have full turbulence being developed and I can do a neat calculation, I can also use it very effectively for this. The disadvantage is you know immediately you say well, I am losing some amount of fuel here.

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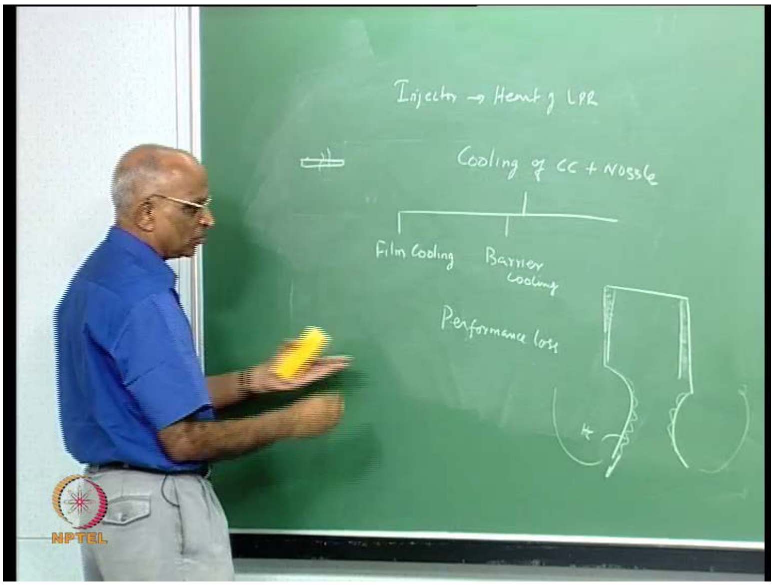

Therefore, to that extent my specific impulse gets affected. Therefore, I have a performance loss; that means, my specific impulse is little poorer, and second thing is when I have a nozzle and I have the coolant coming over here, the velocity at this is not very large, and also these are may be hydrocarbon gases and since the velocity is not large, it is not thrown off along the plume it comes back to the surfaces and when I use these film cool things for the space craft, it sometime contaminates the glass in the space craft. A space craft consist of sensors, what are sensors? You have optical quality glass which allow radiation to go in some way or it looks at the radiation from the earth sometime these get contaminated because of the film cooling.

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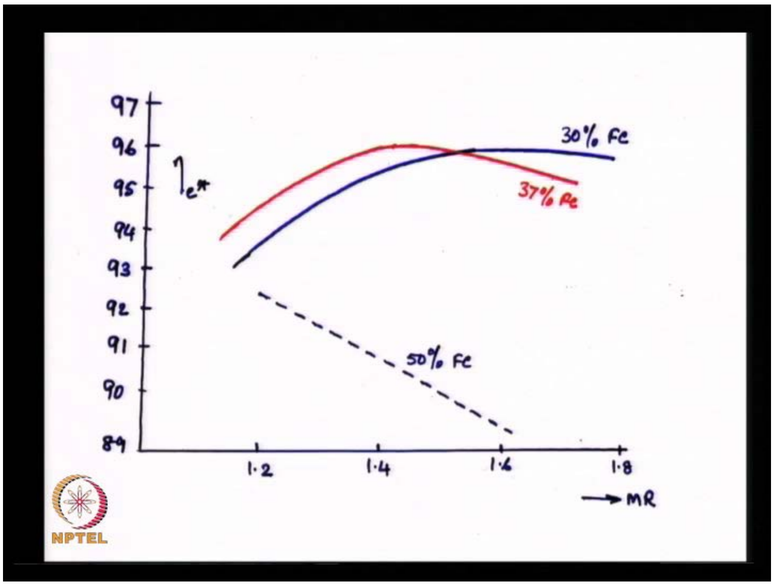

We will keep that in mind. Well, this all about film cooling; other cooling methods you all are very well aware of. But, let us come back to this figure may be after we finish discussions on efficiencies, but just to highlight when I give something like 30 percent film cooling this is an experiment which we conducted. If we give, if we increase the cooling from 30 percent to 37 percent, the peak value of of of c star shifts to somewhat like a fuel rich region, because I already have fuel over here. I can I have to make the total mixture ratio oxidize rich, I will cover this again. If I give very much types of say 50 percent of the fuel for film cooling my my c star value keeps falling as mixture ratio increases, I will I will revisit this graph a little later.

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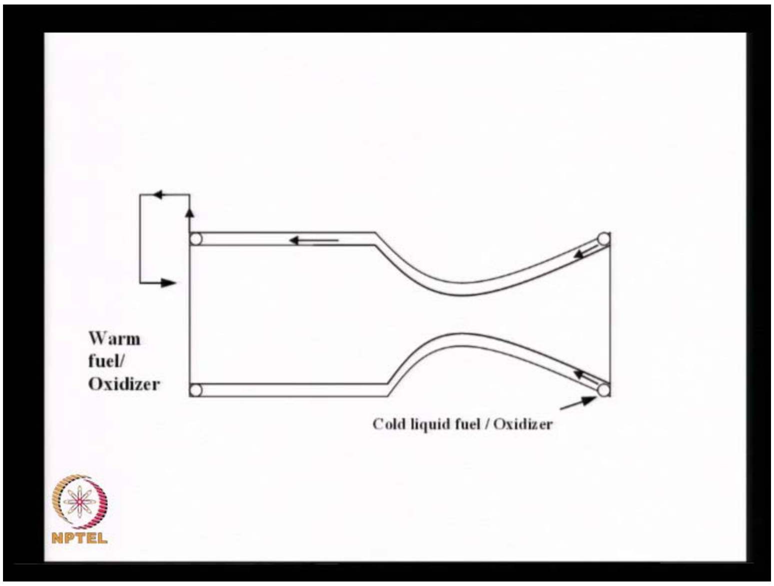

Well, the next type of cooling is what we call as regenerative cooling, I will not use the blackboard I will show with the slide. In regenerative cooling, like we have the regenerative Rankin cycle which is used for the feed water heating. I admit the fuel at the end of the nozzle; I keep heating the fuel over here, the heated fuel is admitted. Therefore, the heated fuel is much warmer and therefore, it has some enthalpy it is used regeneratively. Therefore, the next type of cooling which we can write is regenerative cooling, it is a regenerative process.

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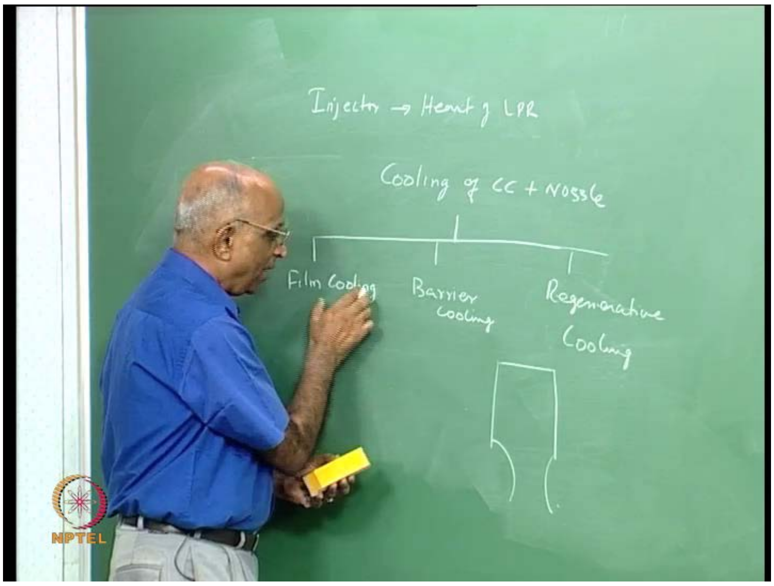

Like feed water heating I use it to regenerative cooling. Invariably, regenerative cooling is always used with film cooling. The reason being in regenerative cooling you know I have the chamber; I cannot admit it I have to make a series of tubes which go in between regenerative cooling passage is it still might get hot and film cooling can smear out the temperature increases.

Therefore, this is regenerative cooling. There are problems relating to I must have very high conductive materials, otherwise I get some high stresses and it leads to cracking known as ratcheting and all that, maybe we will not go into those details.

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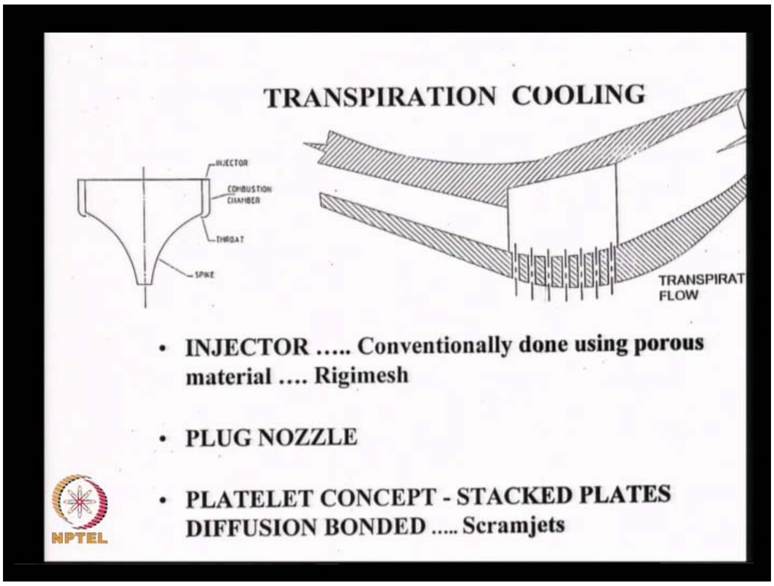

Let us get into the next one, just like the body sweats and keeps as our temperature cool so also I can have the nozzle wherein I admit the liquid coolant in this particular direction through small orifices these things evaporate and keep the temperature cool, or rather this has been extremely used extremely well used in the case of the cryogenic rockets for the injectors.

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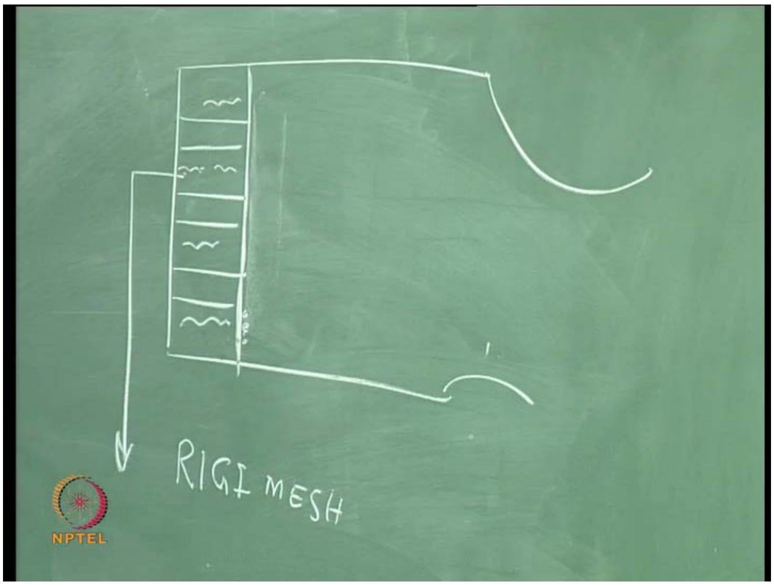

Let us again make a schematic of the injector. This is let us say the injector block; I have the combustion chamber here; I have let us say a series of coaxial injectors over here, and now this surface runs hot; maybe I make this of a material which can ooze out may be the liquid hydrogen over here, and when it oozes out over here, it is like perspiring or transpiration through this holes, and when it does this it keeps the injector cool. And this particular configuration is what is known as a RIGIMESH. It is a commercial name, but all what is said you have a series of meshes which allow the liquid to get sweated out through this part and it evaporates and keeps it cool. This is what we call as transpiration cooling that is the third cooling.

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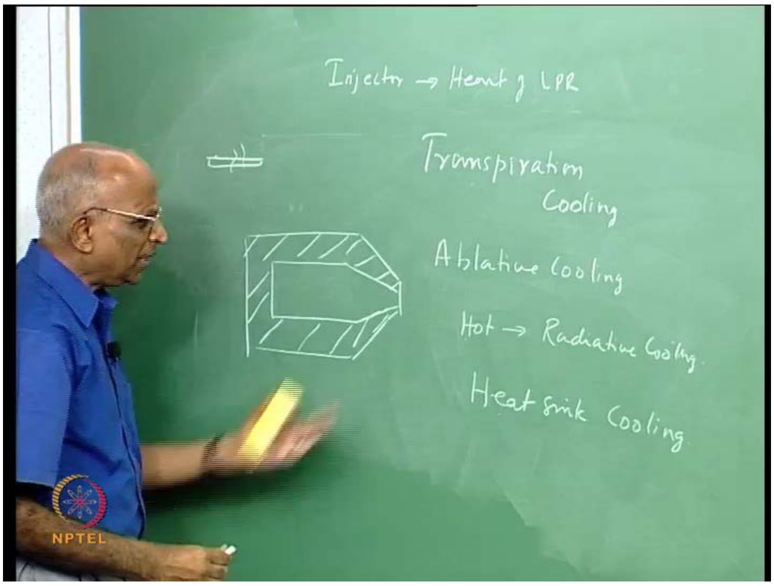

Well, we have a few more cooling, the other ways maybe I could use an ablative material. You remember I talked of ablative materials when I talked in terms of the nozzles, what was it? We have something like resin which is a some resin or a glue which is a hot body. If I allow it is temperature to increase it softens and evaporates and I make the resin I increase the strength by laminating it I put some fibers in it, I have something like a composite material. A composite material when heat when exposed to high temperature evaporates at the ablation temperature at a particular temperature and it gives raise to evaporative cooling and that is known as ablative cooling. Well, instead of cooling I just allow the body to run hot in which case I allow radiation itself to dissipate the heat I can talk in terms of radiative cooling.

Or if I have just want a rocket to do a ground test, I can make the rocket so heavy so much of material such that I operate the rocket only during the transient. Let us say this is the thickness of my rocket wall of the rocket. Maybe I operate it for 1 second, in 1 second the mass of the rocket or the thermal mass absorbs the heat and this known as a heat sink rocket.

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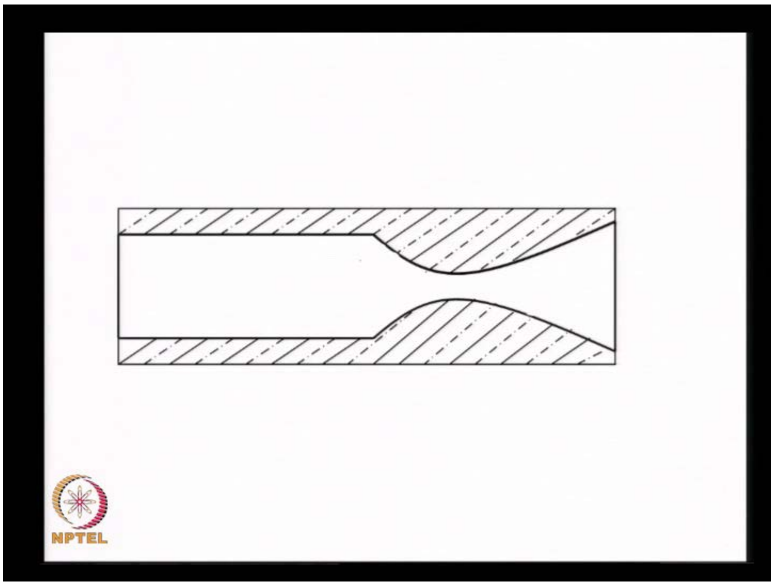

Let us quickly look at some of these things in somewhat application oriented mode. You have an ablative material which evaporates when it when the hot gases go and maintains the integrity and the temperature of your liner.

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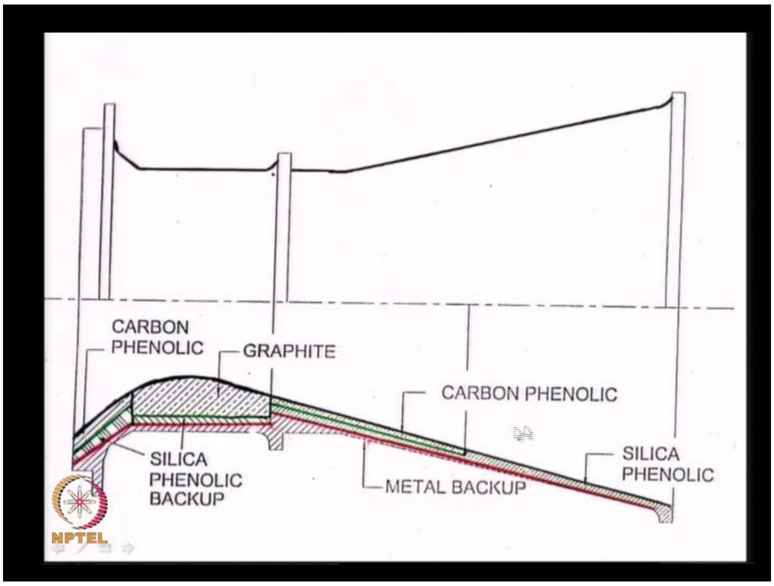

And this is what we said when we studied about nozzles, we could have the ablative materials which will evaporate. We use both carbon phenolic carbon as a fiber and silica is a fiber, carbon is more prone to oxidation. Therefore, silica is better for cooling, because silica is an inert material.

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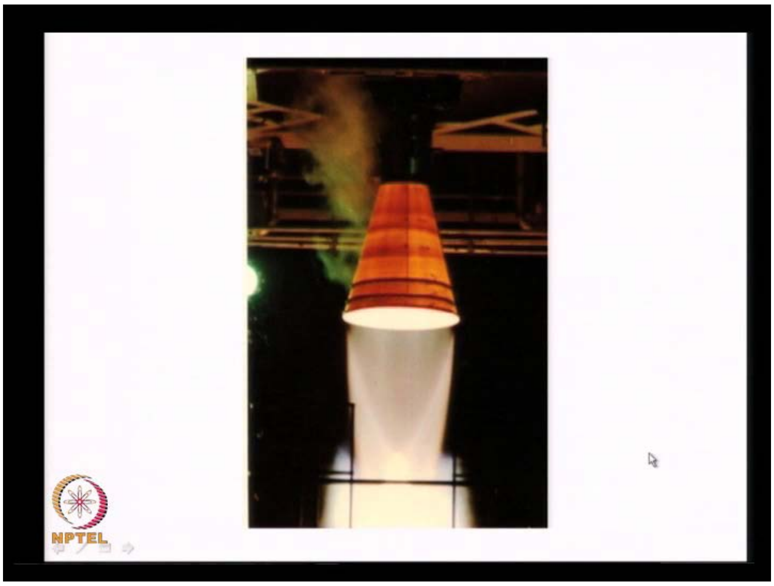

And this is a radiative material we looked at this figure the nozzle runs red hot and radiates away the heat.

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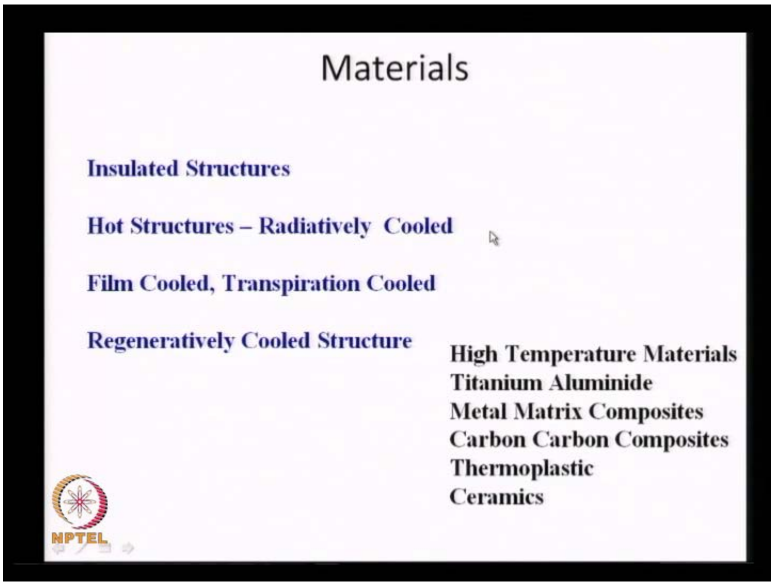

Therefore, to just summarize this cooling, we can say well I co use something like an insulation like ablative. I use a hot structure that means I use a high temperature materials like carbon-carbon composites; maybe metal may be high temperature materials I use, and radiatively cool it or I have regenerative cooling along with film cooling or barrier cooling and also transpiration cooling. These are different cooling strategies.

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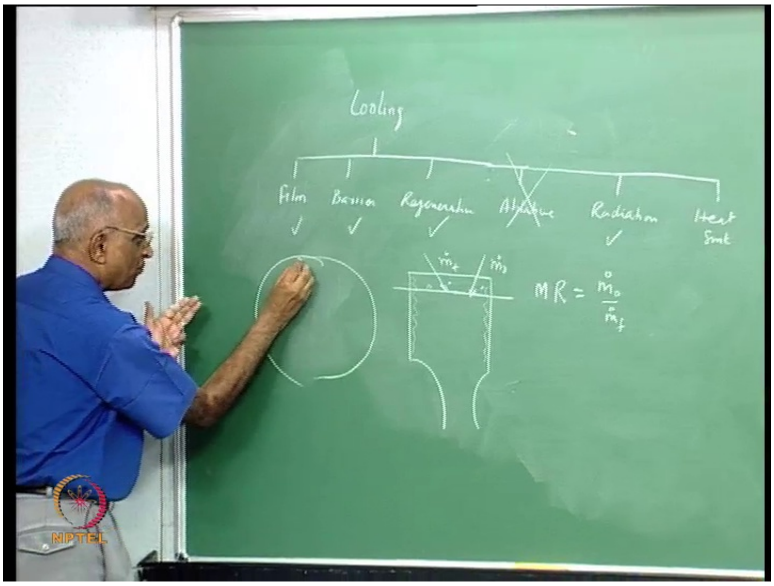

Having talked of cooling and injection, what is the problem we have now created? We said well cooling is important let us quickly go through the cooling procedures again before I put the two things together. We said the cooling could be film; could be barrier; could be regenerative; could be ablative; could be radiation or could be heat sink. Well, heat sink is only for ground test for short duration transient heating. Radiation yes, I need high temperature materials. Ablative, it is little difficult to use we use it when we start off with rockets, but to fly it you need so much of insulation that it becomes heavy. Well, regenerative is positive, barrier is positive, film is positive. Therefore, in practice we make use of film cooling, barrier cooling, regenerative cooling and also radiation cooling. Having said that now what is the problem we have got into? We have got a chamber.

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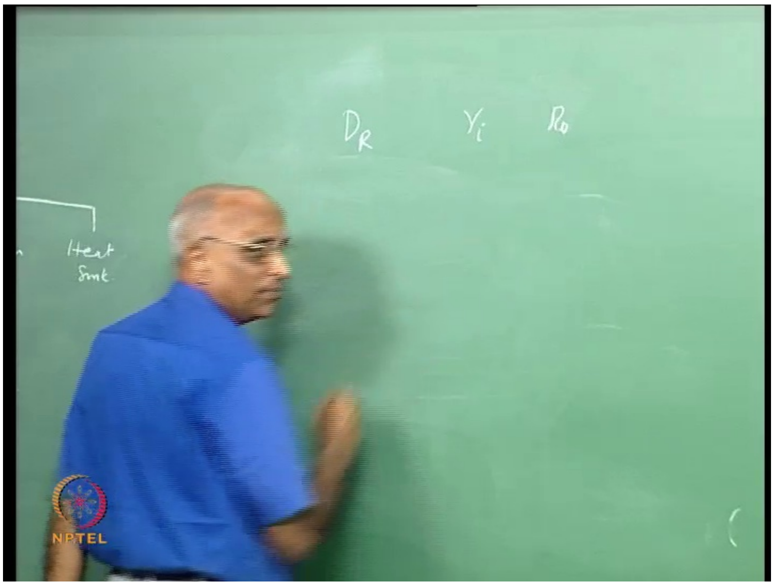

Now, we are injecting fuel into it m dot F; we are injecting oxidizer m dot O into the chamber. We thought the mixture ratio in the chamber r or rather M R is equal to m dot O by m dot F. But, what is the problem we have now created? We now say at the wall it is little bit fuel rich if I have barrier cooling or film cooling, maybe depending on the injector, may be the distribution of fuel and the oxidizer along this; that means, if take a section over here, I have fuel rich zone which are over here; maybe I have a oxidizer rich zone, I have zones which are different in distribution. Therefore, I do not have uniform mixture ratio distribution in the chamber.

In other words, if I were to now define a a a a parameter like let us say a mixture ratio distribution which I call as a D R, then this D R will represent the difference between the local mixture ratio r i at any point i, and the overall mixture ratio r naught and that will affect my combustion efficiency, and this is what I will do in the next class. And we will take a look what are the penalties we pay because of the mixture ratio distribution, and if I have the finite length of the chamber is it possible for me to get combustion completed or will I have another efficiency coming over here. Therefore, what is it I have done in today's class? We revisited injectors, we define different types of injectors, then we went into cooling strategies. And then we have now put a problem which we must solve in the next class namely, what is the impact of mixture ratio distribution in a chamber and how to look at the effective specific impulse what we get. We will do that in the next class and well, thank you I think that is about it.