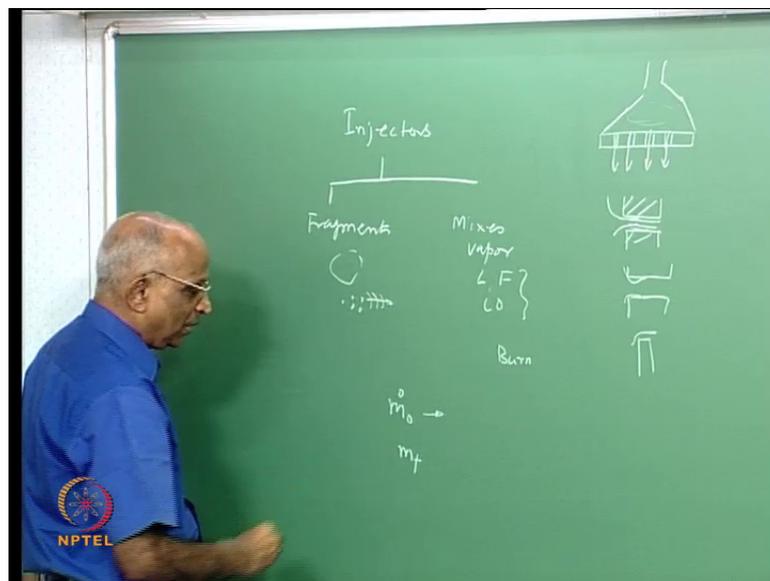


Rocket Propulsion
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Lecture No. # 29
Injectors, Cooling of Chambers and Mixture Ratio Distribution

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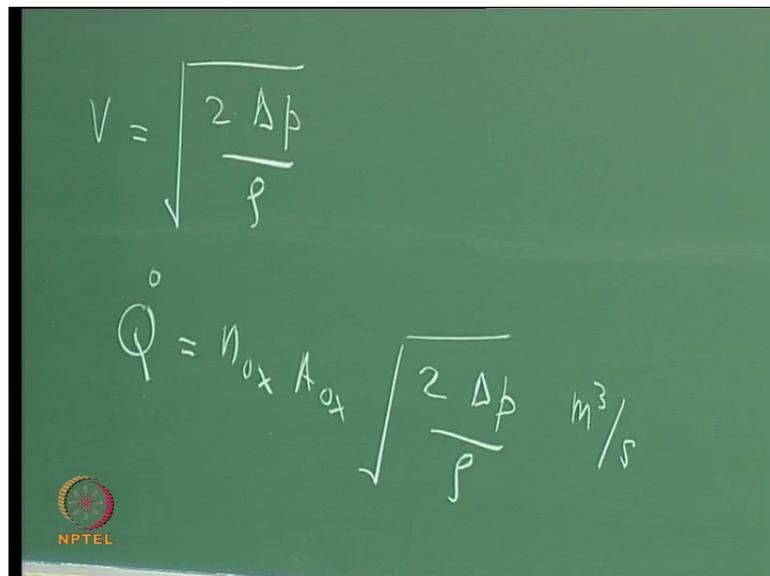


We will continue with the discussion on liquid propellant rockets. In the last class, we were looking at injectors. And what does an injector do? It admits the required liquid fuel and liquid oxidizer in the combustion chamber, breaks it up into particles; why do you have to break it up? So that the surface area increases, it will evaporate. It mixes the fuel and oxidizer vapor, and after mixing the propellant vapors burn. Therefore the purpose of injectors what we said in the last class is maybe it fragments the liquid, then once it is fragmented; that means, the liquid is made into fine drops such that the surface area increases, then there is something like an evaporation taking place. And then it mixes the vapors 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 discuss further on the injectors; and what did we do in injector in the last class? We told we could have something like a shower head injector which we normally use for bathing. It consists of a series of orifices or holes, and then you have the water, which comes from your tap into the shower head, and in the manifold where water collects, and then the jets are generated as parallel streams and this is what was a shower head. But, we had said that the flow of the water in the shower head is such that if we consider a single hole, it is not uniform flow throughout its length in the orifice. We have a vena contracta wherein the flow contracts and thereafter it diverges and gets attached to the walls of the orifice. If the aspect ratio of the orifice is small we have a detached flow after the vena contracta. And we could have different flow patterns, and if the flow cavitates it detaches from the walls. Therefore, the flow does not happen fully through the orifice.

How did we calculate the flow of let us say the oxidizer and the flow of fuel through this particular set of shower head orifices? We spent 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 that we want to calculate could be had from the following.

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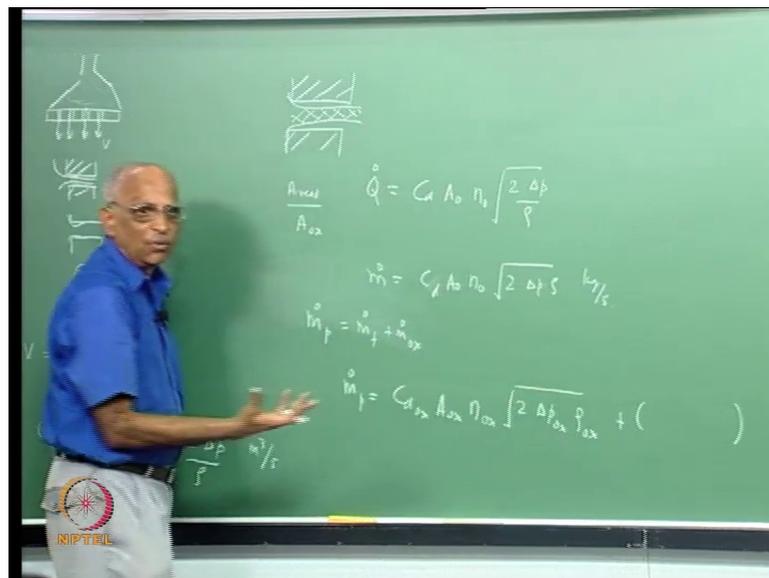

$$V = \sqrt{\frac{2 \Delta p}{\rho}}$$
$$Q = N_{ox} A_{ox} \sqrt{\frac{2 \Delta p}{\rho}} \text{ m}^3/\text{s}$$

We need to know the velocity of the flow, and we derived an expression using Bernoulli equation that velocity is equal to $\sqrt{2}$ × the pressure drop /divided by density. The pressure

drop was Pressure at in the manifold minus the pressure in the combustion chamber is denoted by Δp .

Therefore, $V = \sqrt{2 \Delta p / \rho}$, and to be able to get the quantity of flow which is taking place; we had all these holes n_{ox} for the oxidizer, and the area of each hole was A_{ox} . So the flow rate of oxidizer was Δp is in Newton per meter² $A_{ox} m^2$, the number n_{ox} and flow in meter³/second. But mind you, we are still missing something what is that missing?

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You know when flow is taking place through the orifice, very often flow gets detached here and sometimes the flow gets detached attached. That means, this is the flow taking as detached and the entire orifice is not fully flowing, and but still I have to base it on the actual area of the orifice. The real area of flow is only this. The apparent area is the area of the orifice, which for oxidizer is A_{ox} .

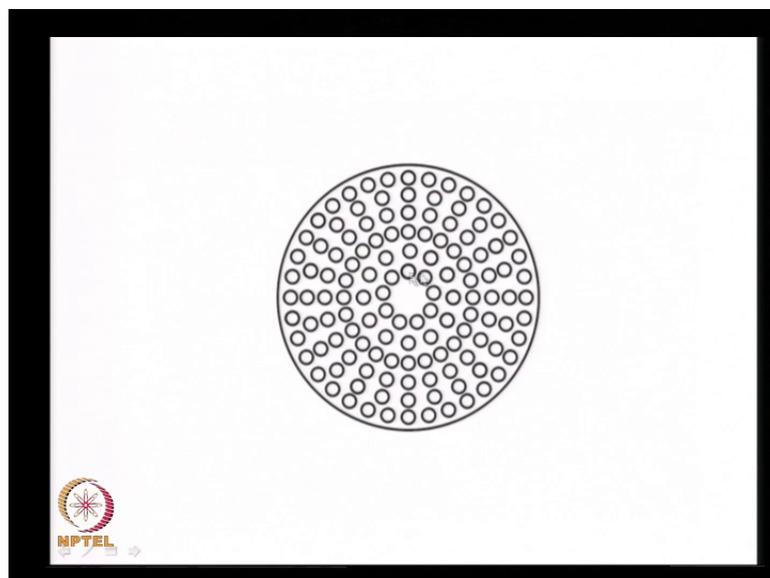
And therefore, the volume rate that flows through the orifice is much lower than what we have calculated. Not only for this detached flow but even when the flow gets attached; let us say we have the orifice like this; we have a vena contracta and it gets attached. There is some frictional drop here the flow may not be axially progressing. It may go at an angle and therefore, I still have losses and therefore, the losses apparently lower value of the flow rate. But we are basing on the orifice area. And therefore, we said that the Q actual which is flowing is multiplied by a coefficient which I call as discharge coefficient C_d . The volume flow rate is therefore area of the orifice A into the value n of the number

of holes into $\sqrt{2} \Delta p / \rho \times$ the discharge coefficient C_d or rather this is the rate of flow in meter cube per second. We convert it to mass flow rate and we get the mass flow rate multiplying by density to give $m^{\circ} = C_d \times A \times n \times \sqrt{2 \Delta p} \times \rho$ so many kilograms per second.

We did so far in the last class. We can calculate the total propellant flow and the mass flow rate of fuel and oxidizer. And therefore, we have a number of holes for the oxidizer and a number of holes for the fuel and we can get the required flow. The total oxidizer flow will be equal to C_d for the oxidizer orifices into area of the oxidizer orifices into the number of oxidizer orifices into $\sqrt{2} \Delta p$ across the oxidizer orifices into the density of the oxidizer.

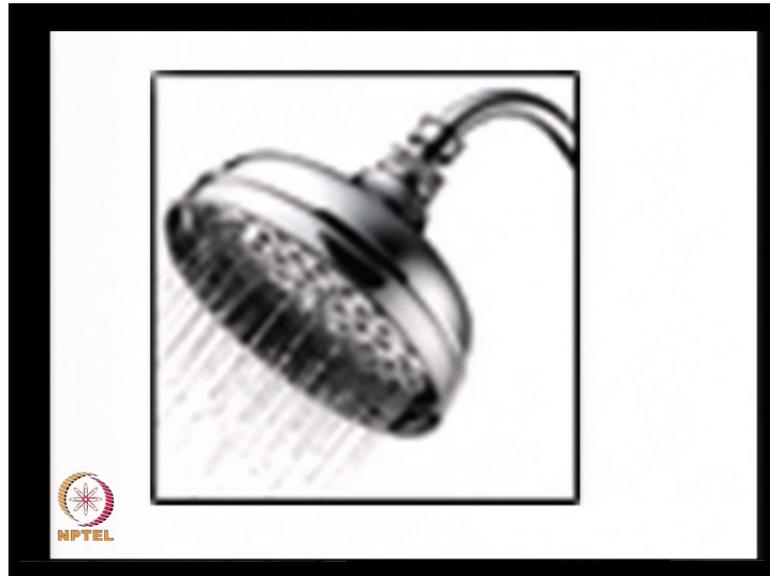
And similarly, for fuel we have its mass flow rate as C_d of the fuel orifice into area of the fuel orifice into the number of fuel orifices and the other terms like pressure drop across fuel orifice and density of fuel. What was the mixture ratio? Mixture ratio is this quantity of oxidizer divided by the mass flow rate of the fuel.

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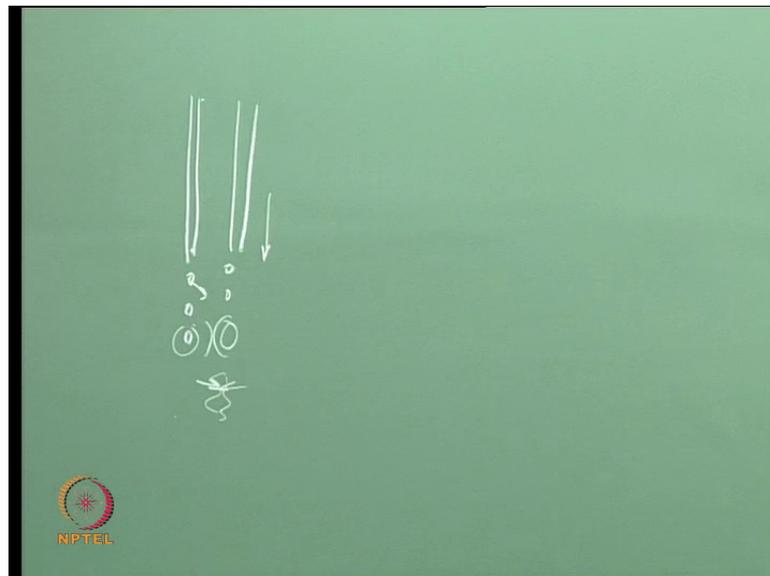
You have the number of holes in the shower head. We compartmentalize it for the oxidizer and fuel. We have oxidizer orifices and fuel orifices.

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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. But, there is one problem with shower head; we have something like jets coming like this from the holes in the orifices and these become droplets.

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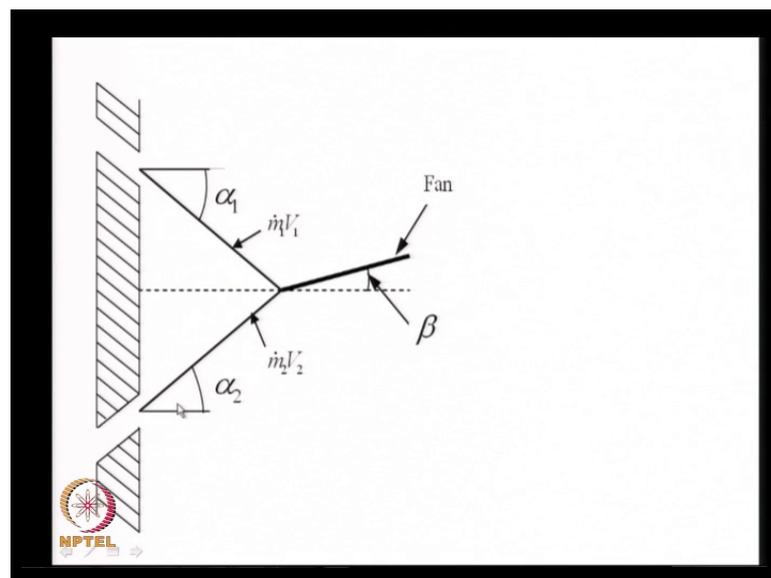


The direction of flow is axial like this. If I have one fuel jet and one oxidizer jet, I am not promoting the mixing, I am not giving it an angle such that the vapors can come and mix. Therefore, mixing is poor in a shower head injector, and we need good mixing for

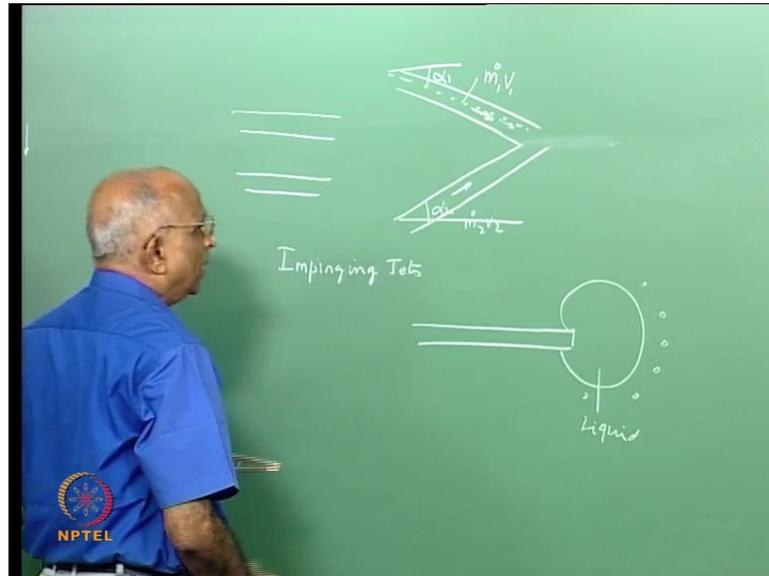
combustion to take place? We need to have some strategies such that we can have the fuel vapor formed by evaporation of the fuel droplets to mix with the oxidizer vapor formed from oxidizer droplets.

If the jets were to impinge on each other such that we could get something like a mixing zone. If we can get a mixing zone then we will be better off. And therefore, I schematically show this scheme of impinging jets. Let us say for the present that we have this as the jet which is coming from a shower head, then we reorient the second jet and make the two jets impinge on each other at this particular point.

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And when we make the jets impinge at a point; we have momentum change, rate of change of momentum taking place at the point of impingement. We have something like a jet coming over at the point of impingement; one liquid jet coming from one orifice. I say that the mass of flow is m° here, let the velocity of the flow is V . Therefore, the momentum or the rate of change of momentum along this is equal to $m^{\circ} V$. We take another jet with mass flow rate $m^{\circ 2}$ and velocity V_2 which impinges on the previous jet. And at the point where these two jets are impinging, let us say they impinge, we have something like a pressure which is built up at this contact point due to rate of change of momentum. At this particular impingement point we have a higher pressure and therefore, the liquid jets spread out; I get something like a sheet, which is known as a fan.

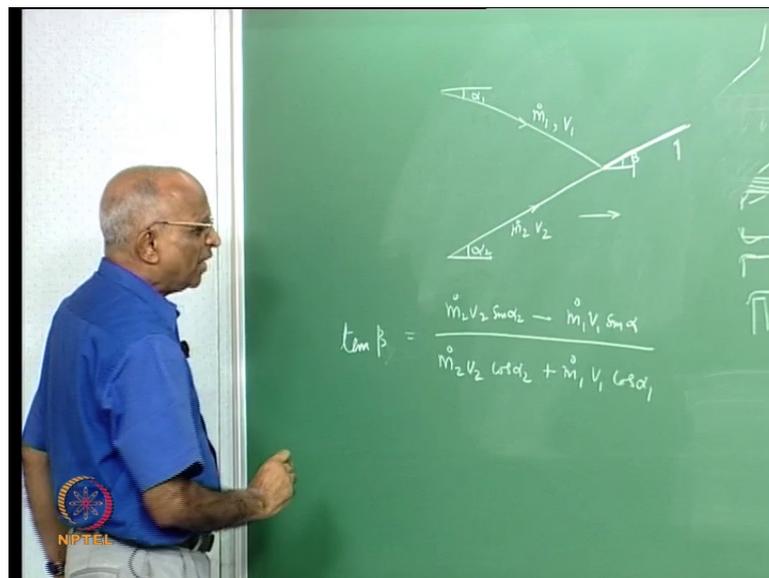
Therefore, if we look at it the two jets impinging on each other symmetrically, we get a fan like this in a plane normal to the plane of the jets. In the plane of the jets we cannot see the fan. Let us try to draw it such that it is clear. I have two jets just like I told you; I have a jet coming over here; 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 formed.

Therefore, if instead of using single jets in a shower head we have lot of impinging jets like this and form many thin liquid fans at different orientations which then breaks into

droplets. In this way instead of having something like a shower head we have impinging jets which form fine droplets from the thin fans and also mix the fuel and oxidizer.

We can make this final jet or fan in any direction we want. How do we do it? Let us consider a small example. Let us say the angle of this first jet with respect to the horizontal is α_1 , the angle of the second one with respect to the horizontal is α_2 . Let me draw it distinctly on the other side of the board.

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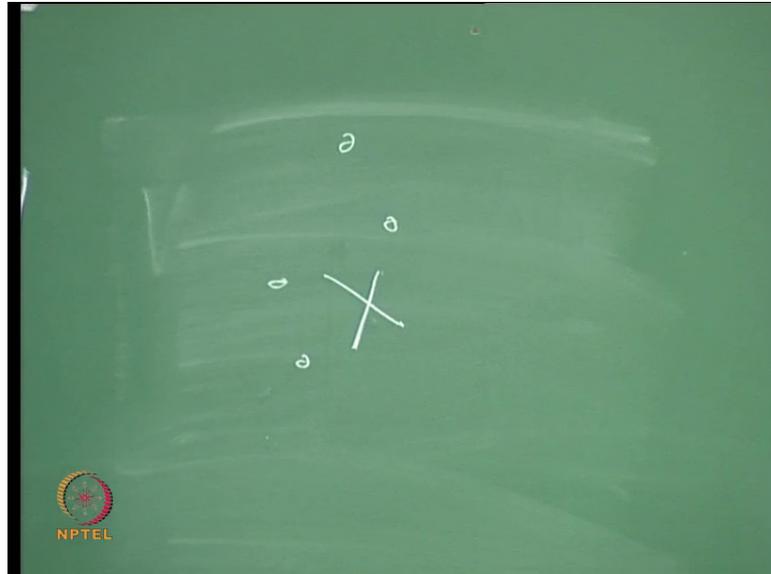


We have one jet, the angle with the horizontal is α_1 ; let the mass flow rate of this jet be m°_1 let its velocity be V_1 . I have another jet which impinges it over here, let the angle be α_2 ; let the mass flow rate be m°_2 and the velocity be V_2 . Rather than the mass we consider mass flow rate m°_1 and m°_2 .

Now, depending on the rate of change of momentum we get a force here, and we can make this final or resultant jet at any angle we want. How do we do that? That means, the resultant jet or the resultant fan or a sheet is formed.. It could be at any angle what we want and this angle β will depend on the momentum and the angles of these two incident jets. We want to determine this angle β . The rate of change of momentum in the axial direction is equal to $m^{\circ}_2 V_2 \cos \alpha_2$ for jet 2 and for jet 1 the change is in the same direction. Therefore, we have $+ m^{\circ}_1 V_1 \cos \alpha_1$. What is the vertical component? The vertical component is $m^{\circ}_2 V_2 \sin \alpha_2 -$ in the downward direcm $m^{\circ}_1 V_1 \sin \alpha_1$. The tangent

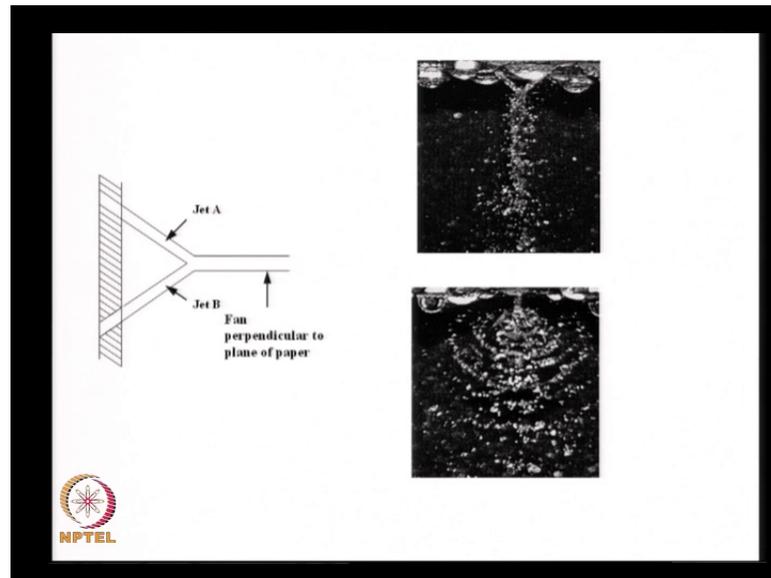
of the angle β would be the resulting vertical component divided by the horizontal component.

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Therefore, depending on the angle what we choose and the momentum of the two jets we can get any angle beta that we desire. And therefore, if we have something like these holes; I have another set of hole like this. By changing the angle we 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 summarize what we said. We have one jet impinging with the other to form a fan, and this angle we can choose and therefore the 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 impinging injectors. Well, we have one jet here; the other jet here, equivalent to saying one jet comes here; the other jet comes over here. We have the fan which is formed along this plane perpendicular to the plane of the two jets. How does the fan look? When we take these two jets which are meeting at a point; that means, the two jets are impinging. We have an impingement point and therefore, I get something like a fan over here. The fan is typically of this particular shape over here, and when we 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 the side view, we get a fan like this; and I get a series of droplets. This is the principle of impinging jets which are used for injection.

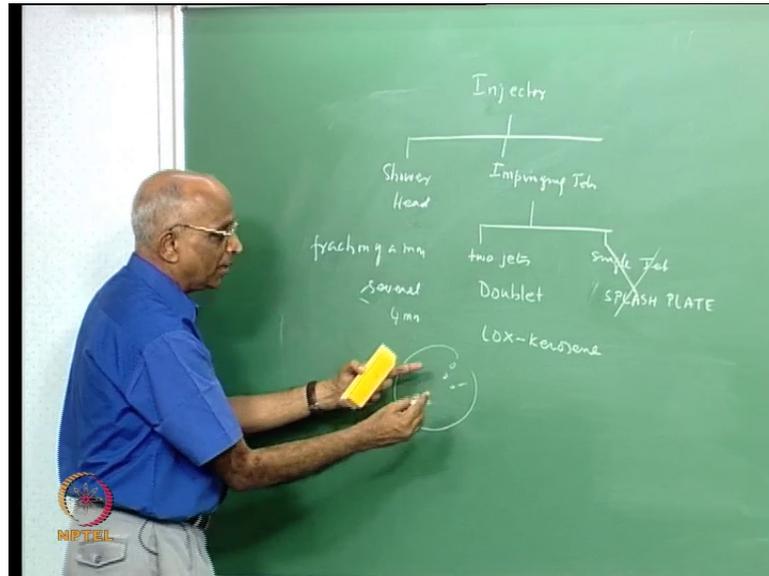
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I show the impinging jets and the formation of the fan with the incident jets at different Reynolds numbers. At low Reynolds number when the jets are clean, when the jets are smooth I get neat fan like this; it forms a fan over here, and disintegrates into droplets. I go into the very turbulent regime at higher Reynolds number; the incident jets are that smooth, but still I get fine droplets. But, I told you about cavitation flow wherein the disturbances in the incident jets are quite profound. In this case we do not form a clear fan and fine droplets. Therefore, we have to choose a proper Reynolds number or a proper Weber number to make sure that we get fine droplets. This is the principle of impinging jet injectors.

Now we can go a little faster and we can tell that injectors can be classified into some simple schemes, and what are the simple ones that we can talk of?

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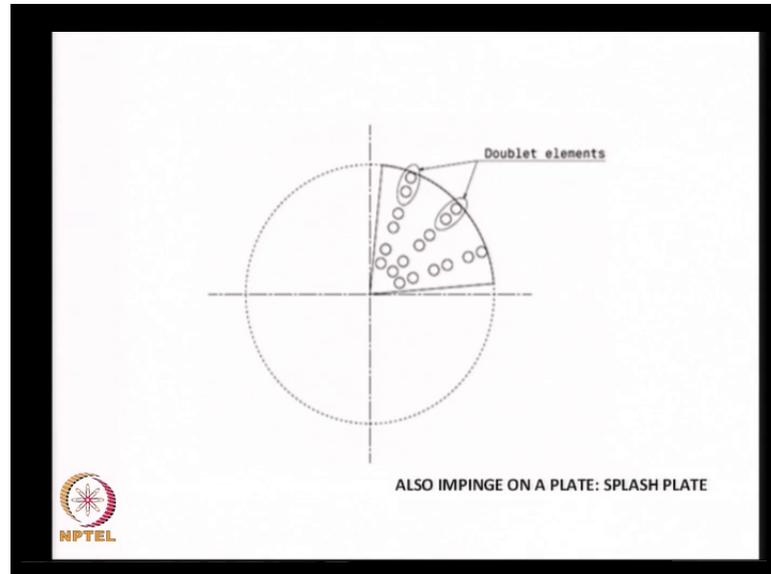


We can say injector could either be the simple shower head injector, but we said shower head is not good because mixing is poor and therefore, it is not very widely used. Instead of using a single series of straight jets, we can have something like impinging jets and in both these cases what is it we use for forming the jets? We use the pressure of the liquid in forming the jets and breaking up the liquid into droplets and these are also known as pressure induced atomization. What we use is impinging jets. Impinging jet could 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.

We call it as doublet;. could we do the function with a single jet? If we use a single jet and make it impinge on a plate i.e., make it splash on this plate and what we get is droplets here and this is known as a splash plate injector. Splash plate injector was used originally by the Germans, but now they are used in some missiles; it is not very efficient, because compared to doublet it does not have flexibility. I think the doublet is much more important and doublets have been used in lox kerosene rockets. You remember I showed you the F 1 engine which is we said is a very high thrust engine; it uses doublet injectors. What is done is you choose the dimensions of the sharp edged orifice in between a fraction of an mm to several mm depending on the size of the engine, may be upto 4 mm 5 mm. You put a lot of these orifices together and may be

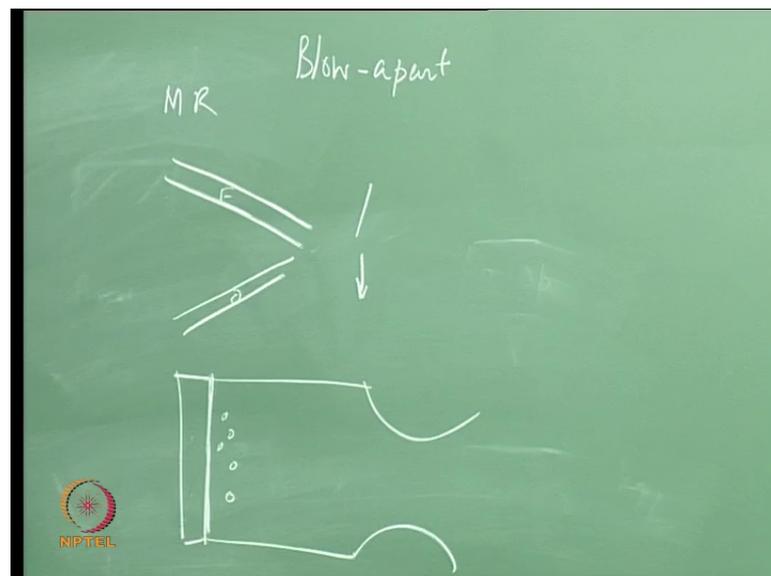
impinge them on one on each other and you call them as a doublet injector. Well, we will just see one more example.

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This is how we mount the doublets. We put one orifice by the side of the other; create a number of fans, make the fans interact with the other.

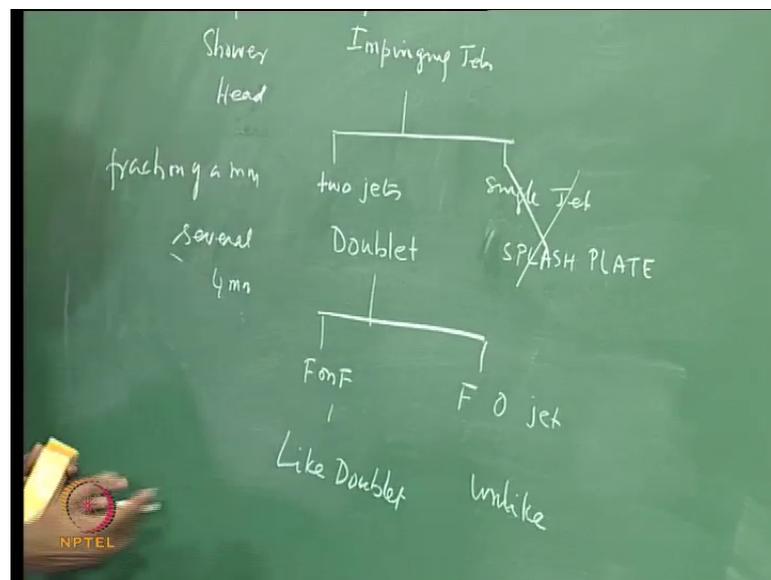
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Well, this is about the doublet injector. If we vary the mixture ratio what would happen to the fans? We have designed the fan based on the mass flow rate and velocity of the incident jets. If we vary the mixture ratio, we would be varying the quantity of fuel with

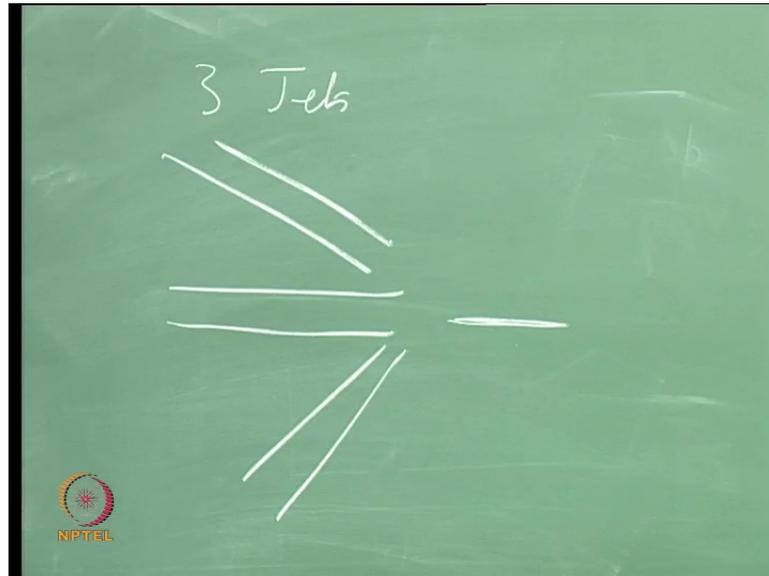
respect to the oxidizer and therefore we will have a different type of a fan coming. Therefore, doublet is not good when the mixture ratio varies. For a fixed mixture ratio and for a fixed flow doublet is good enough. But then, we must also remember doublet is very efficient, because I can get whatever droplet size that we want. But at the injector head, if atomization is taking place and combustion proceeds then the injector head of the rocket tends to get heated. Let us say this is the combustion chamber; this is the injector. We 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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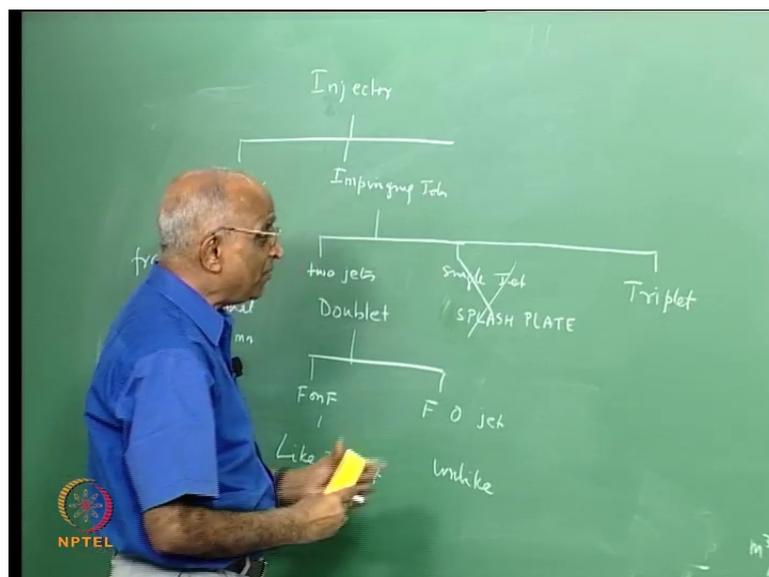
Therefore, we observe that impinging jet injectors could be doublet. In the doublet we could impinge fuel jet on fuel jet or we could also take an oxidizer jet and impinge it on an oxidizer jet; these are known as a like doublets. When a fuel jet impinges on an oxidizer jet, it is known as an unlike doublet. This is because we take unlike substances fuel and oxidizer and impinge them and what happens in a unlike doublet? When we have a jet of fuel with a jet of oxidizer and because of chemical reactions which can occur we could have something like a “blowing apart” of the two jets and this is problematic. The formation of the fan and fine droplets get drastically affected.

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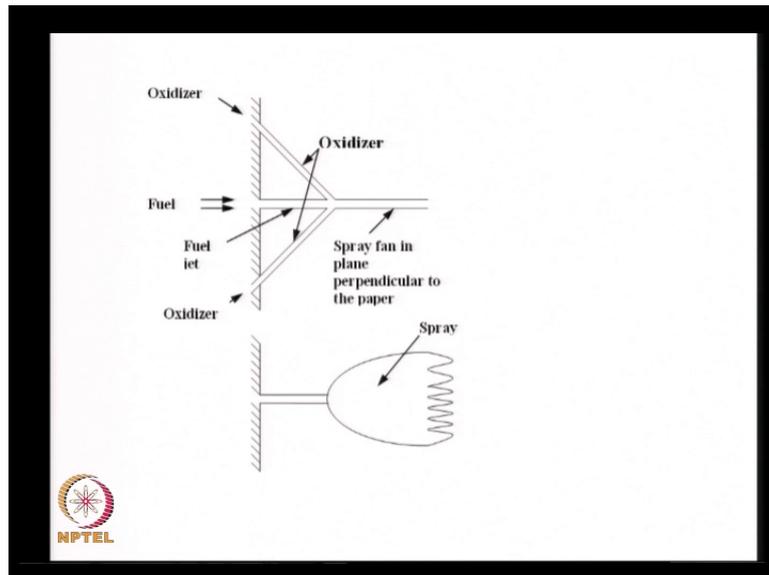
Instead of using two jets, which do not function adequately under different mixture ratio conditions, we can use three impinging jets. What I do is have a central jet may be of oxidizer; I have fuel jets coming over here on either side of the oxidizer jet; and now I have a fan in this particular direction along the central oxidizer jet. The use of three jets impinging at a point is known as triplet element.

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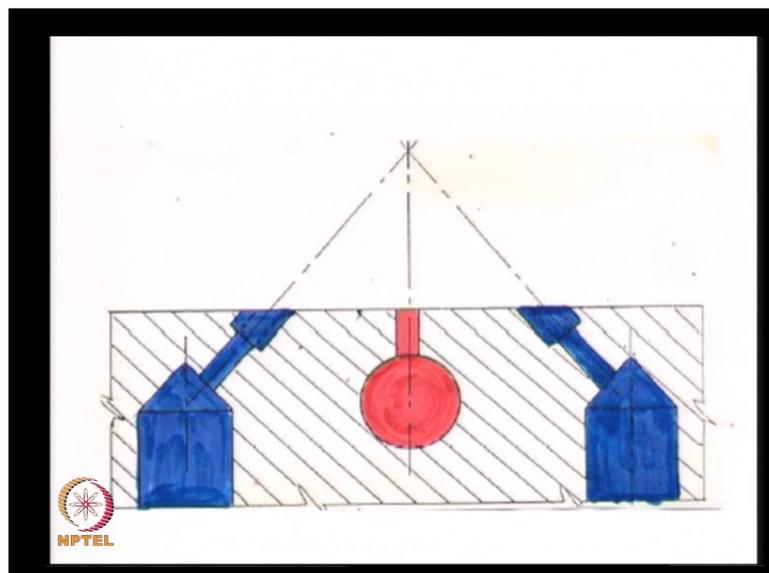
This is again very widely used in the industry, because we have a stable fan which is formed. Let us take the configuration of a triplet.

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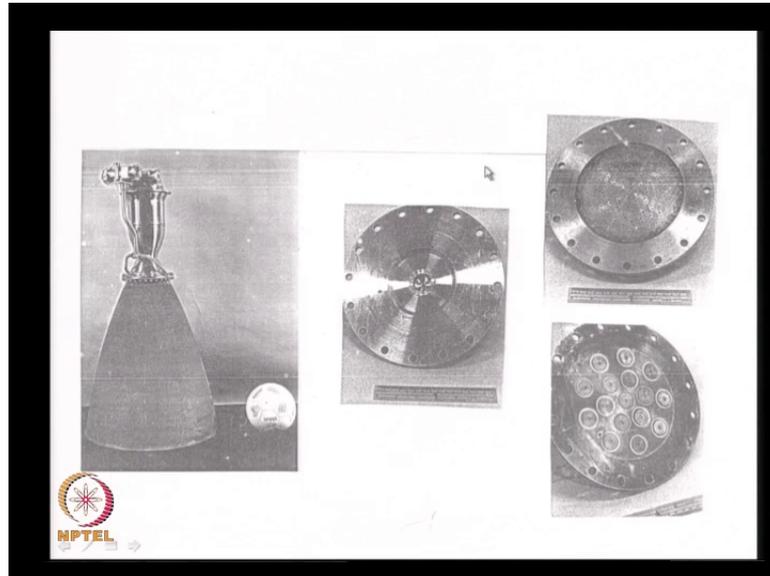
I have in the above figure, a fuel jet impinging on two oxidizer jets. We form a fan. I look at it from the top, I see a spray fan. The impingement of three jets gives the triplet impinging injector. The advantage of a triplet is when I change mixture ratio, I do not really change the direction of the fan which as before is in the plane bisecting the outer jets along the central jet. Therefore, the spray fan does not change its angle and that is the advantage with triplets.

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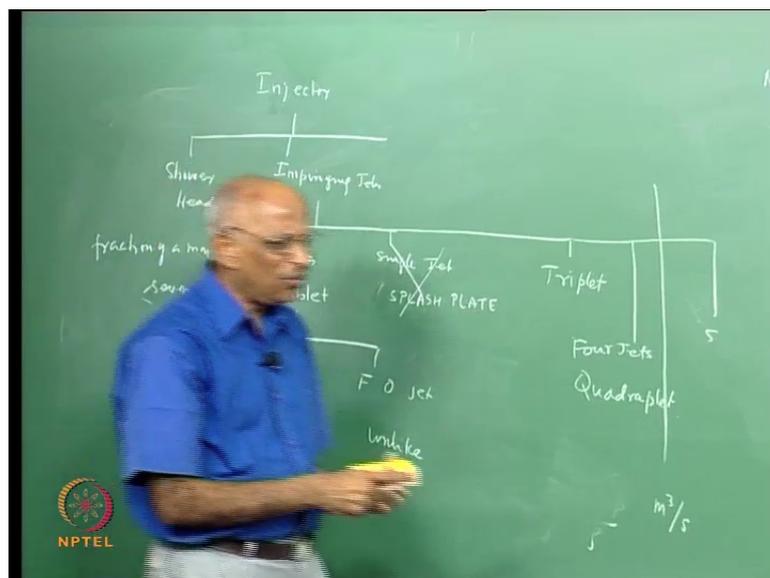
And I show an example of a triplet. This is where you have may be a fuel jet coming in blue, the oxidizer jet coming in red; here you form a fan and it breaks into droplets in the combustion chamber.

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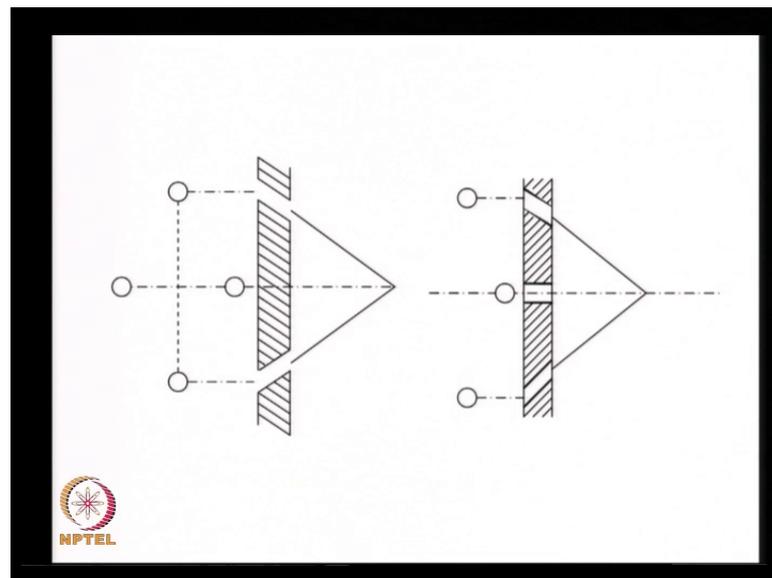
This is a particular engine which was used as an upper stage. This is the injector, when I look at the injector here have a series of small holes three holes together which form the triplet elements. We will disregard the other two injectors and address them later.

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This is about triplet injectors. We can also think instead of having triplet why not use four of them i.e., 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 pentad. I have not seen injectors use more than four jets - a quadruplet, but quadruplet as we say is not as efficient as the triplet, because you do not really gain much. How does the quadruplet look like?

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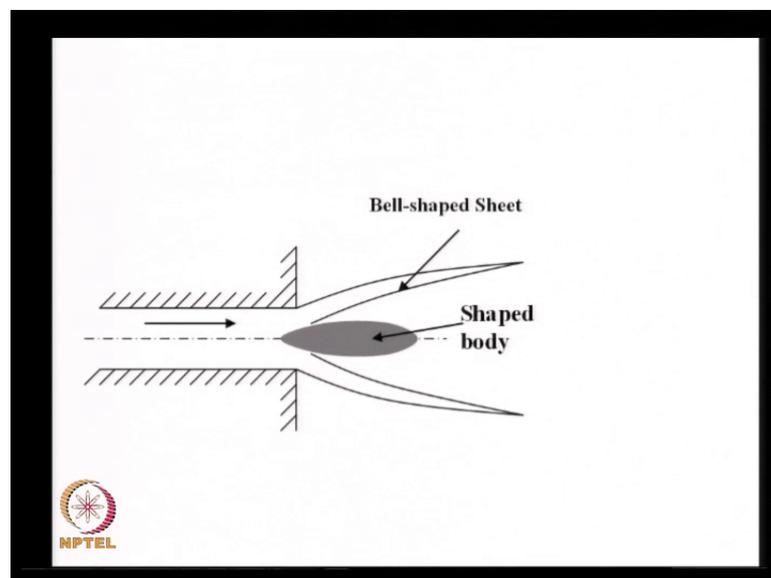


We show it in the above figure. I have something like a hole at the four corners of a square on a flat head through which four jets issue. The four jets come and impinge on each other and form a fan. In the case of five jets, we have one additional jet issuing at the center of the square and we have these five jets impinging as shown in the figure on the right. All five jets impinge to generate high pressure and form a fan. Actually, what I should have shown are the two jets in another plane. We will have one central and then these two on a different plane. Let us sketch it

impinging respectively. All these come in the category of pressure driven injectors, since the jets were formed under pressure right from a shower head onwards. In the case of a shower head we do not have impingement of the jets.

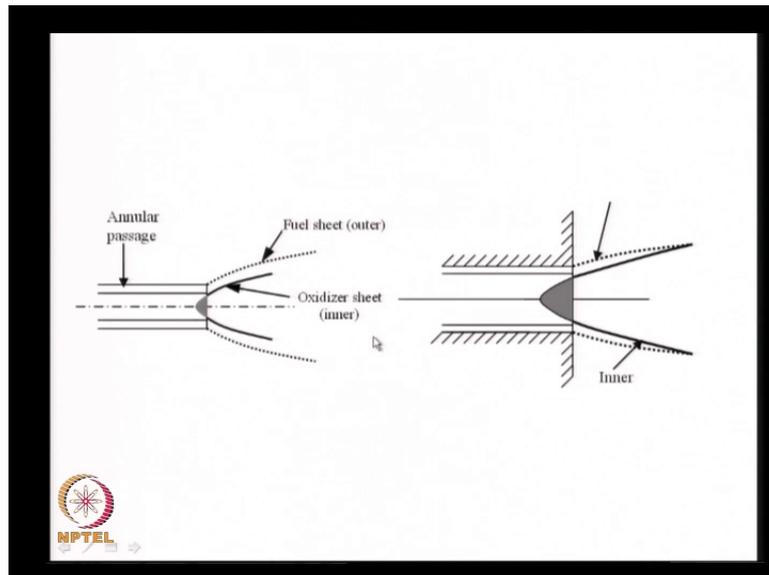
Now, the question that comes up is whether we really need liquid jets? In most cases we have been forming fans or thin liquid sheets that break into droplets. We were forming first a liquid jet; something like what I was trying to show is from the shower head; you have something like a jet which issues out. Either this is impinged on a plate or you impinge against each other and form a fan.

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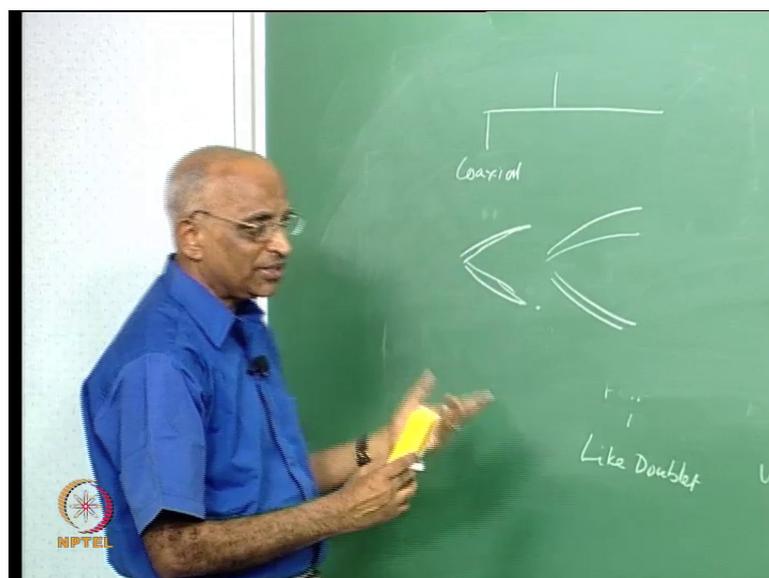
It is also possible for us to have another construction, wherein you allow the liquid to come from the orifice, you put a shaped body here and when you put a shaped body, the liquid jet gets diverted to form something like a water bell. The water bell is something like a bulbous liquid sheet and this sheet breaks into droplets; that means, you convert the liquid jet into a sheet. Rather than a jet, we transform it into a sheet and form droplets.

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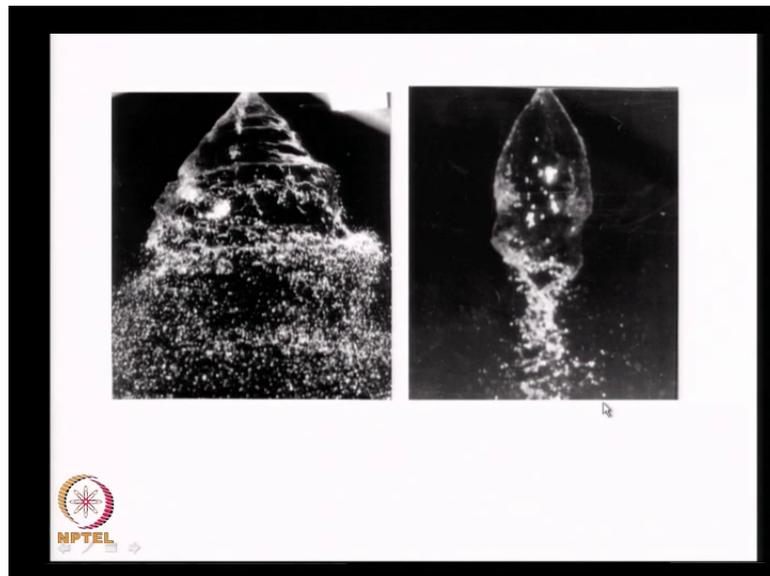
Maybe we have something like a shaped body at the exit of the orifice and form a liquid sheet here. We have an annulus surrounding the central orifice from which we get a cylindrical sheet which diverges out. These two sheets break up into droplets. We could also allow the two sheets to impinge on each other and we get an impinging sheet injector. This is shown on the right side. We have the coaxial liquid sheets which breaks into droplets, and these are known as coaxial injectors because the two sheets are coaxial around the central axis.

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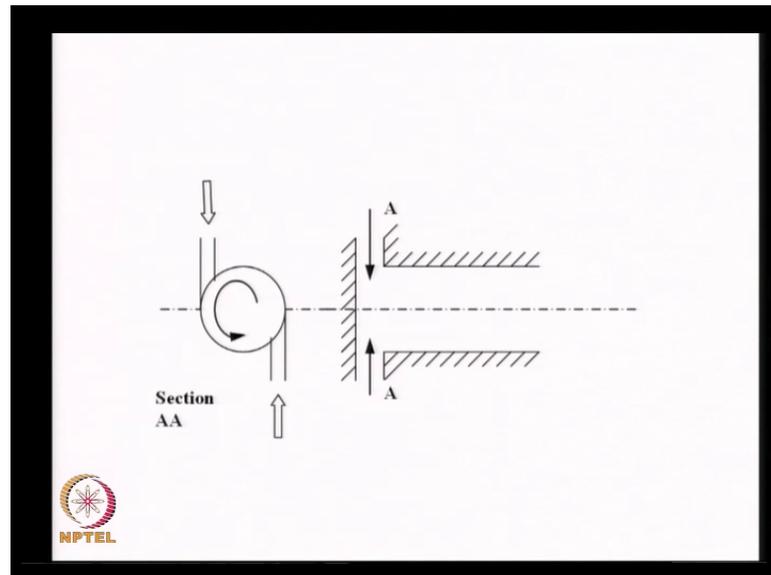
We could therefore think of having injectors, wherein instead of jets we form sheets, I have something like a coaxial configuration, wherein I have a conical sheet; maybe I have another conical sheet which impinges on it and breaks into droplets, or I have the central sheet like this inner cone; outer sheet and so on. These are known as coaxial injectors, because these are coaxial with each other. Maybe we will take view of an injector which uses the coaxial elements. A number of coaxial elements are arranged in an injector head to give the required flow rates. We have central elements surrounded by coaxial elements each issuing sheets and breaking them into droplets. In the picture of injectors of the upper stage engine, coaxial elements injector was seen below the picture of the impinging jet injector.

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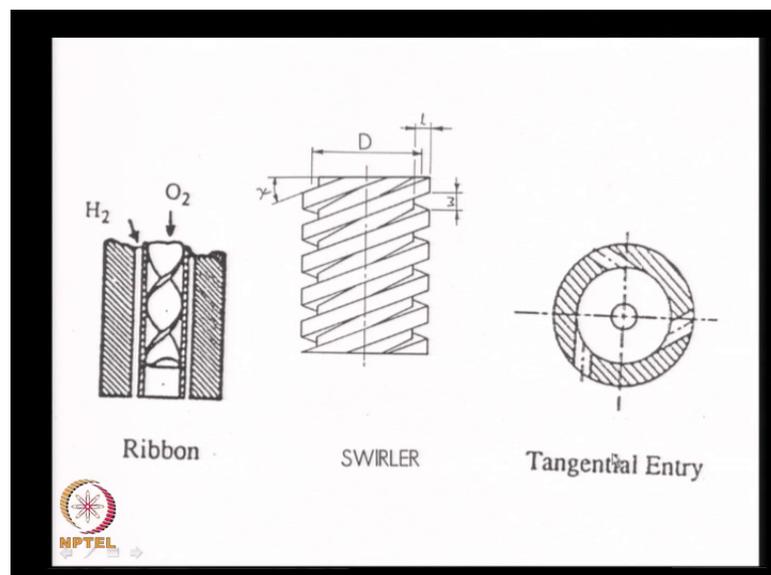
Let us take a look at the coaxial injectors. We have a sheet which comes out like this, a diverging cone and this sheet breaks into droplets over here. Similarly, surrounding this I could have another sheet which comes parallel to this and breaks into droplets. The droplets evaporate, mix and burn. This injection scheme is what we call as coaxial. But, if the pressure is not sufficient and we do not get a particular diverging geometry of the sheet, and instead we get something like a bulb or a tulip shape sheet it does not give good atomization. Therefore, in the case of coaxial sheet injectors, it is necessary that we have something like a divergent sheet.

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Having said this we could, instead of having the liquid come in axially, rotate the liquid. How do we rotate the liquid? We admit it tangentially. Therefore, when we admit it tangentially the liquid rotates and when a liquid rotates because of the centrifugal force in the frame of its own reference, the jet is thrown off.

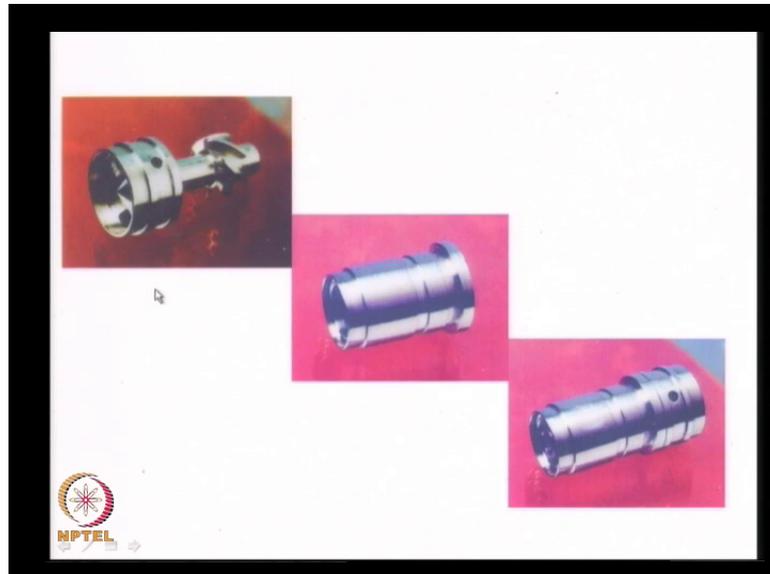
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And therefore, how do I rotate it? Either we admit the liquid tangentially into the orifice as was shown earlier. Or else, we place something like a spiral or shaped vanes in the path of the liquid flow. The spiral or swirler or vane induces rotational motion in the

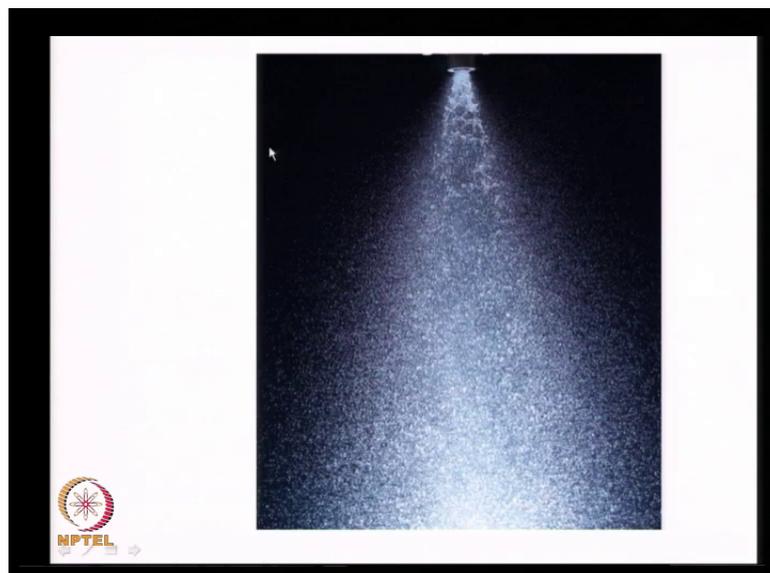
liquid. We could also place a ribbon or something protruding spirally on the surface of the orifice make the liquid rotate.

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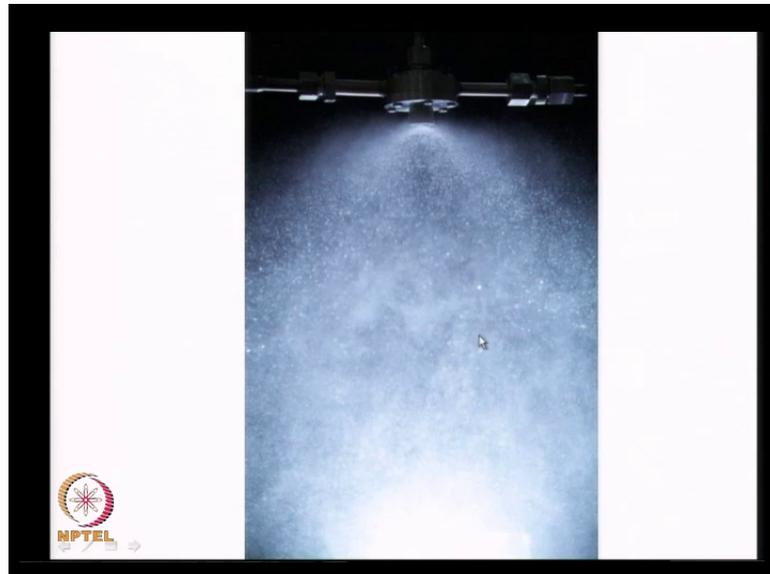
Here again I show shaped vanes being placed within the central outer casing which causes the flow of liquid through it to have rotational motion. We place the casing shown in the center over the vane shown on the left and achieve the rotational motion of the liquid. In the picture shown on the right, tangential holes are made in the walls to provide the rotation.

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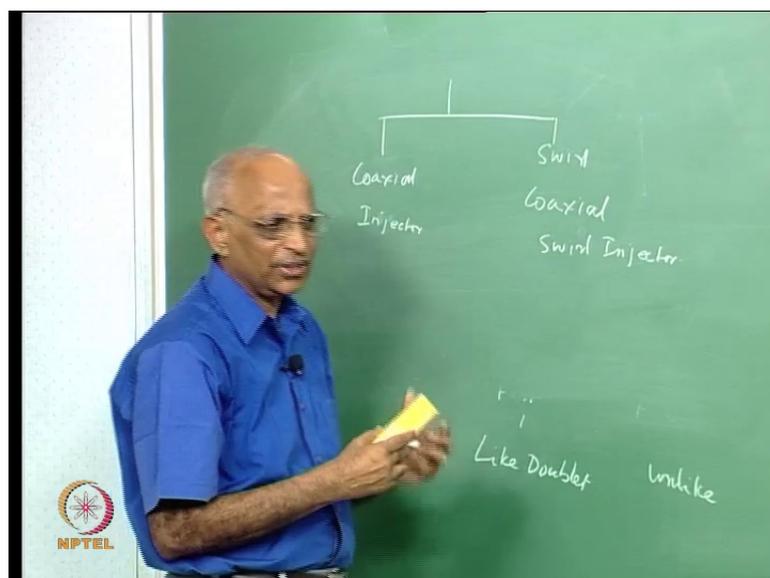
And then, instead of getting something like a jet which atomizes we get a very diverging jet due to the rotation of the liquid.

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This finer atomization and the increases divergence of the jet when rotated is seen in the above figure. When we rotate a liquid, we say that the liquid is swirled.

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And therefore, such injectors that incorporate rotation of the liquid propellant are known as coaxial swirl injectors as compared to a simple straight flow coaxial injector. All these configurations are used in practice. People who come from the gas turbine discipline into

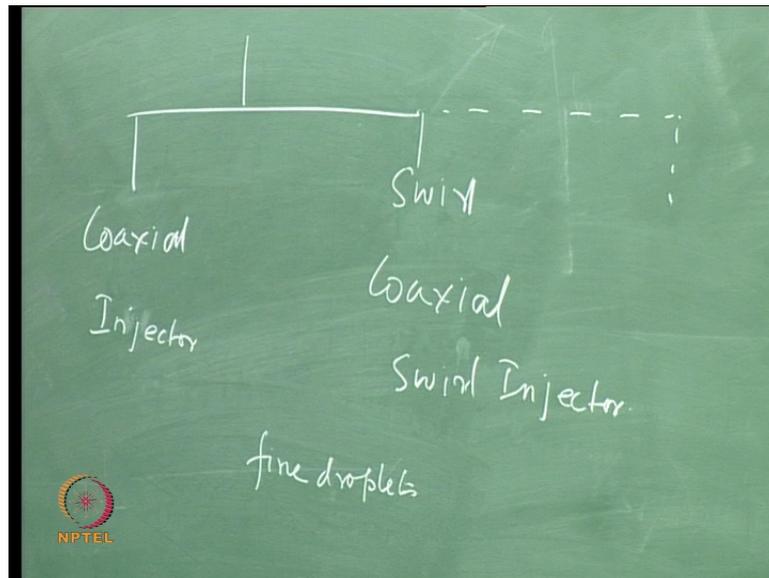
rocket design prefer the use of swirl coaxial injectors. A coaxial injector also does the job well.

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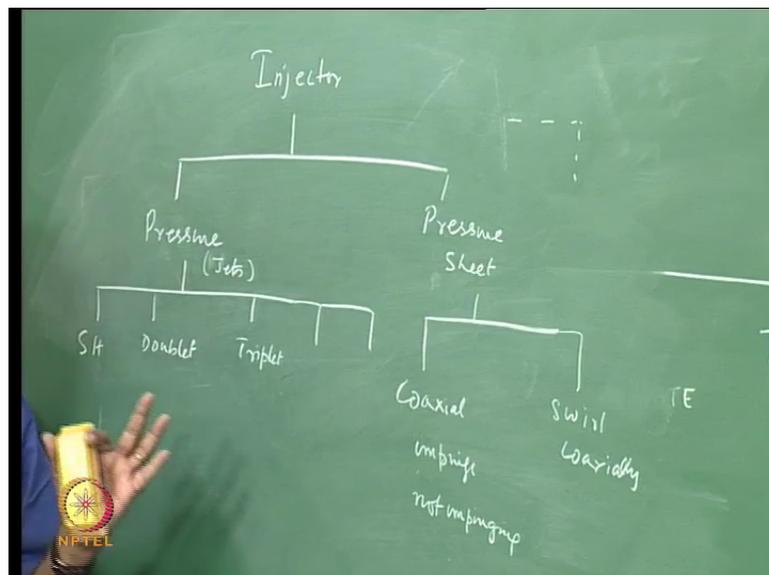
I think this is all about injectors. But I have still not completed the portion, because I can always think in terms of different ways of atomization and different designs. I now show an injector that we experimented with in our lab here at IIT. You know what we do is instead of admitting the liquid, 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 its improvement.

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Therefore, we can keep on adding different types of injectors and all have a requirement of generating fine droplets which can evaporate and the motion given to the droplets brings about good mixing and burning. The injector, let us not forget, also meters the required quantity of fuel and oxidizer into the chamber.

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Now, we formal classify the different types of injectors. They could be pressure or pressure atomizing injectors, these could be shower head; could be doublet. The doublet could be like or unlike. We could have triplet, quadruplet, pentad; all these use liquid

jets. We could use the same pressure to create a sheet. We could have coaxial injector, wherein we have the liquid oxidizer and liquid sheets impinge on each other or they may not impinge on each other; but just breaking into droplets, or we could also have swirl which is used co-axially. These are all about injectors which we use in liquid rockets.

But, you would ask me, in cryogenic propellant 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 be a gas.

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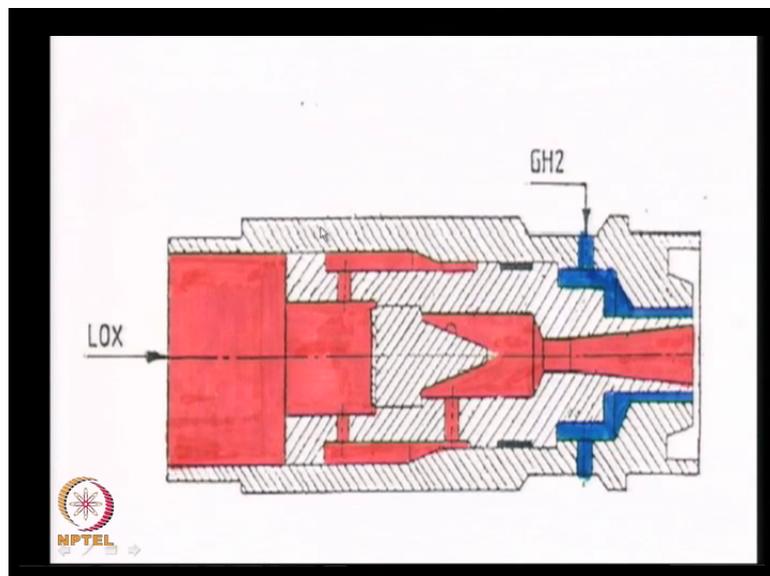
Also we talked of staged combustion cycle engine wherein products from the exhaust of the turbine are admitted into the combustion chamber as a hot gas. Can I use the hot turbine exhaust gas or the hydrogen gas to atomize the liquid oxidizer? In other words, we have a liquid jet, issuing from an orifice; what we do is on the outside of this jet just surrounding it just after the metal portion, by the hydrogen jet or the gas from the turbine to co-flow at high velocities. This means we force the hot gas over the liquid surface at high velocities. And when we force gas over liquid surface, it picks up the liquid because of the shear and we get the droplets. This way of forming droplets is known as gas assist atomization and such injectors are known as gas assist injectors. We use a gas for atomization and hence gas assist. This gas assist could again be simple coaxial. Or, we could rotate the liquid in which case I have swirl coaxial; we could rotate the gas and we could have different configurations of gas assist injectors..

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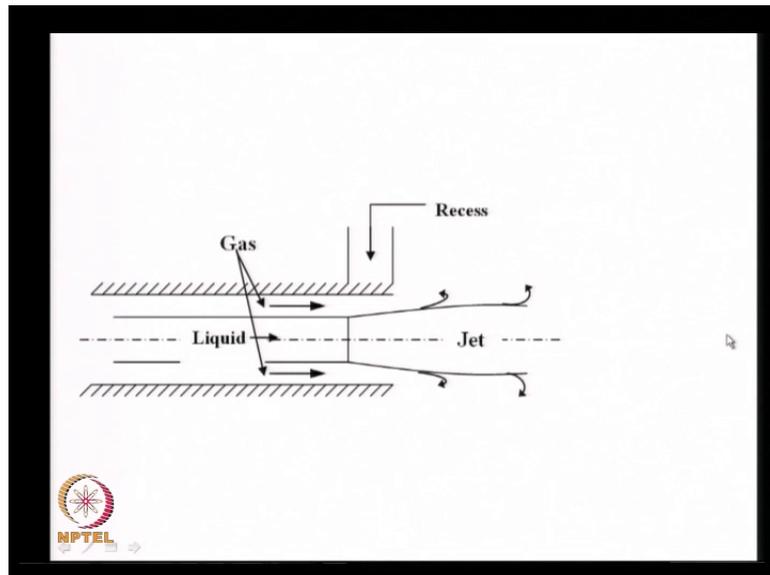
Let us quickly go through a few examples of injectors. This picture shows the multiple elements in a coaxial injector. You have liquid coming through these holes.

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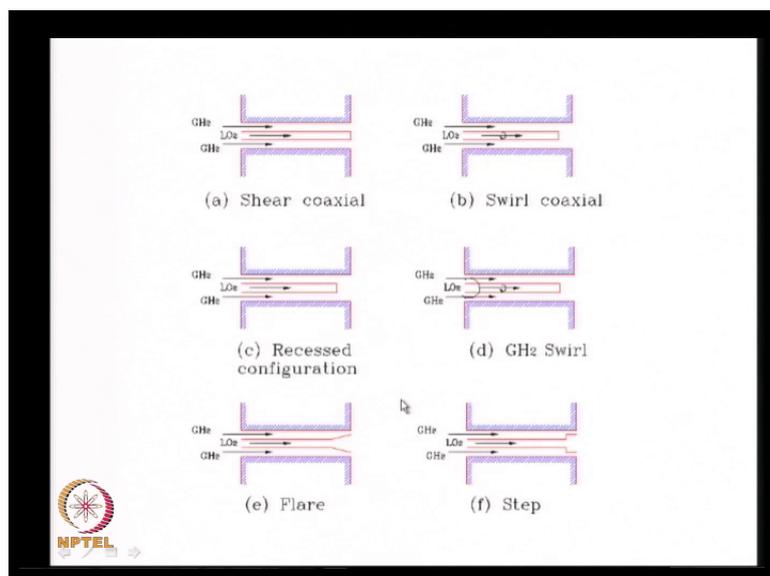
When we talk of gas assist, well I have gaseous hydrogen which is coming through the outside shown in blue. I have the liquid oxygen which is coming through the central orifice shown in red. We have liquid oxygen jet over which hydrogen flows at high velocities causing it to atomize..

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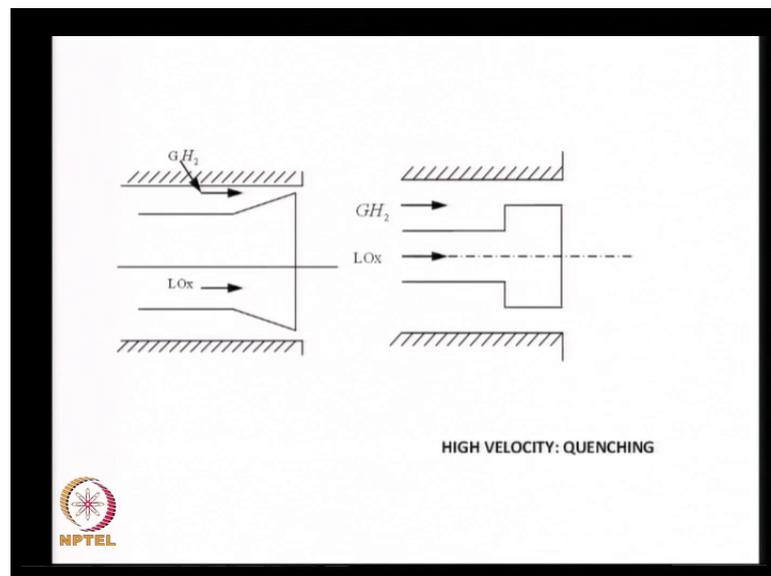
Well, when we have liquid flowing and we have gas coming on the outside, we want the gas to have high velocities compared to the liquid so that it can shear the liquid. We allow the liquid to be within the gas flow orifices such that the gas velocity is felt by the liquid. We say the gas must not relax such that we can use the high velocity of the gas. The distance between the outlet of the liquid orifices and the gas orifice is what is known as a recess length. Recess essentially makes sure that the gas velocity is available for atomization of the liquid in the gas assist injector.

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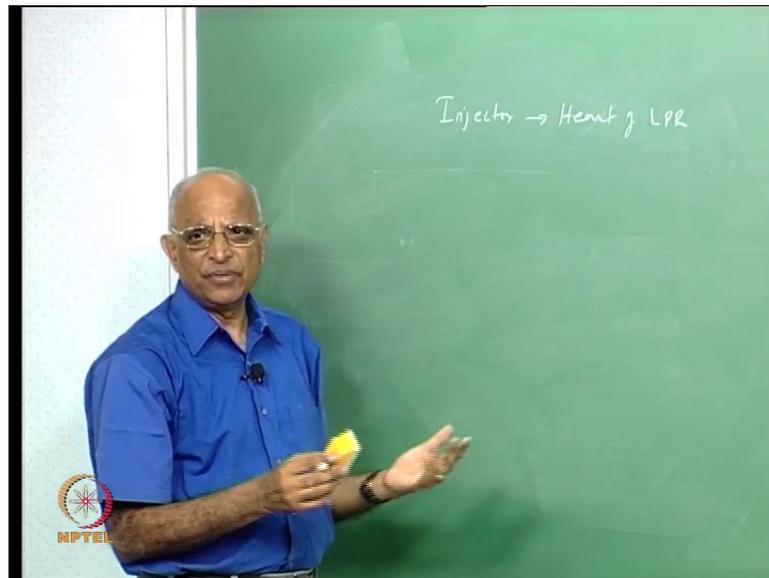
And therefore, we can talk in terms of shear coaxial, swirl coaxial; maybe we could have a recessed configuration; we could give rotation to the gaseous hydrogen; we could give rotation to the liquid oxygen. We could also make the passages of the orifices conveying the liquid oxygen to flare or make a step in it to reduce the injection velocities of the liquid. In this way the differential velocity between the gas and the liquid increases and atomization improves. You can keep on innovating and a study of injector by itself becomes a major portion of the liquid propellant rocket.

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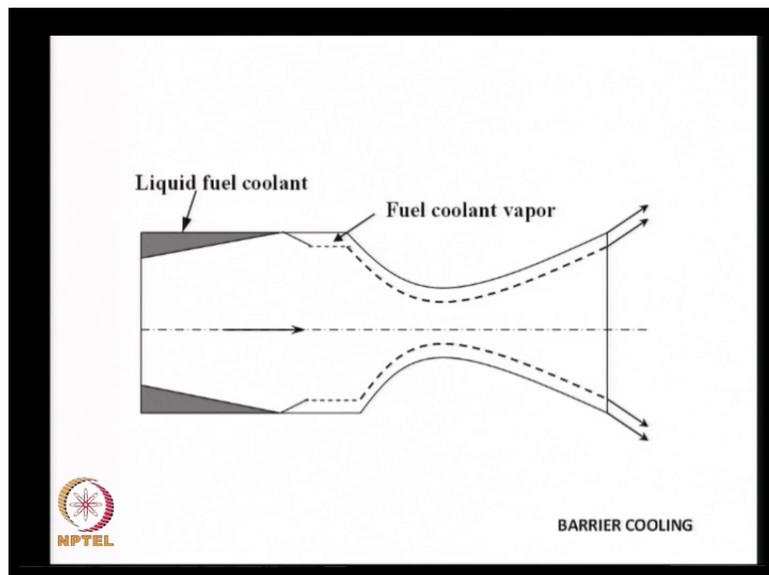
I show the flare and the step in the liquid orifice in this figure. In addition to providing better atomization in view of the higher velocity differential, the reduction in velocity provides better flame stabilization and prevents quenching of the flame. To sustain a flame at high velocities is difficult.

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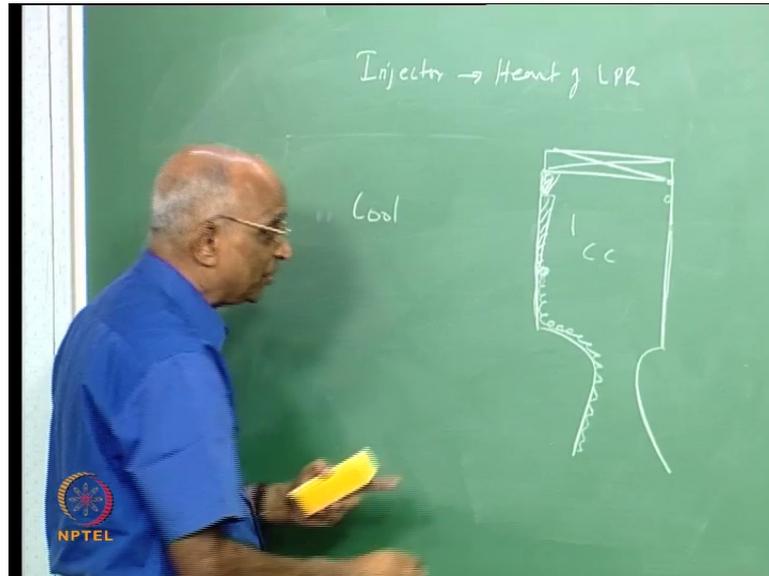
Therefore, injector design I would say is the heart of liquid propellant rockets, because this is what produces the droplets, makes it evaporate, mix and burn. I think I will stop with the injectors here; I will get back to injectors when we talk of combustion instability and to a certain extent when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

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Let us look at cooling of liquid propellant rockets which is again closely related to injectors that we have studied.

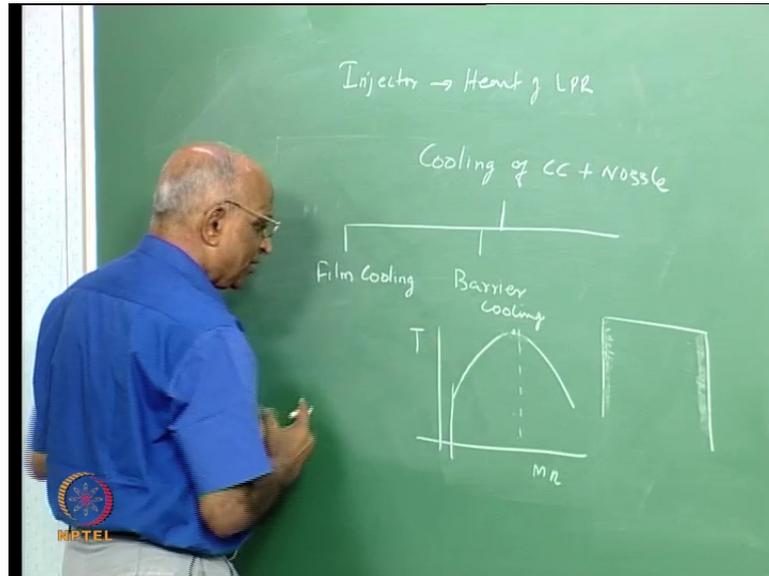
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We have considered a combustion chamber in a cylindrical configuration. We had an injector on top of the chamber over here. We considered different ways of injection. We also found how to calculate the mixture ratio and the mass flow rates. Now hot gases are produced in the chamber and it expands out in the nozzle. We told that the mixture ratios are such that the temperatures in the combustion chamber are quite high of the order of 3000 to 3600 Kelvin and learnt how to calculate it. If this be so, the material used to form the combustion chamber will burn out of within seconds, because the gases are extremely hot.

Therefore, the question is how do we cool the combustion chamber? One of the ways is may be if we can admit some fuel near the wall of the chamber; We admit a quantity of the fuel near the wall, give it some velocity, and rotate it such that we make sure it sticks to the wall.. We have lot of liquid in the wall region near the injector and the length of the combustion chamber is small. Therefore, turbulence cannot be fully developed. This liquid, in the wall region, is entrained by the gas and accelerates. I have a certain thickness, the liquid thickness, 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 the vapor can still further continue to cool the combustion chamber. The chamber wall thus remains cool. In other words, I have a film of liquid, which is injected along the walls of the combustion chamber and this method of cooling is what we call as film cooling.

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Let us take an example. We have a liquid coolant being injected along the cylindrical walls of the chamber; hot gases are evaporating it; vapor is formed and the vapor further cools the combustion chamber and nozzle and this is known as film cooling.

Instead of film cooling, we could also make sure that in the combustion chamber we could have more of the fuel vapor in the wall region. We make the mixture ratio to be a little bit fuel rich. If it is fuel rich we can determine the temperature of the gases from my diagram of temperature versus mixture ratio. I know at near stoichiometry I get maximum flame temperature; actually slightly less than stoichiometric. If we can keep the gases in the wall region very fuel rich, then we have low temperature over here we can keep the chamber walls cool. That means, we form a barrier of fuel rich mixture over the walls and this method of cooling is what we call as barrier cooling.

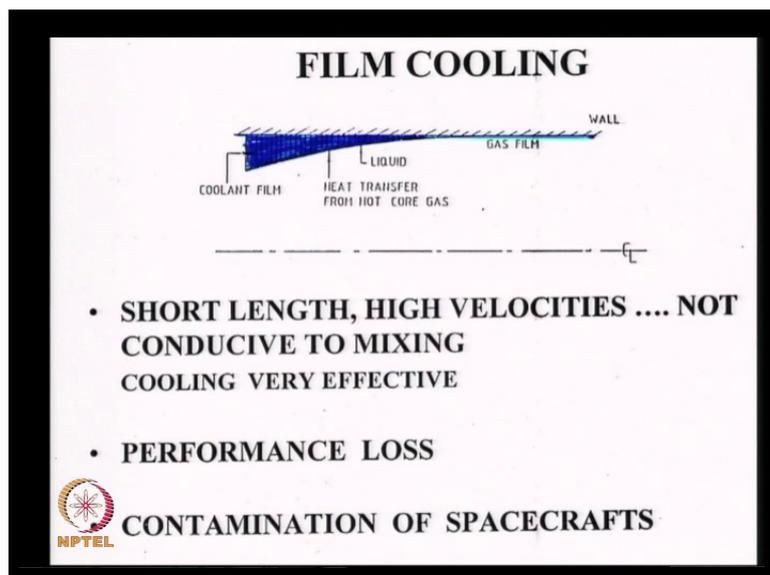
To a certain extent the film cooling incorporates barrier cooling, because what is it we are doing? We have a barrier of the fuel vapor over here; maybe it also reacts to some extent, but it is still much cooler than the core gases and therefore, we keep the wall cool.

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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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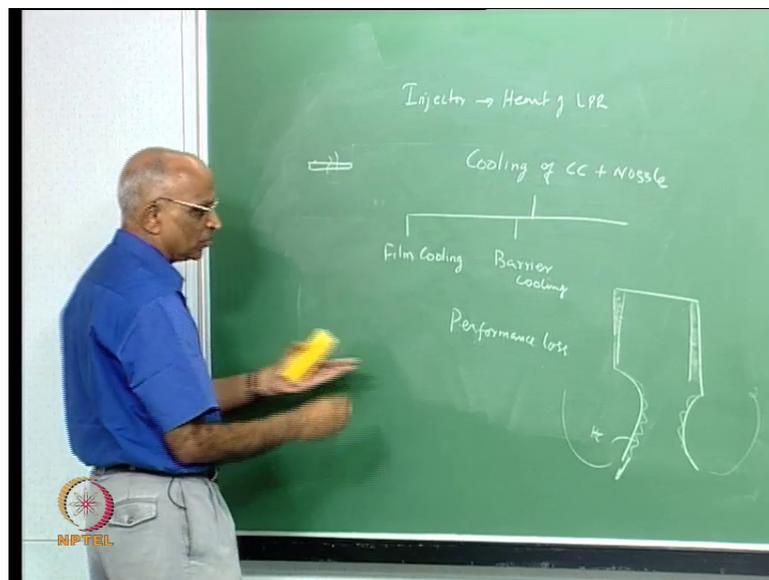


We can write the equation for the evolution of the thickness from the initial thickness of the film. We know the heat transfer coefficient between the hot gases and the film. We

can calculate the rate at which it evaporates. I know the heat transfer coefficient between the film and the wall. I do a composite calculation. I can calculate the thickness of the film. I can do the same type of calculation for a gas film.

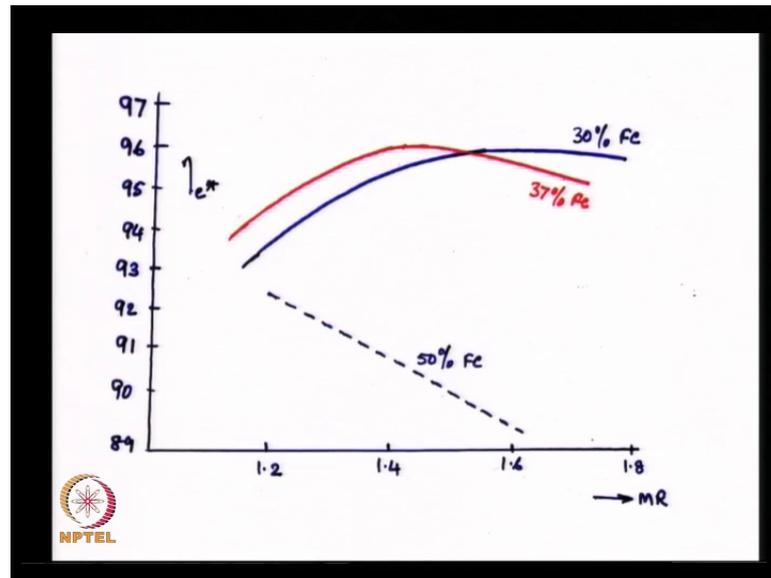
Film cooling is used in rockets, and why it is very effective? The combustion chamber length is small, you do not have full turbulence being developed within the short length and we can very effectively use it. The disadvantage is - you know immediately that we lose some amount of fuel in the film cooling process.

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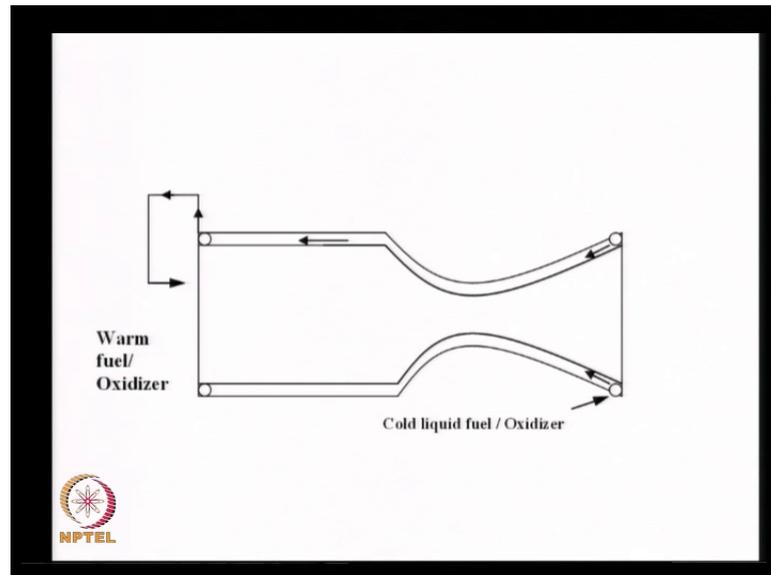
Therefore, to some extent the specific impulse gets affected. Therefore, I have a performance loss; that means, the specific impulse is little poorer, and second point is when we have a nozzle and we have the coolant coming over here, the velocity in the wall region at the exit may not be very large, and also these are may be fuel rich hydrocarbon gases in it. Since the velocity is not large, it is not thrown off along the plume; it comes back to the surfaces and when we use these film cooling for the spacecraft, it sometime contaminates the glass surfaces of the sensors in the spacecraft. A spacecraft consist of sensors; what are sensors? You have optical quality glass encasing the sensor which measures radiation. The Earth sensor, as an example, monitors radiation from the Earth and helps to point the spacecraft towards the Earth. It should not get contaminated because of film cooling.

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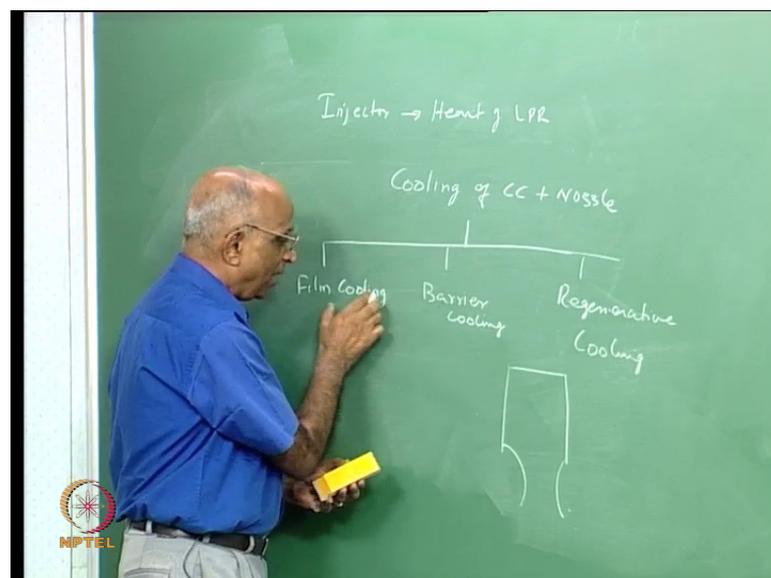
We will keep this in mind. Well, this all about film cooling; other cooling methods you all are very well aware of. But, let us come back to this figure on loss of performance due to film cooling after we finish discussions on efficiencies; but just to highlight when we use something like 30 percent film of fuel for cooling, we get the efficiencies as a function of mixture ratio as shown by the dark line. If we increase the cooling from 30 percent to 37 percent, the peak value of efficiency shifts to somewhat in the fuel rich region, because we make the core less fuel rich. The core is still not oxidizer rich. If we provide 50 percent of the fuel for film cooling the efficiency falls rapidly as mixture ratio increases the core becomes oxidizer rich. This is an experiment that we conducted. We will revisit this graph a little later.

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The next type of cooling is what we call as regenerative cooling. I will not use the blackboard I will show it with the slide. In regenerative cooling, like we have the regenerative Rankine cycle which is used for the feed water heating, we admit the fuel at the end of the nozzle. The liquid fuel gets heated while cooling the chamber. The heated fuel being much warmer has more enthalpy as sensible heat and it is used re-generatively in the chamber. Therefore, the next type of cooling which we can write is regenerative cooling; it is a regenerative process.

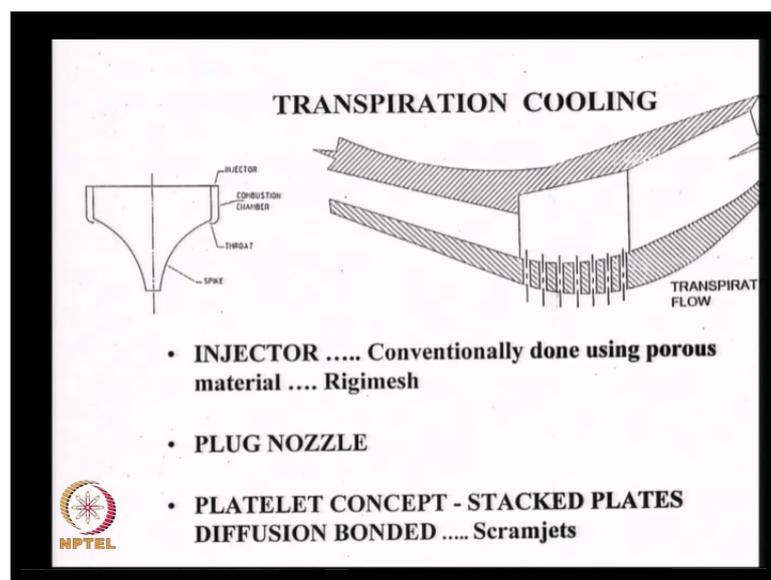
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Like feed water heating in boilers we use heating of propellants by regenerative cooling before being admitted into the chamber. Invariably, regenerative cooling is always used with film cooling. The reason is that in regenerative cooling we form channels for the cooling or have tubes mounted over the chamber. If in some region the cooling is not effective, that portion becomes red hot and burns off. However, if film cooling is also provided, it can smear out the temperature increases in the local hot zones and protect the chamber.

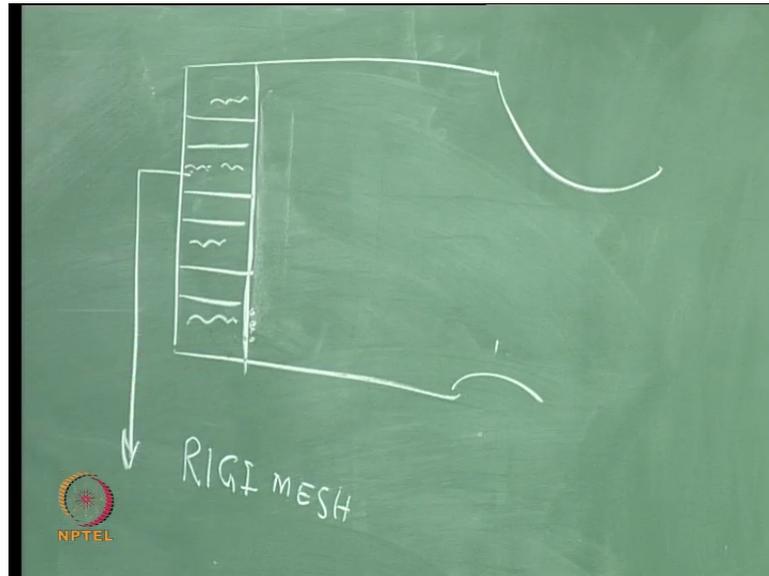
Therefore, this is regenerative cooling. There are problems related to very high conductive materials and the thermal stresses. With repeated operation over a large number of cycles, the stresses induced cause cracking. This is known as ratcheting and we will not go into these details.

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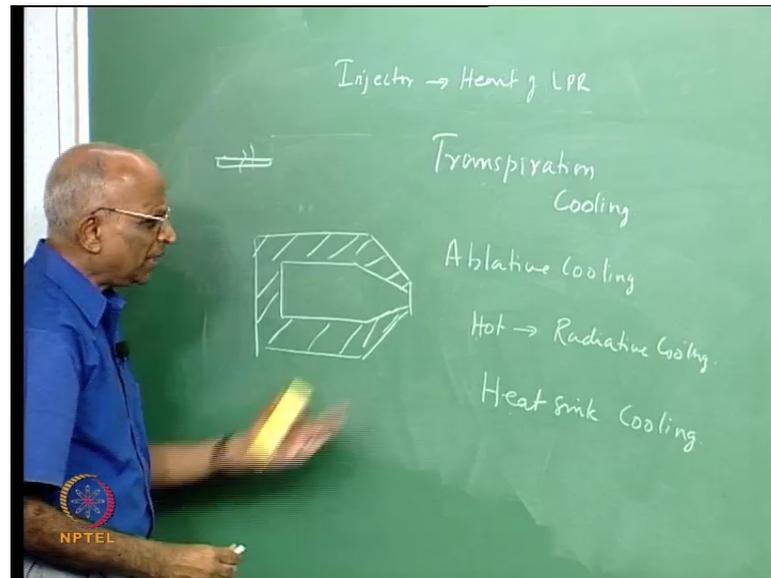
Let us get into the other forms of cooling. Just like the body sweats and keeps as our temperature cool so also we can have the nozzle wherein we admit the liquid coolant in this particular direction through small orifices in the high heat flux region. The liquid coolant, which could be fuel, evaporates and keeps the temperature within limits. This mode of cooling has been used extremely well in the case of the cryogenic rockets for the injector cooling.

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Let us again make a schematic of the injector. This is 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 our body perspiring or transpiration taking place through these pores. The hydrogen absorbs the heat and keeps the injector cool. And the particular configuration of the porous material is known as a Rigimesh. It is a commercial name, but all what it consists of is a series of meshes which allow the liquid to get sweated out through this part and as the liquid evaporates it absorbs heat and cools the injector plate. This is what we call as transpiration cooling or sweat cooling.

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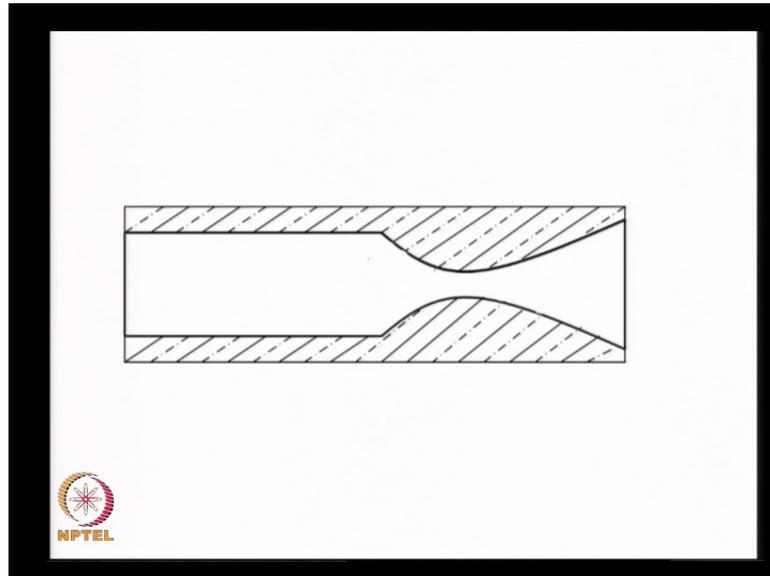


Well, we have a few more cooling strategies. We could use an ablative material for cooling. You remember we talked of ablative materials when we discussed the nozzles. What was it? We have something like resin, which is a some form of glue which is cured as a solid. If we heat it, its temperature increase and it softens and evaporates at higher range of temperatures. We increase the strength of it by introducing some fibers in it. We therefore have something like a composite material. A composite material when exposed to high temperature evaporates at the ablation temperature; at a particular temperature where it forms vapors is known as ablation temperature. This gives rise to evaporative cooling and is known as ablative cooling. The material is sacrificed but protects the metal.

Instead of cooling we could allow the walls to run hot provided we have a strong material of construction. In this case we allow radiation itself to dissipate the heat and we can talk in terms of radiative cooling.

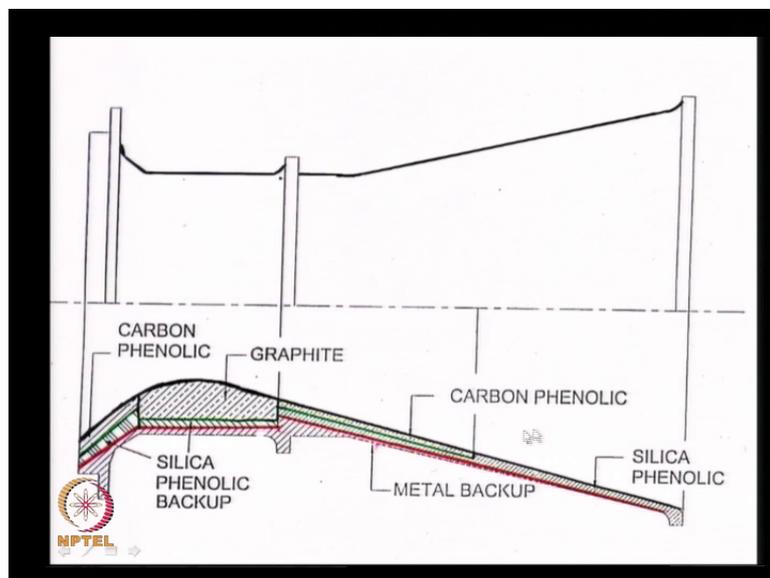
Or if we have want a rocket only for a ground application or test, we can make the rocket so heavy so much of material such that we operate the rocket only during the transient heating time of the chamber and nozzle. Let us say the we provide large thicknesses for the chamber and nozzle walls of the rocket. Maybe I operate it for a second. In a second the mass of the rocket or the thermal mass absorbs the heat and is known as a heat sink rocket.

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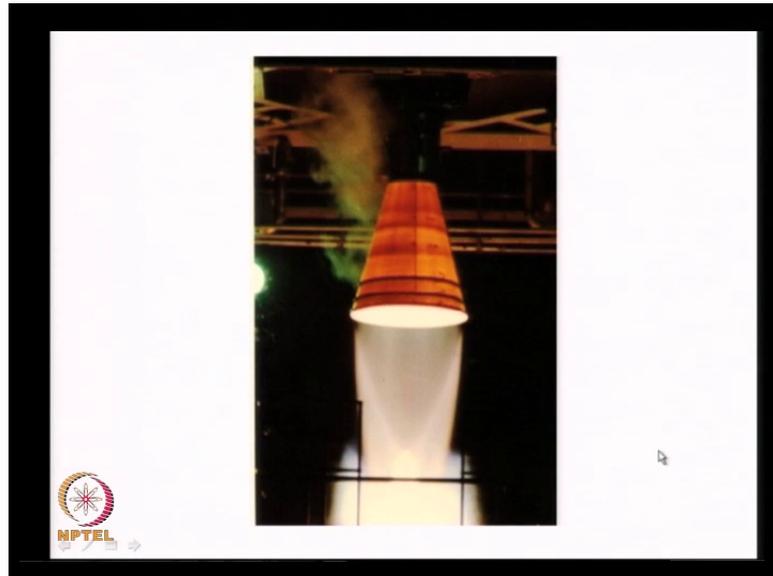
Let us quickly review some of the cooling strategies with a view to application. You have an ablative material which evaporates when it is exposed to the hot gas flow and maintains the integrity and the temperature of the liner.

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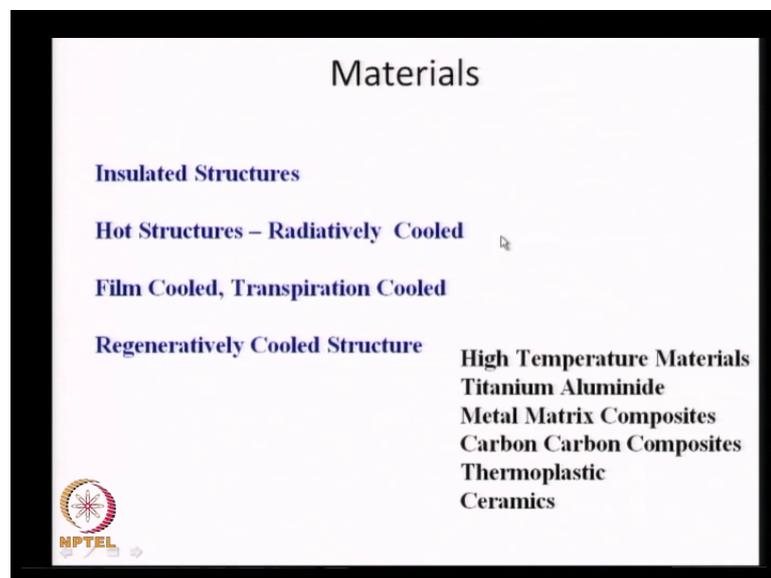
And this is what we said when we studied about nozzles, we could have the ablative materials which will evaporate. We use both carbon phenolic and silica phenolic ablatives, with carbon as a fiber and silica as a fiber. Carbon is more prone to oxidation. Therefore, silica is better for the cooling, because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

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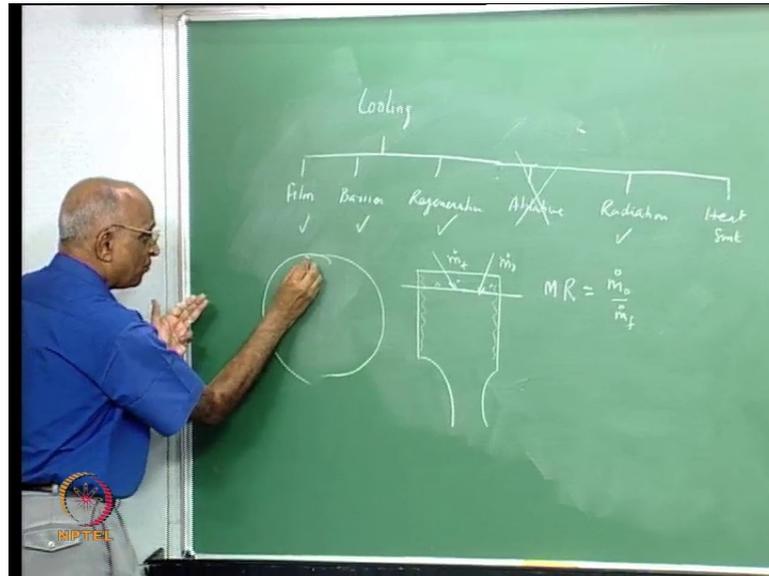
In this figure we see a metal nozzle cooled by film cooling running red hot and it radiates away the heat.

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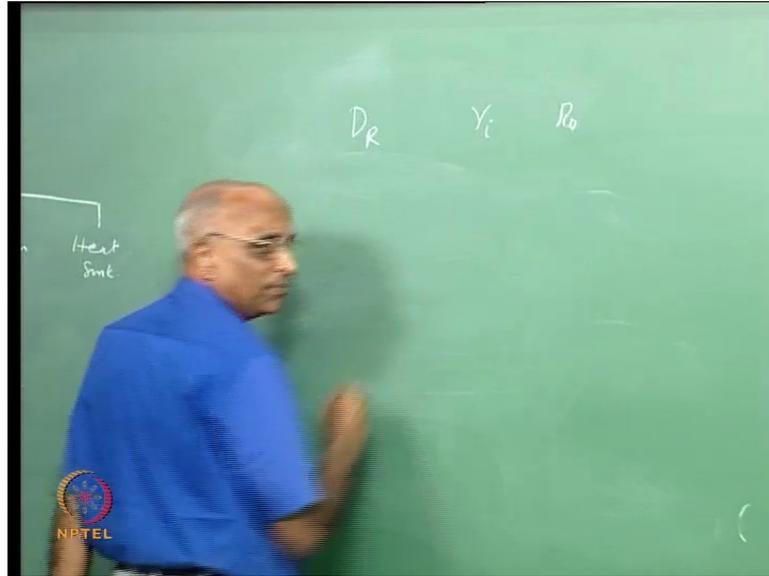
Therefore, to summarize we can use something like an insulation material like ablatives for cooling. We use a hot structure that means we use high temperature materials like carbon-carbon composites; may be high temperature resisting materials and radiatively cool the hardware. We could use regenerative cooling along with film cooling or barrier cooling and also transpiration cooling. These are the different types of 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 to protect the hardware of the rocket. Let us quickly go through the cooling procedures again before we put them 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 cooling is also possible but we need high temperature resistant materials. Ablative cooling may be difficult to use as the rocket becomes heavy. Well, regenerative, barrier and film cooling have more positive features. 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 of reduced performance that we have got into?

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We are injecting fuel into the chamber $m^{\circ}f$; we are injecting oxidizer $m^{\circ}o$ into the chamber. We determine the mixture ratio in the chamber R or rather MR is equal to $m^{\circ}o/m^{\circ}f$. But, what is the problem we have now created? We now say at the wall the mixture ratio is fuel rich if I have barrier cooling or film cooling. Depending on the injector we distribute the fuel and the oxidizer non-uniformly along the radius of the chamber; that means, if we take a section near the wall, we have fuel rich zone. We may have a oxidizer rich zone in the core region. We have zones which are different in the mixture ratios. The mixture ratio is distributed. We do not have uniform mixture ratio distribution in the chamber.

In other words, if we were to now define a parameter like let us say a mixture ratio distribution which we 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_0 and that will affect the combustion efficiency, and this is what we will do in the next class. And we will take a look what are the penalties we pay because of the mixture ratio distribution. If we have a finite length of the chamber is it possible to get combustion completed or will we have another efficiency influencing combustion?.

To sum up, in today's class, we revisited injectors, we defined different types of injectors, then we went into cooling strategies. And then we have now posed 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 that we get.