Rocket Propulsion

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Lecture No. # 30
Analysis of Gas Generator and Staged Combustion Cycles and introduction to injectors

Well good afternoon; I think we will get started with what we were doing in the last class. In the last class, we derived an expression for the fraction of the total propellant flow into the gas generator is equal to 1 plus 1 over R, R was the overall mixture ratio that means, from the tank whatever be the oxidizer, which is being supplied to the fuel which is supplied was R. We also had the density of the fuel which we called as rho f density of the oxidizer rho naught, the pressure increase across the pump delta p is so much Newton meter square, the value of C p and the expansion ratio in the turbine.

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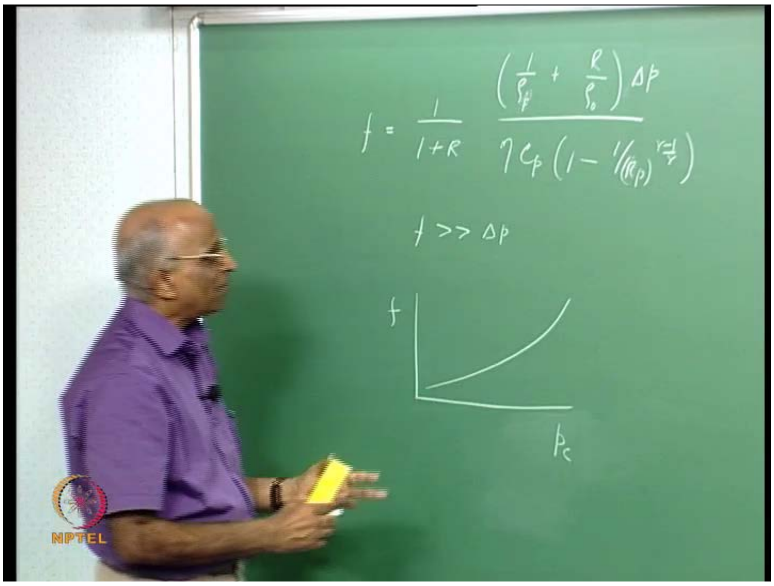

What does this expression tell us? Immediately we see f increases as delta p goes up, delta p is the pressure increase across the pump. That means, for a high pressure engine and high pressure engine will demand a high pressure at the inlet to the engine. Therefore, the pump pressure ratio must be high. Therefore, the fraction of the propellant, which goes into the gas generator, must be high. What is the implication rather if went to plot, the value of f as a function of delta p across the pump, the trend of the change of delta p should be similar, to the trend of the change of chamber pressure. I can write this expression as being equal to let us let us put that down.

I can write here as p c chamber pressure. The amount of propellant required as propellant which is required fraction of propellant, which is required to flow through the gas generator should increase as pressure increases; this is first observation; is this alright according to you? How will it change with let us say the overall mixture ratio? If overall mixture ratio is higher that means, the f will be smaller, because I have R over here, R over here. This R is modulated by the density and multiplied by some number therefore, this R tends to be stronger or rather the value of f will decrease as R increases.

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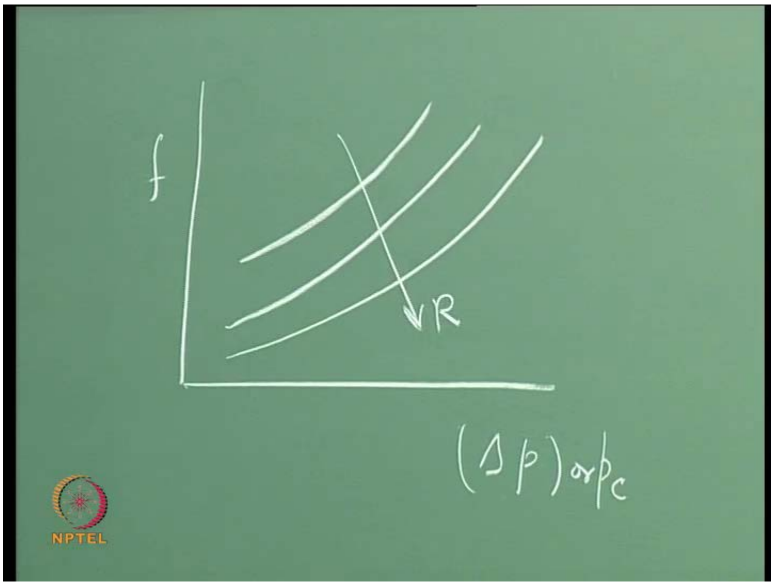

And therefore, I can plot the second ratio as if I plot delta p over here or which is same as I said as p c or p c as a function of f, may be I will get a series of lines for different values of R and as R increases the value of f decreases. Let us try to interpret these two graphs which I have just drawn all what I am saying is, as the pump pressure increases the equivalently the chamber pressure increases, I need more of the fraction of the fuel or of the propellant to be introduced through the gas generator and what is the implication.

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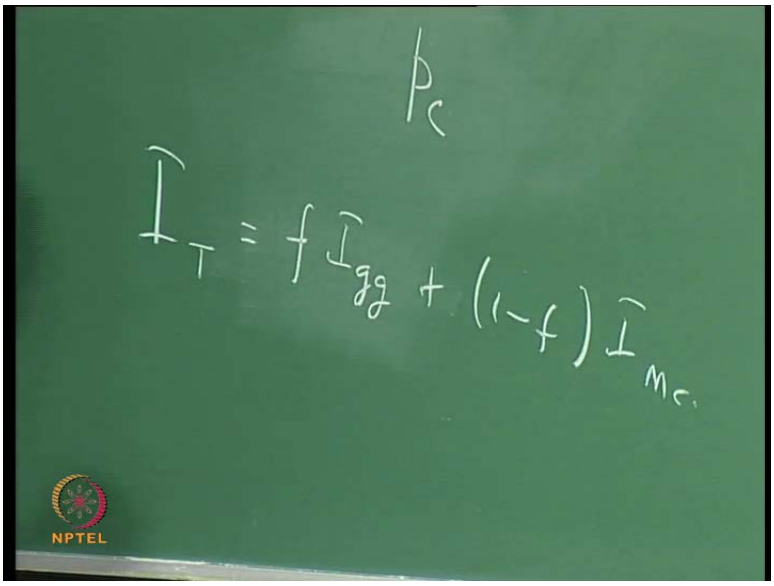

The total impulse now I call it is total specific impulse is equal to f through your gas generator whatever was available, plus 1 minus f of through the main chamber.

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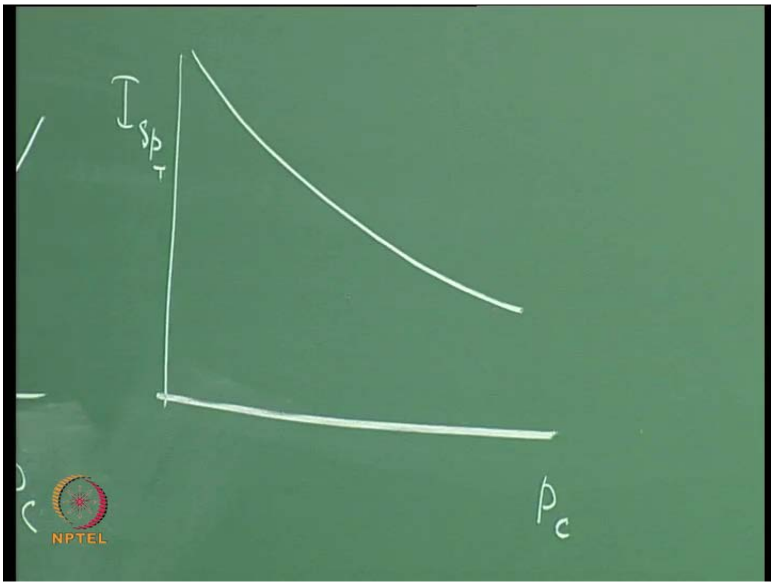

And we found g g was small if I increase this f the I T will decrease or rather I can tell myself in the gas generator cycle, if I by to plot the total specific impulse of your system as a function of let us say your value of p c. In your gas generator cycle even though the specific impulse will increase with chamber pressure.

The net effect of the flow is such that the specific impulse decreases may not be. So, drastic may be constant and something like that, but the effect will be to decrease it what is the why why should the fraction of the propellant which flows through the gas generator decrease with mixture ratio.

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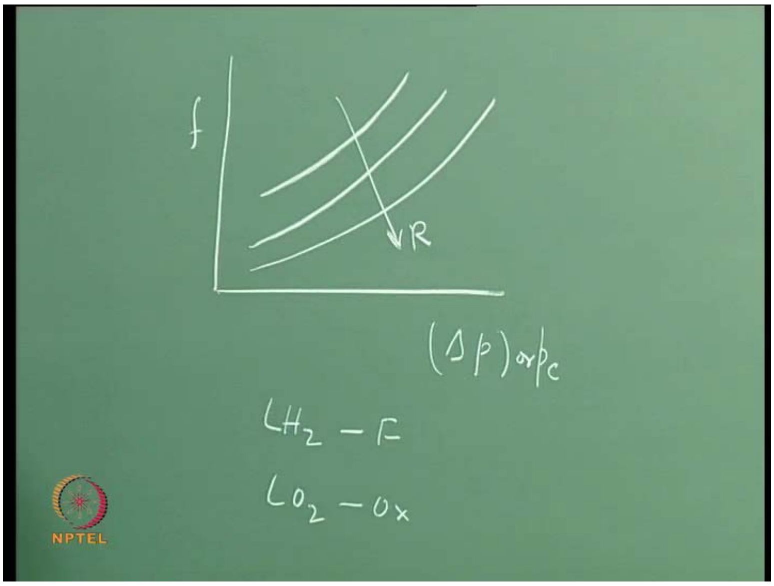

We find for the specific case of let us say hydrogen, liquid hydrogen as fuel, liquid oxygen as oxidizer, be quantity the volume of liquid hydrogen is somewhat you know the density of liquid hydrogen is very much smaller than liquid oxygen. And therefore, if the mixture ratio increases, I have more of oxygen and therefore, oxygen is easier to pump compared to light very light density liquid hydrogen, which you calls for a large volume. And therefore, more pump power and that is why this dependence comes.

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$$(\dot{m}_{O.GG} + \dot{m}_{H.GG}) C_p (T_{GG} - T_{OT}) \eta = \dot{Q} \Delta p$$

$$\frac{\dot{m}_H}{\dot{m}_{H.GG}} \left(\frac{1}{\rho_H} + \frac{R}{\rho_O} \right) \Delta p = \eta C_p T_{GG} (1 + R_{GG}) (1 - \frac{T_{OT}}{T_{GG}})$$

$$f = \frac{\dot{m}_{H.GG} + \dot{m}_{O.GG}}{\dot{m}_H + \dot{m}_O} = \frac{1 + R_{GG}}{1 + R} \frac{\dot{m}_{H.GG}}{\dot{m}_H}$$

$$f = \frac{\dot{m}_{H.GG} + \dot{m}_{O.GG}}{\dot{m}_H + \dot{m}_O} = \frac{1}{1+R} \left\{ \frac{\left(\frac{1}{\rho_H} + \frac{R}{\rho_O} \right) \Delta p}{\eta C_p T_{GG} \left(1 - \frac{1}{r_p^{[\frac{\gamma - 1}{\gamma}]}}\right)} \right\}$$

Therefore, let us summarize these two observations, which I show through these slides here. We had derived the expression that f is equal to this much, which I had written on the board earlier.

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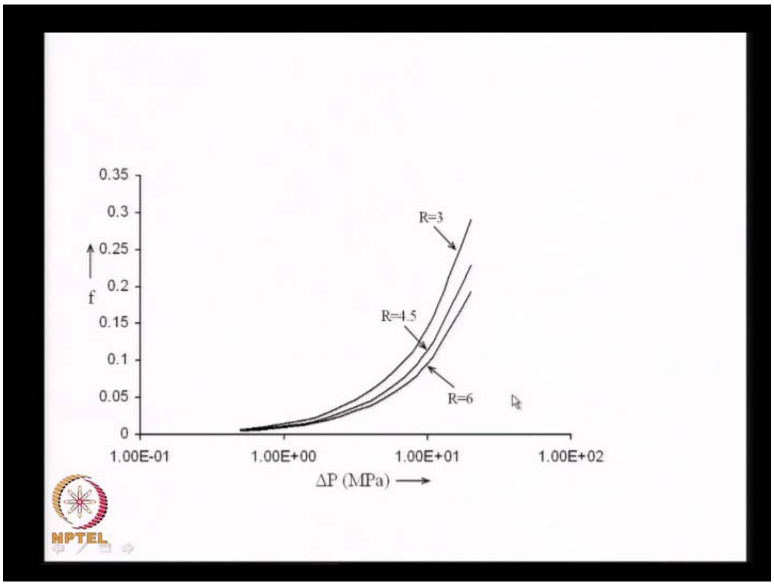

And we said as f the fraction of the propellant which flows through the gas generator as a function of p for maybe. I am considering the the delta p as point 1 MPa, 1 MPa, 10 MPa, 100 MPa it tends to increase. You know it is it is a linear with respect to delta p, but since I use a logarithmic scale the the values begin to show up as R increases the value of f decreases.

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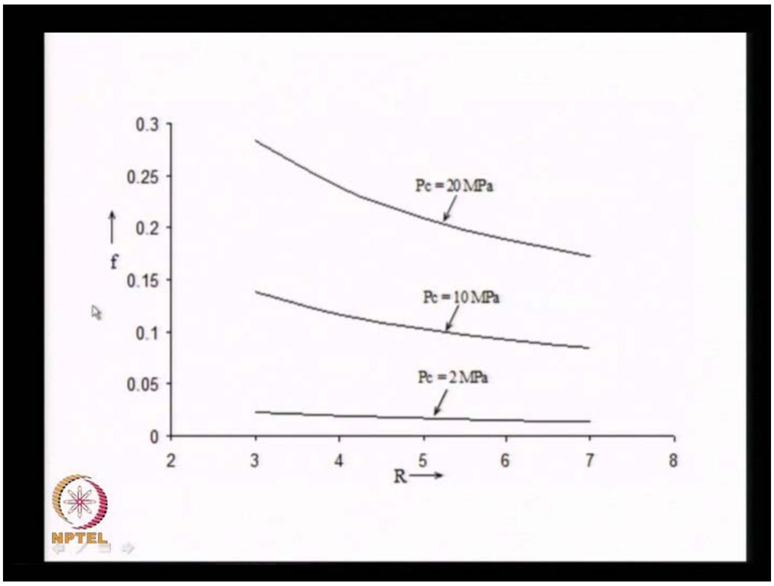

This is one second is the same thing if I now translate into chamber pressure I find that the fraction of the propellant which flows through the gas generator, and is not expanded adequately. At high chamber pressure I have a large fraction may be for this particular example, I took the mixture ratio of the gas generator as something like 0.6. I took the mixture ratio of the engine as being as being the difference what comes out the overall mixture ratio as something like 4. And for eta p s 0.6 the temperatures of gas generator as something like 900. We find that for a high value of chamber pressure I require large flow rates through your gas generator whereas, if the chamber pressure is small I need a small flow rate.

What is the implication of this I think this is something which you all can readily work out and see? The implication is if my chamber pressure is small, then what is it I find my f is small.

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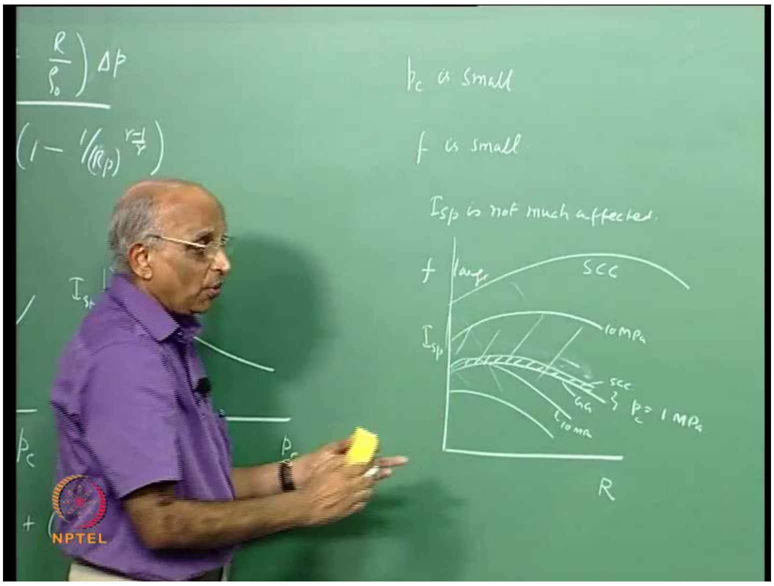

If f is small you know I do not really waste so much in this and therefore, my I s p is not much affected. Whereas, if your f is going to be large I am unnecessarily pumping so much fuel into your gas generator, that my net I s p comes down or rather if I have to make a plot now, of my value of the net I s p. As a function of let us say the chamber pressure, I find or let us let us make it in in in terms of the mixture ratio overall mixture ratio, I find may be at at low chamber pressure I get my I s p, which is may be as mixture ratio increases it comes like this. And if I have to plot for let us say a case of a G G cycle this is there.

Whereas if I allow the net propellant without bypassing bypassing the the gas generator and directly into your chamber like I have a stage combustion cycle, may be in that case may be, I will get a small increase for the stage combustion cycle. This is value at low pressure let us say pressure is equal to 1 M Pa 10 bar, but now if I have to operate my engine at a value of let us say 10 M P a, which is slightly higher pressure. In that case the G G cycle which I showed over here, let let us let us keep the terminologies clear G G cycle. If I were to have a slightly higher pressure my may be my G G cycle will give a performance over here, slightly higher performance, but my stage combustion cycle is going to give me a performance, which is going to be very much higher, because this I s p came from pressure even though the f dropped. In fact, you know how it will be use it will it will be slightly higher over here, and maybe it will keep coming down with mixture ratio whereas, my stage combustion cycle will give a performance over here. If I go to still higher pressures, this is I am talking of 10 MPa, and this also 10 MPa if I go to something like 20 MPa or 200 bar may be my G G cycle will come like this, because I am losing lot of lot of my impulse in in the gas generator in the auxiliary nozzle, whereas, my stage combustion cycle will be much better. In other words at low pressures the gain by operating a gas generator cycle is not very I do not lose much whereas, at high pressure I keep losing more and more whereas, at very high pressure I lose so much.

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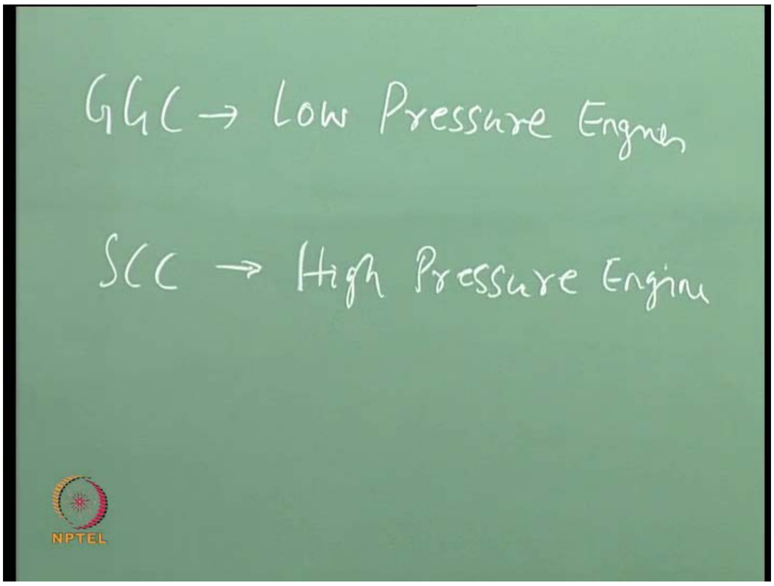

Therefore, I can say that a gas generator cycle is more suited for low pressure engines whereas, the stage combustion cycle or a expander cycle which uses all the propellant in your main chamber is more adapted at for high pressure engines. Of course, if I talk in terms of this stage combustion cycle, I need a high pressure pump and all that and maybe we will examine it when we talk in terms of pumps and turbines. To repeat again let let us let us go through this in the slides, because this tends to be a little important we we go back we said this is the fraction I have calculated I come back to this a little later.

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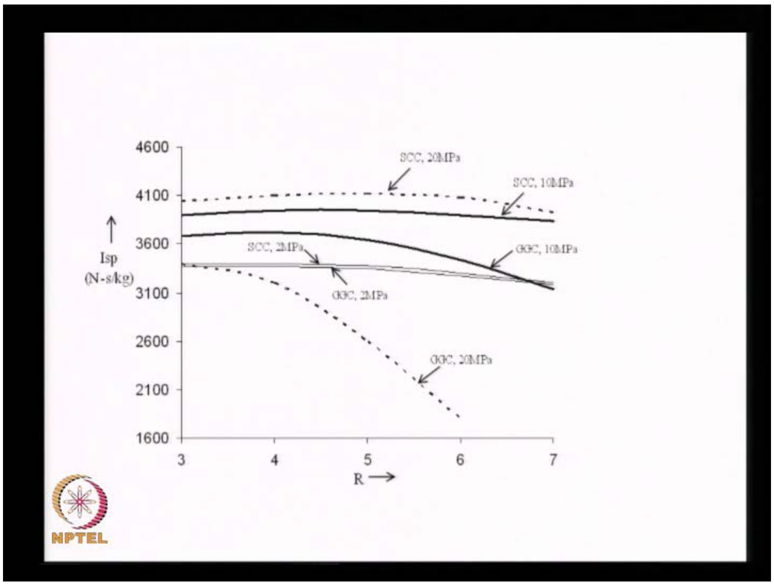

All what I am saying is. If I operate a gas generator cycle at a small value of pressure, this is the net value of specific impulse I get. If I operate the same engine on a stage combustion cycle at low pressure, I get a slightly better performance, because I have I have not lost very much, because f is still small. I have lost something from stage combustion cycle to gas generator cycle, I have I still find gas generator cycle is lower than stage combustion cycle, but the loss is small.

The loss is small, because f might be something like 0.01 or something. If I go to slightly higher pressure what is it I find at slightly higher pressure the gas generator, because the pressure is high I get a slightly higher value of specific impulse, but at the same value the stage combustion gives me a much higher value that means, by operating at something like 100 bar, I i lose if I were to operate as gas gas generator cycle I will have a lower value of specific impulse whereas, if I operate a stage combustion value cycle I get a higher value. Please remember that the x axis in this graph represents, the overall mixture ratio R, and as R increases the quantity of the oxidizer increases, since we are in an oxidizer rich region there is a fall in pressure as the mixture ratio increases.

If I go to something like 20 MPa say 200 bar, because of the very high value of f my G G cycle has this performance whereas, I do not lose anything in stage combustion cycle this is the performance therefore, I have I lose a lot by operating, but G G cycle and not a stage combustion cycle, this is the net influence what I get. In other words all what I am trying to say is if I have a low pressure engine, may be a G G cycle is adequate if I have a high pressure engine it is necessary to go for stage combustion cycle.

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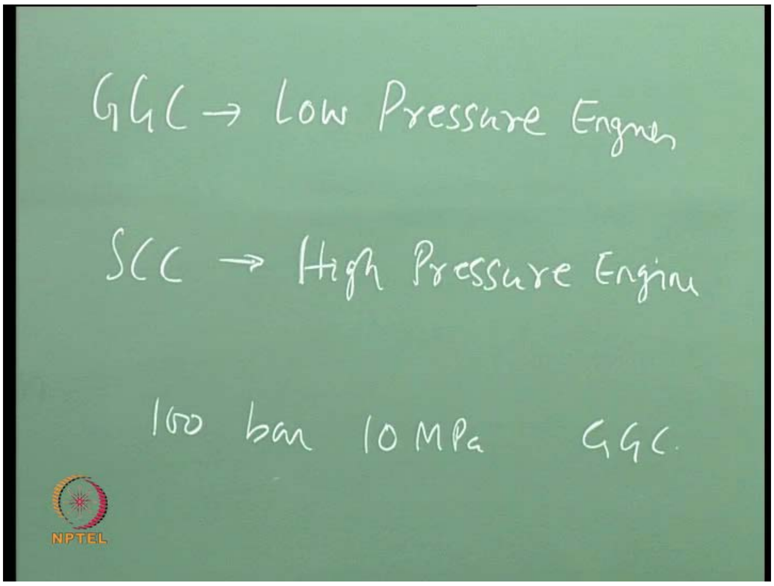

And generally for cryo engines may be 100 100 MPa or I am sorry 100 bar or 10 MPa seems to be the limit for a gas generator cycle, above this to operate a gas generator cycle you will lose more then what you can gain and this is how we do a cycle analysis.

To be able to complete the cycle analysis. I must also tell you why this did it fall down the question is why did the performance of the gas generator cycle falls. So, rapidly at higher pressures it fell it falls, because when I have more of the fuel rich propellants.

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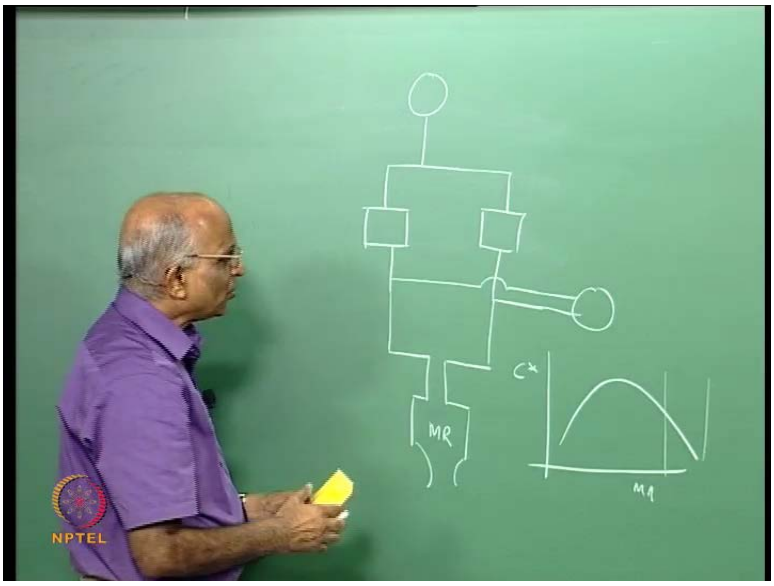

Like like for instance I had a gas bottle from the gas bottle, I had the tanks from the tanks. What did we do we took little bit of the oxidizer little bit of the fuel into your gas generator, and this is mind you very fuel rich. And therefore, I am bleeding more and more of it and. What happens when I bleed more and more of this, the the mixture ratio of the engine keeps increasing, because I am drawing lot of fuel into this more of fuel rich propellants. Therefore, this becomes oxidizer rich and then again what is the dependence C star or I s p with respect to mixture ratio, it is an optimum it comes down, we start operating the engine in these conditions. And that is why the thing begins to fall.

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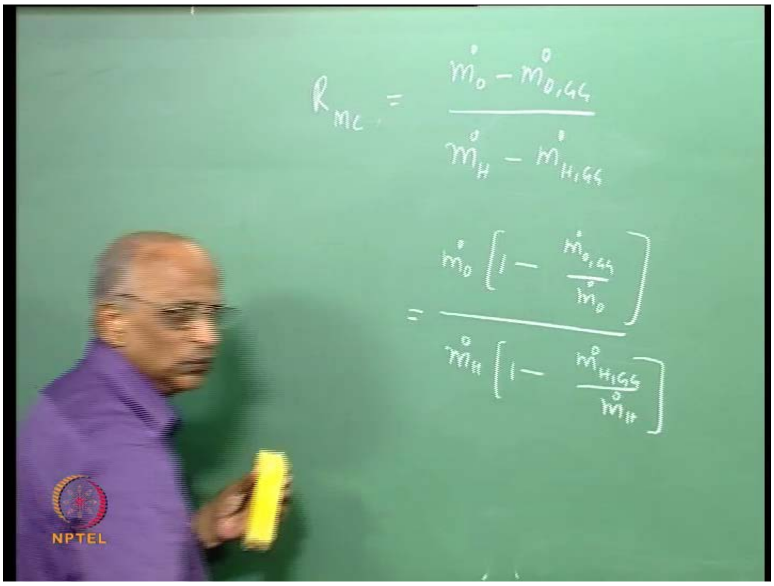

Therefore, let let us quickly derive an expression for a gas generator cycle what will be the value of the mixture ratio in the main thrust chamber main chamber as a function of R and as f you know it is quite simple to do it let us quickly do it on the board.

The value of mixture ratio in your main chamber is equal to let let us picture this gas generator in our minds. We say R m C is equal to m dot o minus m dot o which has bypass entry or gas generator which is not available in the main chamber divided by m dot let us take a specific case of hydrogen, you say m dot h into m dot h into G G it could have been fuel fuel here over here. And this I can now write as equal to m dot o into 1 minus m dot o of G G minus m dot o over here, I have taken it outside and this becomes equal to. And how do I get this value of m dot o which is going through the gas generator or m dot h which is going through the gas generator to the total hydrogen flow, we have already done something very similar, in the last class.

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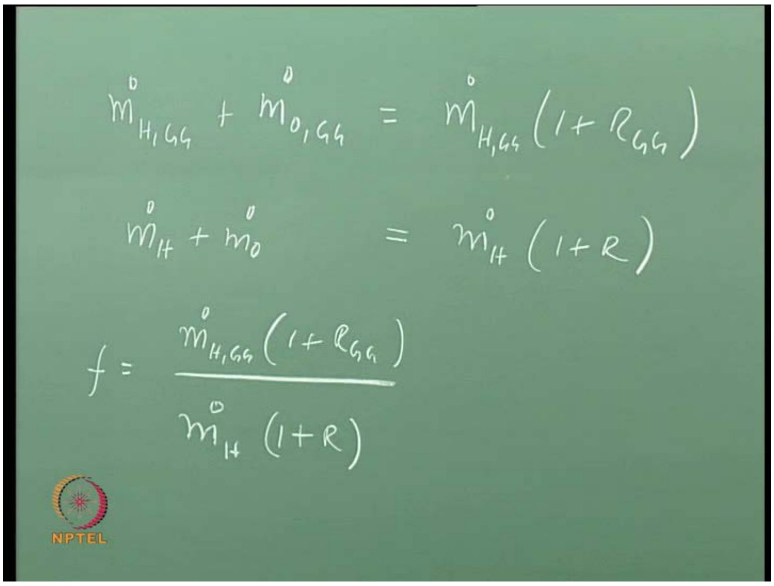

Let let let us take a look m dot h through gas generator is plus m dot o through gas generator, is equal to the total propellant flow in the gas generator, and this is equal to m dot h through the gas generator, let us say m dot h through the gas generator, into 1 plus R G G. And similarly, we can we can write an expression for m dot o and we can write this for the total m dot m dot h plus m dot o is equal to m dot h into 1 plus R. And now we know if we can now say what is the fraction f. Fraction f is equal to m dot h through the G G into 1 plus R G G, divided by m dot h through your main engine, into 1 plus R please please try to check whether things are going all.

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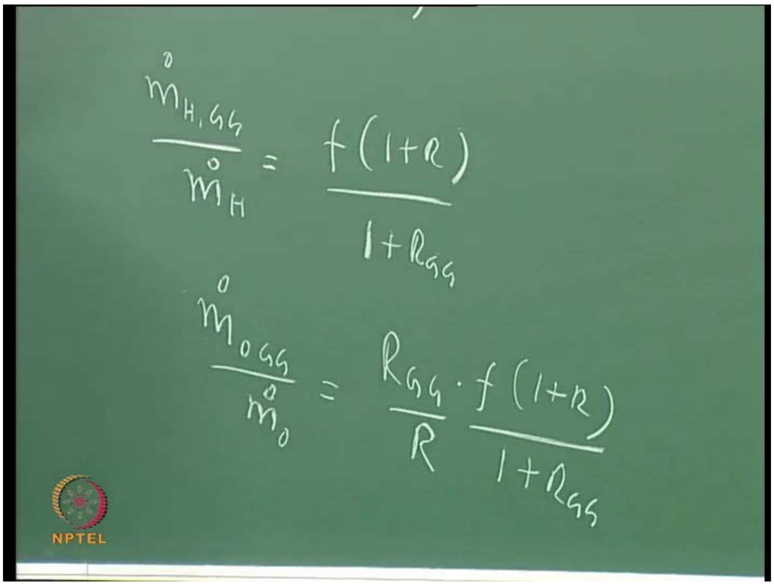

Or rather from this I get m dot h into G G divided by m dot h is equal to f into 1 plus R divided by 1 plus R G G. And now I can also write if this is ok known to us I can readily translate it into m dot o G G divided by m dot o is equal to how do I convert o to this m dot o by m dot this is equal to R G G. Therefore this is equal to R G G into m m h dot therefore, this becomes R G G. And m dot o by m dot h is equal to R therefore, m dot o is equal to R m h therefore, this becomes R into the same value gets repeated into 1 plus R divided by 1 plus R G G. And now I substitute these values of m dot o G G by m dot h from the first expression, and I take m dot o by G G by m dot o from the second expression.

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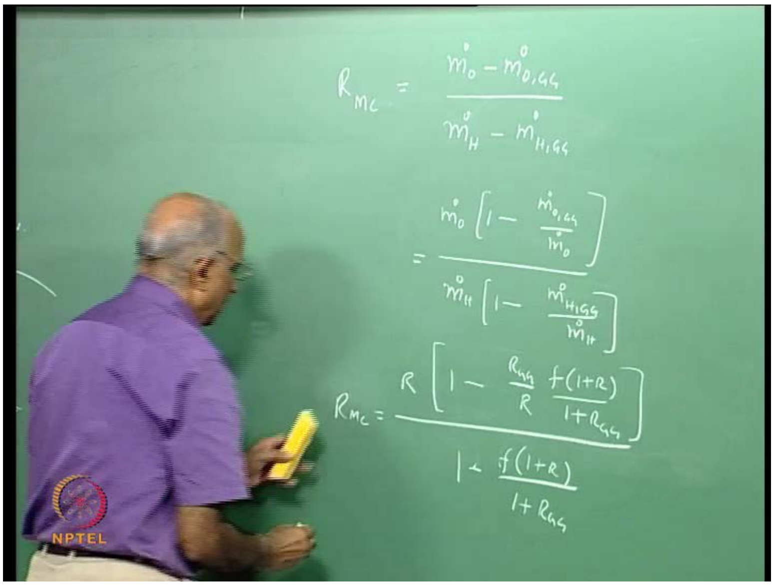

And I get the value of R for the main chamber is equal to I get and m dot o by m dot h is equal to 1 by R, or rather R here mass of oxidizer by fuel into, 1 minus I i take from the second expression, R G G by R into f into 1 plus R by 1 plus R G G divided by 1 minus f into 1 plus R, divided by and this becomes the mixture ratio in my G G. I think we must learn to do these things, we are just doing an analysis for the entire elements, and if I do this what is it I get let let us let us just plot out these results I do not want to spend too much time on it. This we have seen in all what we have done is we got the main mixture ratio in the gas generator, as a function of mixture ratio in your engine. And for combination of parameters like R G G is being 6 and for different values of R, if I plot it out as a function of f. I find that well as f increases the value of the mixture ration in the main chamber keeps increasing, and as the value of R increases this increases in other words.

If the value when f is equal to 0 f is equal to 0, the mixture ratio in the main chamber is the same as overall mixture ratio, and this is the condition for the stage combustion engine, and the expander cycle engine, where in there is no loss in the gas generator, because gas generator supplies the propellant back into the main chamber. That means, when f is equal to 0 I retain or regain my solution, but as f increases the mixture ratio in the main chamber keeps increasing. And if it increases to a very large value you come to a situation where in you start operating the engine.

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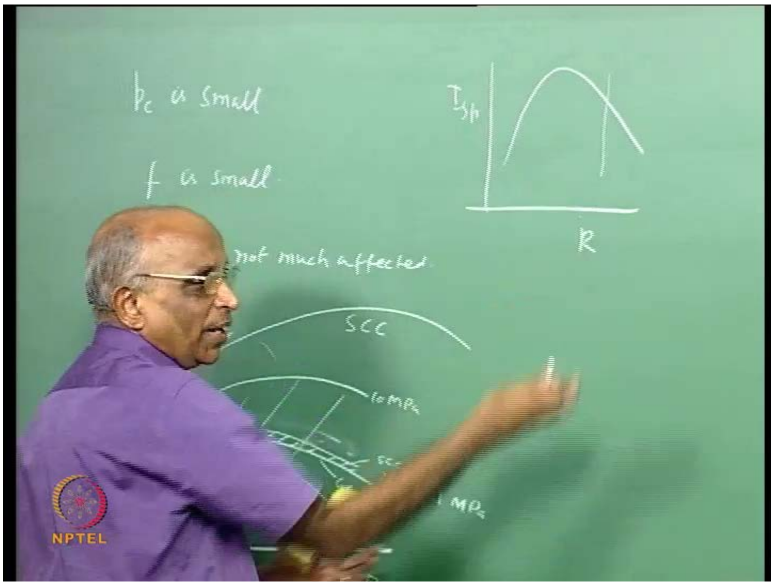

In other words what we just now told you was R, versus the specific impulse or C star goes like this. We start operating at these low values and that is why the specific impulse or equivalently C star or the total performance keeps falling. This is how we compare the different feed system cycles such as, the gas generator cycle the stage combustion cycle the expander cycle etcetera. Therefore, we will quickly submit up by telling the following, we tell ourselves for pump feed systems, in which we we could operate as a gas generator feed system.

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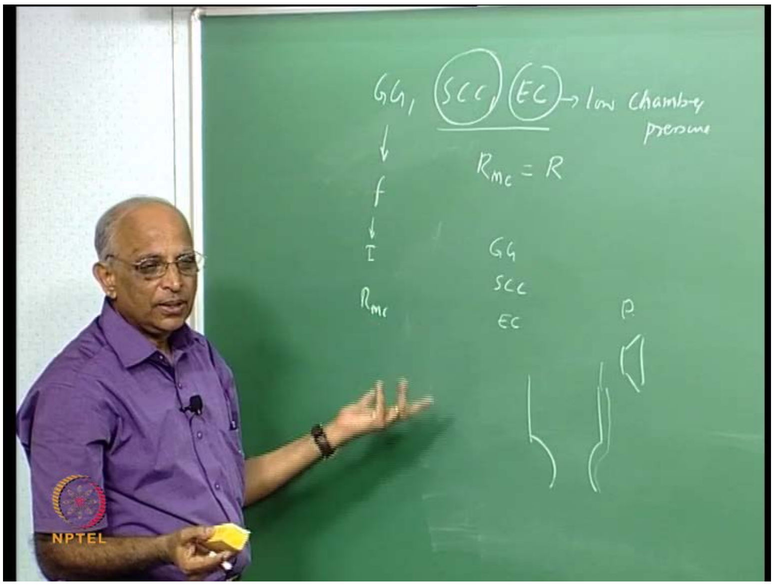

As a stage combustion cycle as an expander cycle, we told ourselves s C c is something like a topping cycle; we find G G suffers at high chamber pressures, because the value of the fraction of the propellant is used to drive the turbine. And what is driven out is at a low value of expansion through an auxiliary nozzle; whereas, in this case the ratio of the main chamber the the mixture ratio in the main chamber is same as the overall mixture ratio. In this case R m C is related to the overall mixture ratio through this expression in your G G cycle where as in your other cycle it is the same.

For high pressure staged combustion cycle is particularly useful, because I gain the advantages of high pressure, but we will have to take a look at the design of pumps which we will take which we will take a look after two or three classes. I think this is all about the gas generator cycles, the stage combustion cycles. And in expander cycle we cannot operate at high pressure, because we use only a vapor which is generated by heating of the chamber, but this also has some powerful implication, maybe we will take a look at some examples, and do why we cannot operate at high pressure in an expander cycle, we are using a chamber which runs hot, to be able to form vapor from the gases and this vapor is used to drive the turbine, I have limited amount of heat transfer in a chamber. And therefore, I cannot have very high power and since I cannot have very high power expander cycle also operates at low chamber pressures.

But, it is performance will be very much higher than the gas generator cycle, because I do not use any amount of propellant in the gas generator which is not effectively expanded. I think this is all about the feed system cycles, and with this is clear let us go to the next element of our discussion namely the thrust chamber. What was the thrust chamber, what is it we have done so far.

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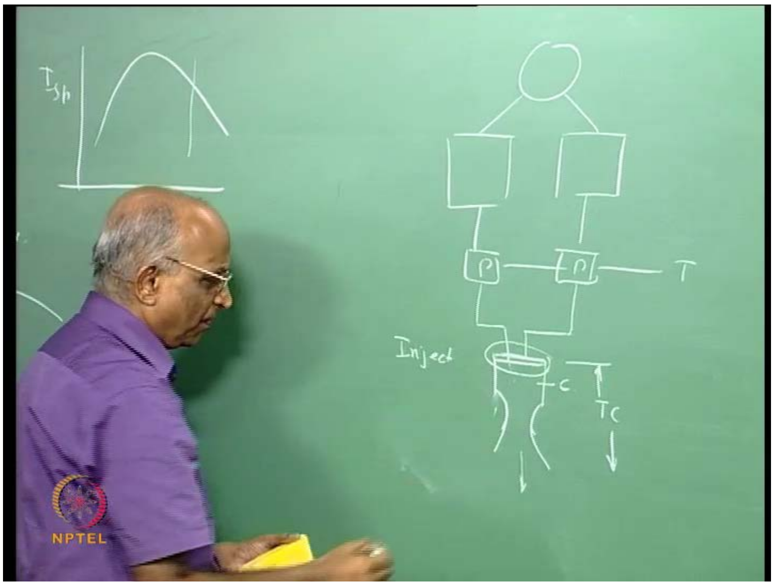

I think if we are able we said well in we need a gas bottle, we could find out how much mass of gas is required. We said well propellants are stored in tanks, then we said we need something like a pump here, we need a pump here, which is driven by the turbine and all that may be we still have to cover this part, may be now we come to the case where in fuel and oxidizer are injected into the chamber. That means, I have something like a fuel to be injected into the chamber, I need how combustion should take place in a chamber and of course, we have considered the nozzle expansion earlier.

I want to concentrate a little bit on this thrust chamber part of it in the following in the following in in this class, and may be first half of the next class. What does that thrust chamber consist of, it consist of something to inject the liquid into it into it. May be the liquid must evaporate mixed together and burn and the products of combustion must get expanded. Therefore, let us consider the first part namely the injection device. How do you inject the high pressure fuel into the chamber, in all what we are trying to say is well

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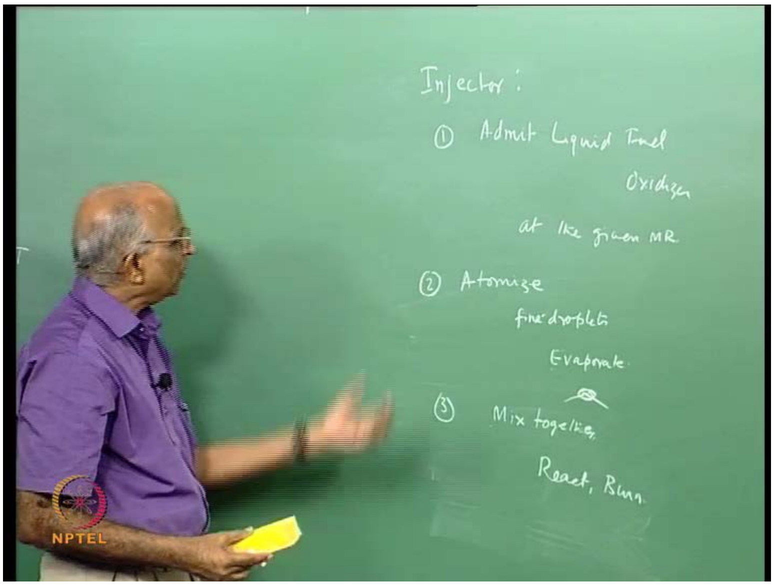

We need something like and injector that means, it will admit the fuel admit liquid fuel liquid oxidizer at the given mixture ratio.

That means, it must have some control of the mixture ratio, it must it must inject the required quantity of propellants into the chamber. Not only does it does it admit the liquid fluid at the given mixture ratio, it must also sort of increase the surface area or it must atomize. What do we mean by atomize. It must disintegrate the liquid fuel into something like fine droplets or let us say droplets, which can easily evaporate not only, but must it evaporate, but second the third point is, it must help the evaporated vapor to mix together that means, it must make sure that it will push the fuel and oxidizer in some form such that may be the vapor will mix together in some way it has to come together and once it mixes together. It can chemically react and burn in some cases you need initially an igniter, but otherwise in a hot environment it can always chemically react and burn. Therefore, the requirement of an injector is it must admit suitable quantities to give the correct mixture ratio

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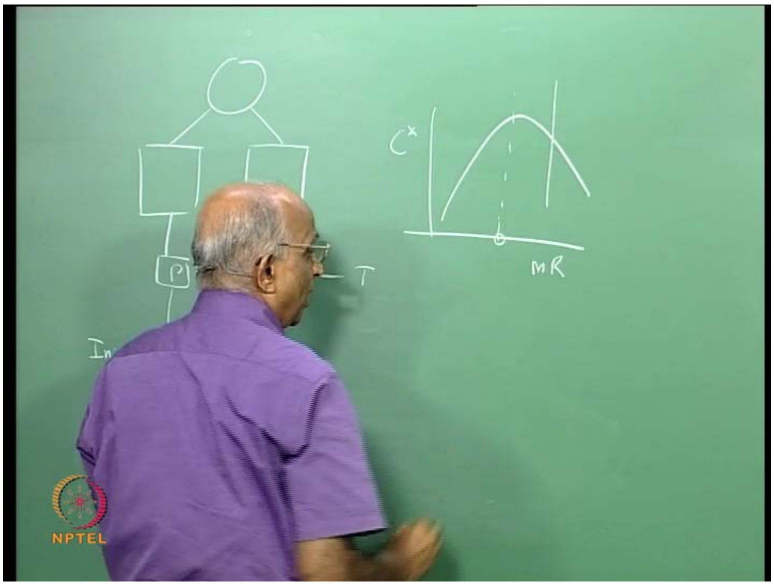

And you are we are interested in a given mixture ratio. What is it we are interested let us not forget this graph we say C star or I s p as a function of mixture ratio, is in the fuel rich region, I get a much higher specific impulse therefore, I am interested in this value of mixture ratio. Therefore it must admit the required amount of fuel oxidizer and fuel such that I get this mixture ratio, it must also break up the liquid into fine droplets. And mix them together this is what an injector should do. Therefore, let us start with the simplest form of injectors which we use daily in our lives and let us let us build up a case on it.

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Well the figure, I show here is a shower head, you know this is what we use for baby what is done in a shower head.

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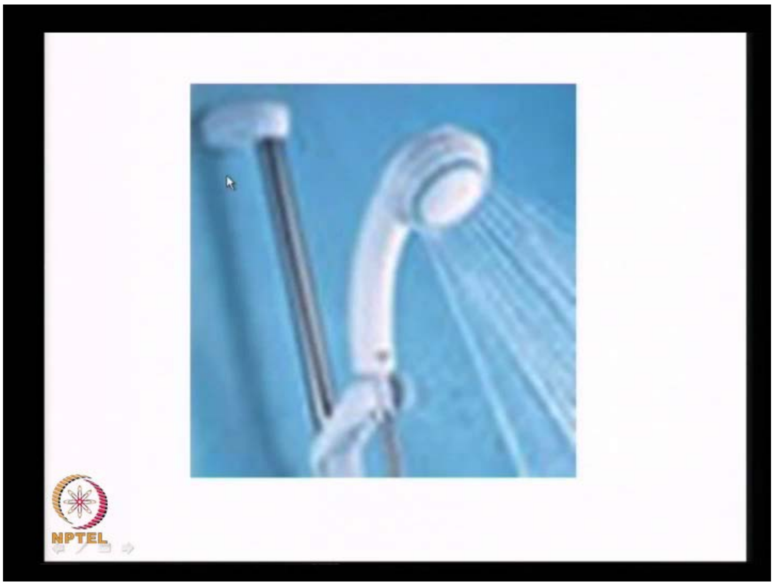

Let let let us take a look at it you have a hand shower liquid comes in or water comes in here, it is broken into streams over here.

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Or rather if I have something like a like a head over here, I have lot of orifices here I brought a shower head. I think I brought one today let see it should be somewhere here yeah.

You know this is something like what we use in our shower you know you have the water coming from the plumbing, and water collects in this region and then you you have something like a series of holes or orifices. And this is what we called as a manifold in which water collects. The pressures exist in this region and water is forced through these orifices. Let me just sketch this shower head on the board you know it tends to be very illustrative of the different types of injectors which we use, and this is also one of the schemes which we can use namely.

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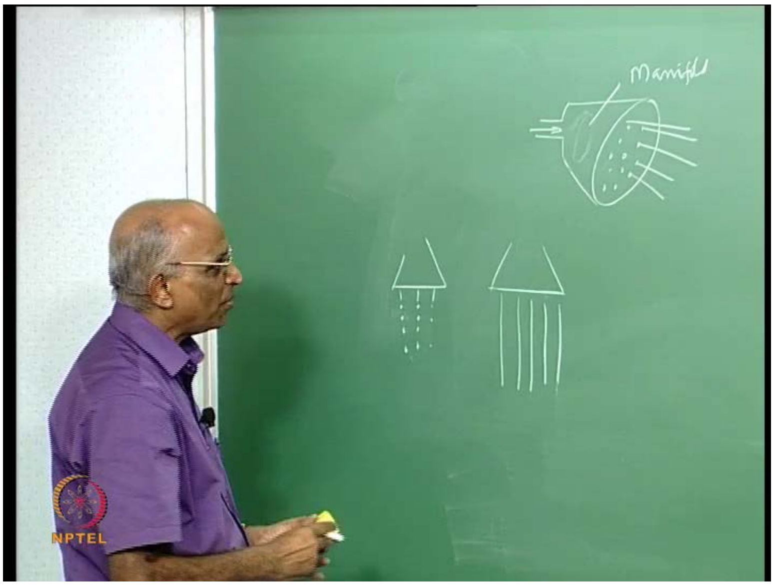

I have something like a surface here; I have holes here fine holes. This is what I said you you have something like a like a head over here, which has lot of this orifices. You have something like a place through which the liquid is admitted. And we say I have spacing between these two. And this is where I I am admitting the water and this is what we called as a manifold. What does the manifold do? It admits the it maintains the pressure over here such that water squirts out through these holes here. And you know very often you find if your injector is not if your shower head is not properly designed. And you are taking a bath let us say, sometimes you know if your injector is if your shower head is very well designed and your standing here you find the jets of water come like this.

If it is not very well designed very well what happens you know you find some drop drops of water coming like this, may be at the same value of velocity. You know we would like to have a shower head, which an injector which is something like a shower head, but which is able to produce droplets and this is one type of injector. And this type of injector which uses this principle is known as a shower head injector. Let let us again go through what what mean, by shower head injector. All what we are saying is we have manifold in which the water collects and forces through the orifices.

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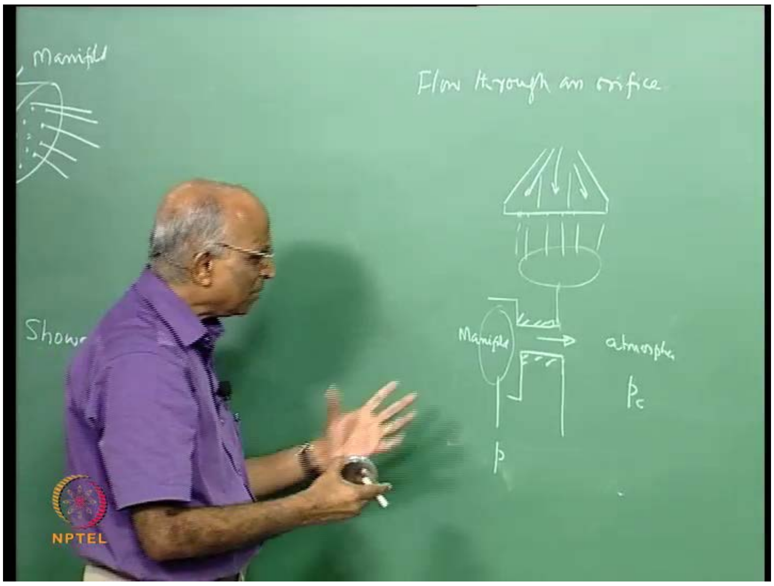

Therefore, we are looking for something like flow, through an orifice or a hole. The shower head consist of lot of these holes through which may be water is being pushed through when we are taking a bath. And a similar, scheme can be used in case of liquid propellants, but what we can do in a liquid propellant. You have the manifold here we have the set of orifices here, maybe I could divide it I could partisan it in some way in some region, and admit the fuel in some region I admit the oxidizer, maybe I admit them like this I allow them to mix in this region and evaporate and burn. This becomes my shower head injector how how do I find out the flow through the orifices let us say.

I now exaggerate one such hole, I say this is my hole over here, this is my manifold here I have lot of the such holes, this is my manifold it gives me see at in the manifold since the volume is large, let us again take a look at this. You know I i deliberately brought this because see you you are supplying water through this particular hole here, it collects in this particular manifold here. That is in the region in the chamber preceding the orifices therefore, the pressure in the chamber is what is the supply pressure.

The velocity is almost 0. And then the the the the water squirts out through these particular holes.

Therefore, all what I am saying is you have something like this is the manifold, in the manifold I have region of may be a supply pressure p. And where does the liquid get supplied it get supplied when we are taking the bath into atmosphere, in the case of rocket it get supplied into your chamber pressure, because this is this is what is the orifice this fits into my chamber. And therefore, I have chamber pressure here I have the supply pressure here and therefore, I am interested in finding out the flow through the orifices. Therefore our shower head is nothing like nothing other than what we use daily while bathing. And this shower head now is modified such that I admit both the fuel and oxidizer through it and now I am interested in finding out.

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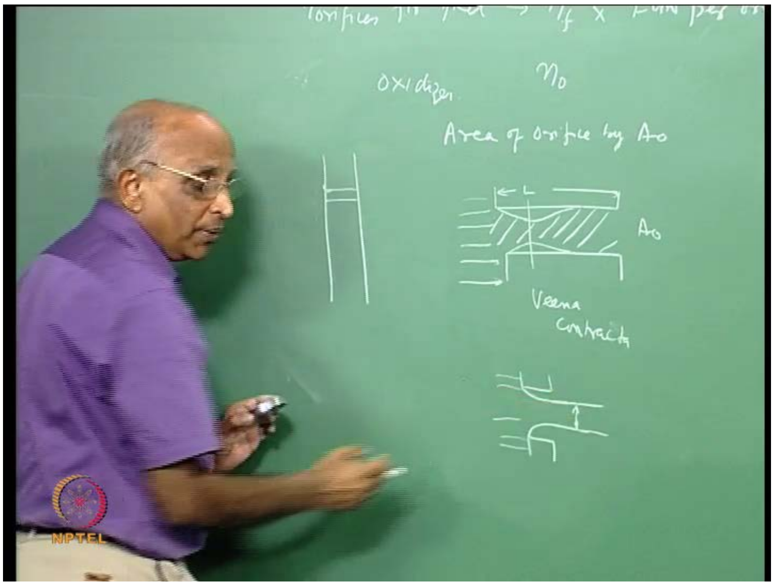

If I have let us say n orifices for fuel if I have let us say m orifices or let us say n orifices for fuel which I call as n f. And I have n o orifices for oxidizer I would like to find out into flow per orifice, if I can find out I can find out what is my mixture ratio, and what is my total flow rate. And how do I find the flow through orifices well I go back and look at this scheme again. I find that there is lot of things even in a small orifice flow, which we need to understand. The thing is that I have an orifice like this most of the orifices are sharp edged. How do I make an orifice you know if you take this particular shower head? You find yes this has something like thirty or forty holes in this, but each of the holes is just drilled when I drill a hole in a plate I take a plate like this.

I I drill a hole I drill a hole like this I remove what are the burs here. That means, it is a sharp edge over here, the edge is very sharp that means, the edge through which the liquid enters the liquid enters from the manifold like this, it has high pressure here almost 0 velocity, and it enters when it enters it sort of contracts over here contracts to a minimum and then reattaches over here, this we called as veena contracta. In other words this is the where the liquid is flowing. If I have my shower head which has a very small dimension that means, instead of having such a length of the orifice, I have something my length is something like this and it is again sharp edged.

The flow is coming over here, and the flow will now contracts and goes like this straight that means, the flow does not reattach back to the wall in fact, the flow is going like this and therefore, the area of flow is going to be much lower than the area of the orifices. If I denote the area of orifice by a 0 the area of flow is going to be much lower. Now how do I define these things how how how how can I write out the mass flow through the orifice let us let us try to derive an expression a simple expression.

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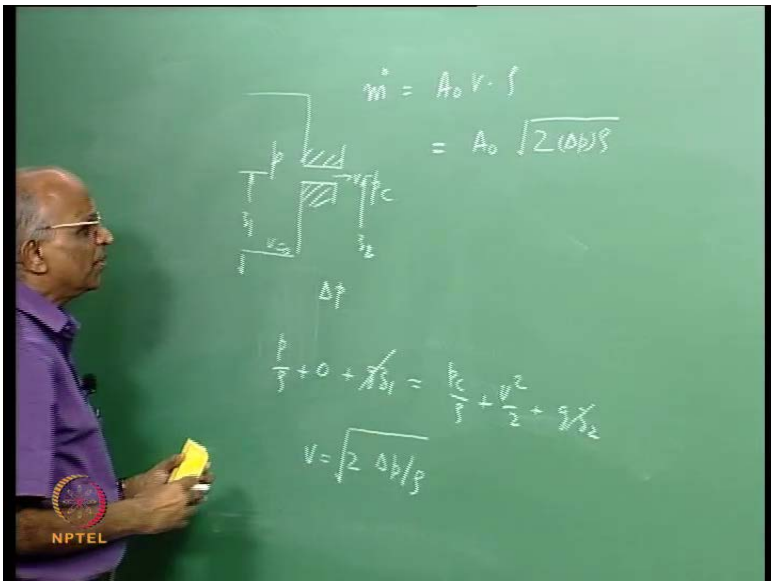

Which you all would have done in your fluid mechanics class, but let let us just try to do it. We have a manifold now I am considering the case of a single orifice, and I can just multiply it by n and get is my single orifice, this is my pressure here, this is my chamber pressure here. The difference is equal to delta p now I want to write an equation I say that the velocity here is 0, I form to find out the velocity here at the exit. I denote it by v I use the Bernoulli equation, the flow is liquid small values of velocities therefore, it is incompressible therefore, I have p by rho plus v 1 square is 2 0 then I have G z 1 inclination that change in height between this and this is very small which is I say G z 1 is the mean height that is a potential energy. The value here is p C by rho plus v square by 2 plus G z 2 is a mean height over here. I can take e z 1 is equal to e z 2, because there is not much change over here. And therefore, I immediately get v is equal to 2 into 2 delta p by rho. That is v is equal to v square is equal to 2 into p minus p C by rho that is 2 delta p by rho therefore, what is the mass flow rate through this particular orifice.

Mass flow rate is equal to I I get area of the orifice into velocity into density, which is equal to a 0, I take outside, and I get into under root 2 into delta p into the value of density this is the mass flow rate for a simple sharp edge orifice, but just now I told you sometimes it flows full like it is attached over here, there is some friction over here sometimes it flows separated like this.

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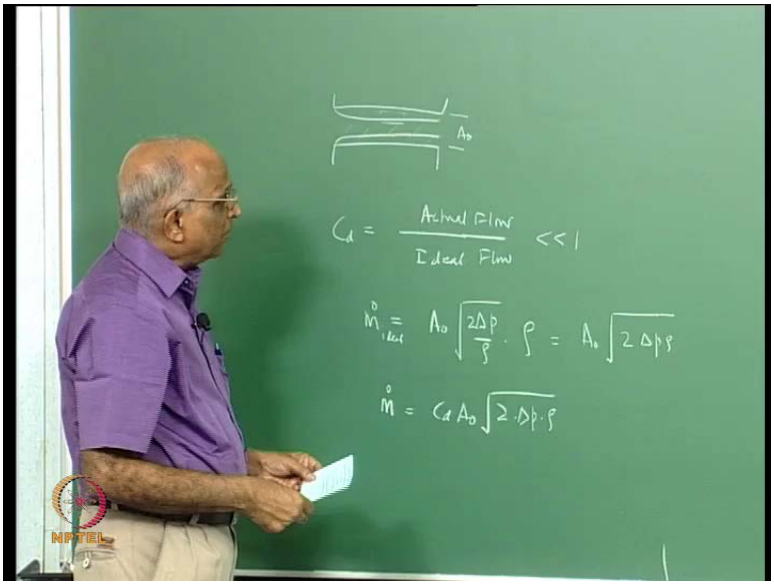

Therefore, there are different regimes of flow you know depending on the type of flow through the orifice. Namely I have an orifice here whether it is fully attached in which case a it runs full, whether it is detached in which case it does not run full. We we find that based on the orifice area which is a naught I can define a coefficient namely a discharge coefficient, as equal to something based on the ideal flow or ideal mass flow what we could have and the actual flow. I could call it as a discharge coefficient and what is the ideal flow when the entire area of the orifice that is the flow is running full when there is no friction at the wall, I could have the total flow corresponding to delta p and in practice I have friction at the wall sometimes the flow is separated and therefore, the actual flow will be less than ideal flow and therefore, I have a discharge coefficient which will always be less than one.

To be able to arrive at this value of discharge coefficient I therefore, write in terms of mass flow rate m dot in the ideal case. What is the value of the flow we will have flow runs full a 0 the the velocity of flow depends on the pressure drop namely delta p 2 delta p by rho is the pressure drop, area into the velocity is the is the volume flow rate I multiply by the density over here. And therefore, I get the ideal flow rate as equal to a 0 into under root I take the rho here into this place I get under root rho rho 2 delta p into rho, but in practice. Since you do get separated flow and you are always you do not know what this area of this separated flow is you base your total flow or the flow on the total area and we also do not correct for friction therefore, the actual flow m dot should be equal to C d into a 0 into under root 2 delta p multiplied by the density that is the incompressible flow and therefore, the density is constant into 2 delta p into rho. This is the value of the flow which takes place in this particular expression, let us again recall a 0 is the area of the orifice through which or area of the hole through which hole is flow is taking place C d is the discharge coefficient rho is the density of the liquid, and delta p is the pressure drop across the particular hole.

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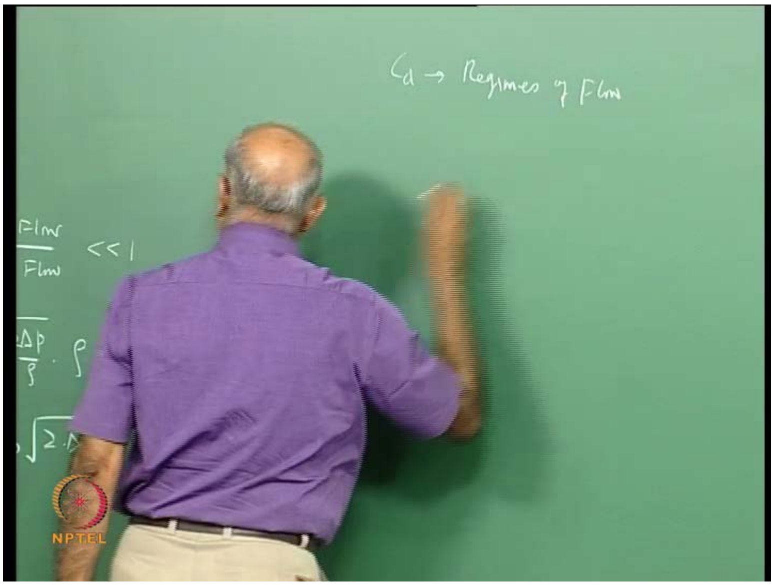

It must be remembered that the value of C d what we have now depends on the regimes of flow through the orifice. What do I mean by regimes of flow? The flow sometimes runs full such as it happens when the orifice is large, sometimes with cavitation it gets separated or when the orifice is very, very small due to the veena contracta it gets separated. And therefore, for the different conditions we would like to examine the value of C d which I do which I do subsequently.

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I thought we should not spend too much time on it, because we are shifting the topic from from liquid propellant rockets to once particular element of it, well this shows your injector head.

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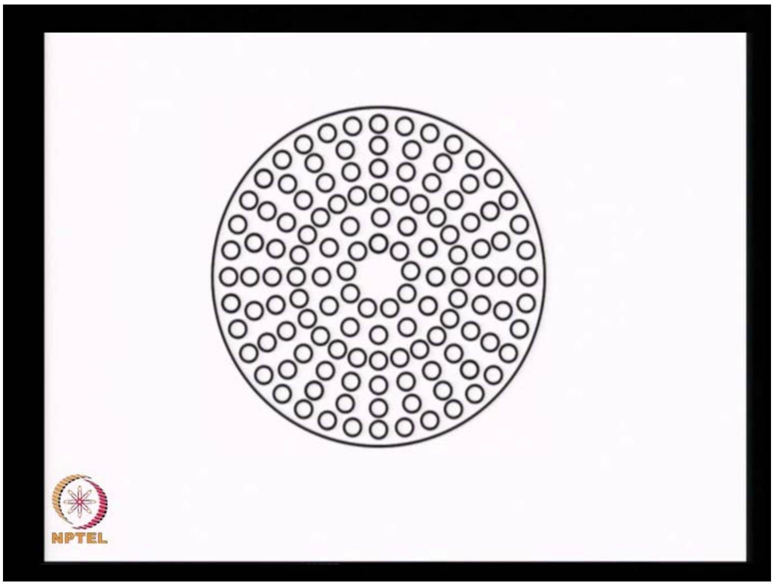

or shower head wherein you have lot of these small holes through which flow is taking place.

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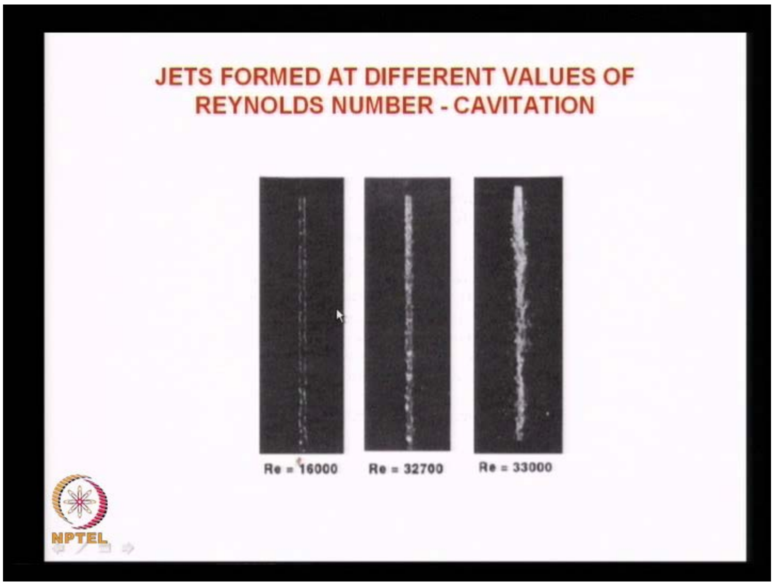

You know if I do some experiments I allow flow at some different Reynolds number I have shown Reynolds number of may be 16,000 32,000 and 33,000. You find that at some Reynolds number the flow is quite smooth the jet is quite smooth the like you stand under a shower you can see silver water coming down you see this coming down. At some Reynolds number it tends to become a little turbulent as it were at some Reynolds number it becomes violent some changes like this what are these things about let us try to understand some of this.

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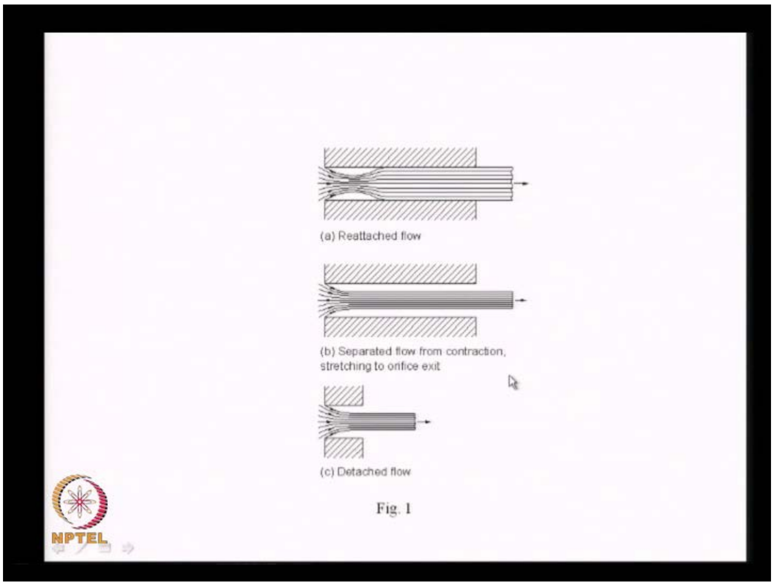

See these things are essentially when I have an orifice I have veena contracta here, flow attaching here. Sometimes even for the same length the flow go straight it does not attach whereas, for a small length is understandable, because if I cut the orifice here, well there is no way of attaching this is understandable, but this also takes place what is the reason for this let let us put it down.

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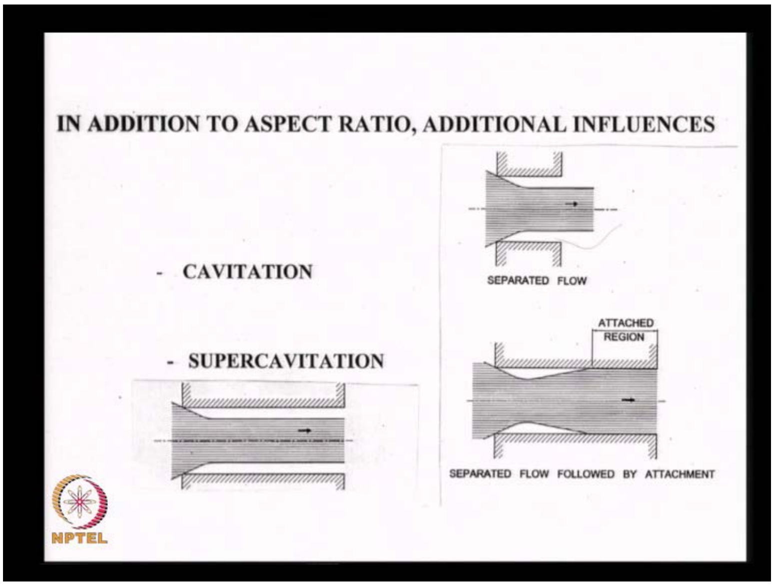

You know if if you have something like a flow taking place, at high velocities when the velocity further increases the pressure of the liquid decreases. If pressure decreases to a value wherein the the pressure in the liquid equals the vapor pressure of the liquid itself then cavities begin to form in the liquid, and once cavities begin to form in the liquid a reattachment like this is not possible and the flow separates out here. Such type of flow is known as cavitation cavitated flow, and some books call it as super cavitation super cavitation is nothing, but even even though the flow should have come over here, the pressure here has gone to a level wherein the pressure of the liquid is equal to or less than the vapor pressure vapor gets generated and the flow separates.

Therefore, essentially we talk in terms of three types of flows. May be reattached flow when I have long value of length to diameter orifices, may be a flow which is separated when I have high velocities or cavitation taking place, and for small length to diameter orifices I could have separated flow. Therefore, I could get three values of discharge coefficients accordingly.

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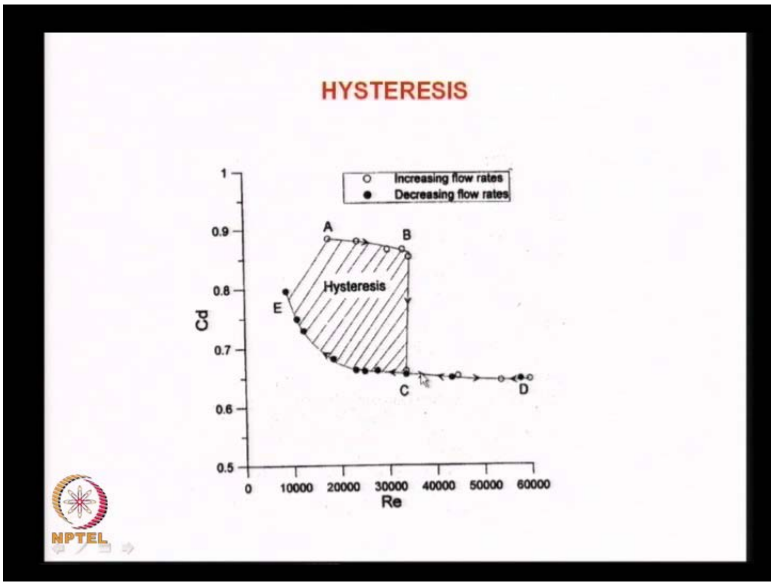

And if I do an experiment I start at low value of Reynolds number wherein I get an attached flow for which, since it is the attached the whole flow area is contributing to the flow and therefore, I get a high value of discharge coefficient it comes here. Somewhere cavitation starts it begins to separate I go over here it is still separated. And now when I start reducing the pressure or reducing the velocity again it goes like this, but it the memory of the separated flow lingers on and C d decreases it never comes back to this. That means, even a small thing like a shower head injector which is nothing but an orifice like this it has it is not that straight forward, and what happens let us let us try to put this down.

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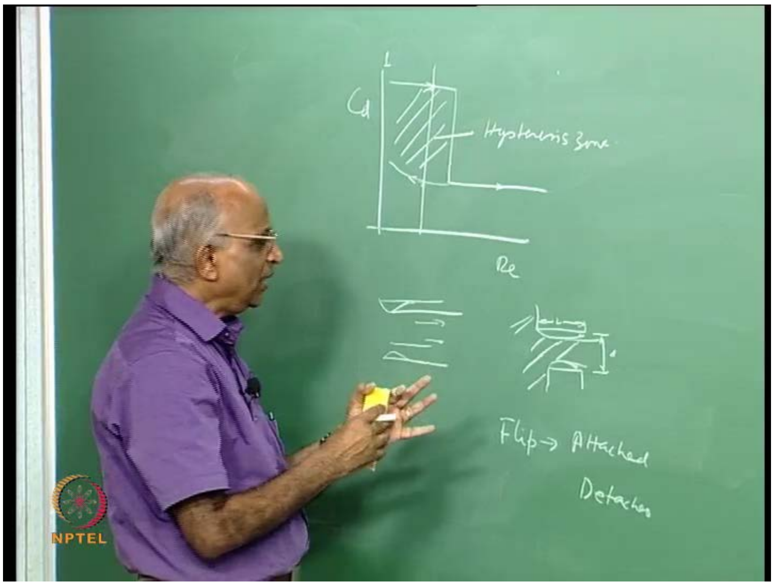

When I start an experiment and I say I measuring the C d, as the function of Reynolds number well I get attached flow for which C d is near to 1, because the flow comes like this gets attached over here, and it flows like flows fully here therefore, only friction drop is what matters here, but all of a sudden when the pressure of the liquid drops to vapor pressure the flow separates. The flow separates and comes over here this is my forward direction, after doing this I want to throttle it back I reduce the pressure it does not go back over here. It goes back like this that means, I have a zone which for the same value of Reynolds number can give me two values of C d, and this zone is known as the hysteresis zone this is one.

Second is if I also have my my length of the orifice to the diameter of the orifice, of some value where in it is just near the attachment that means, flow is coming over here from the manifold. What is going to happen if it is near to attachment sometimes it attaches sometimes it detaches and therefore, I could have a flip I could have a flip between attached region and detached region and this is not what I want.

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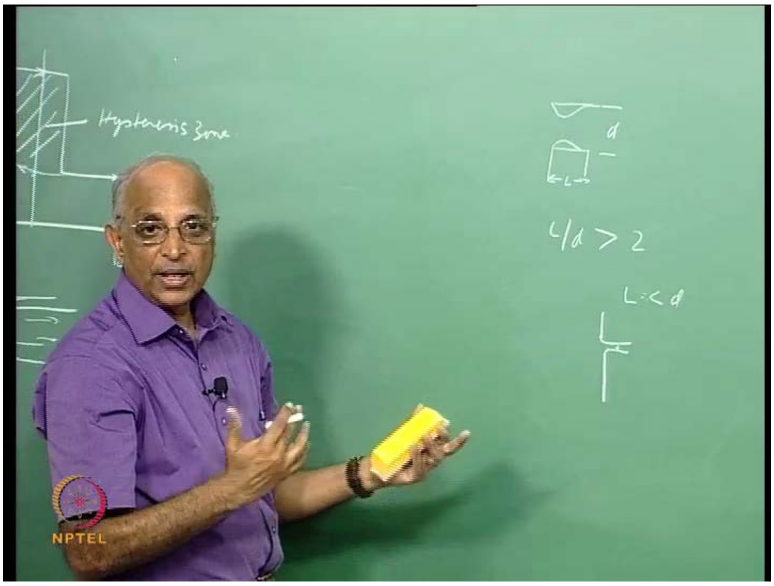

Therefore, even to choose a shower head I need to do I need to understand the mechanics of flow and therefore, normally the shower heads are such that you you keep the length of your orifice. Each orifice to the diameter of the orifice to be something like l over d to be somewhat greater than something like 2 or something such that flow is always attached and you do not get detached flows.

For control purposes whenever you want a controlled experiment or you you use an orifice for flow control. I will use a very thin razor type of blade in which the length is almost 0 length is a very small number compared to d. And the flow in this case is always detached. Therefore, you must choose whether you want detached flow or attached flow and accordingly chose the dimensions therefore, even the shower head injector does give you some some lessons to learn. And therefore, we say that flow through orifices depends on the length to diameter ratio, because the C d depends on it.

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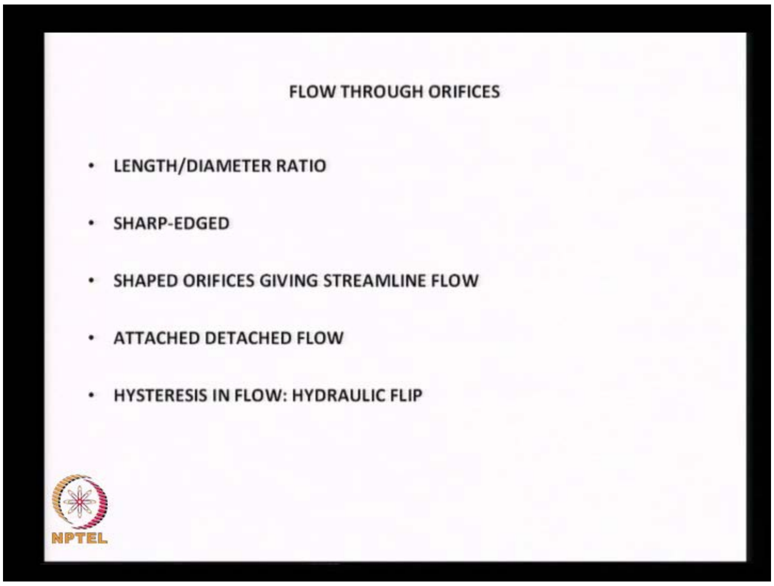

We choose normally sharp edged you know the question is, you go to the market and you want to buy a shower head for bathing. You find well people say why not you make orifices instead of having something like an orifice.

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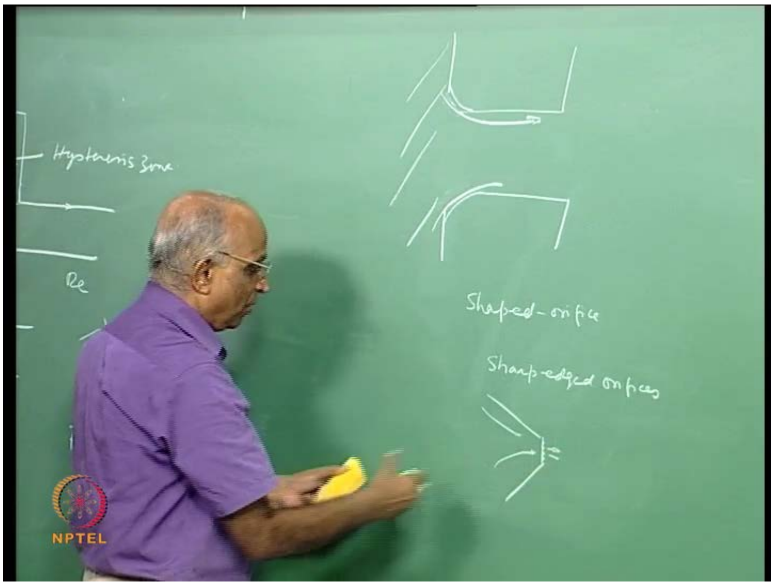

Let say an orifice like this this is the manifold. Why not make the orifice which is smooth streamline streamline along the flow, this will give you full flow, but to fabricate such things is difficult. I could have an orifice which is like this the next one would be different to get reproducibility in something like a shaped orifice is more difficult. And we are going to talk in a shower we have 40 holes in a rocket we may have 80 holes or 100 holes or 200 holes. To get so many holes drilled with shaped orifices is difficult and therefore, we normally use what are known as sharp edged orifices. And with this we we go and operate that means, we we have a manifold in which we admit part of the manifold you admit fuel part of the manifold, you admit oxidizer, you have a series of orifices through which oxidizer flows and fuel flows, and that is how we make a shower head injector.

How do you calculate the the mixer ratio from a shower head injector and which will be the same for many type of injectors.

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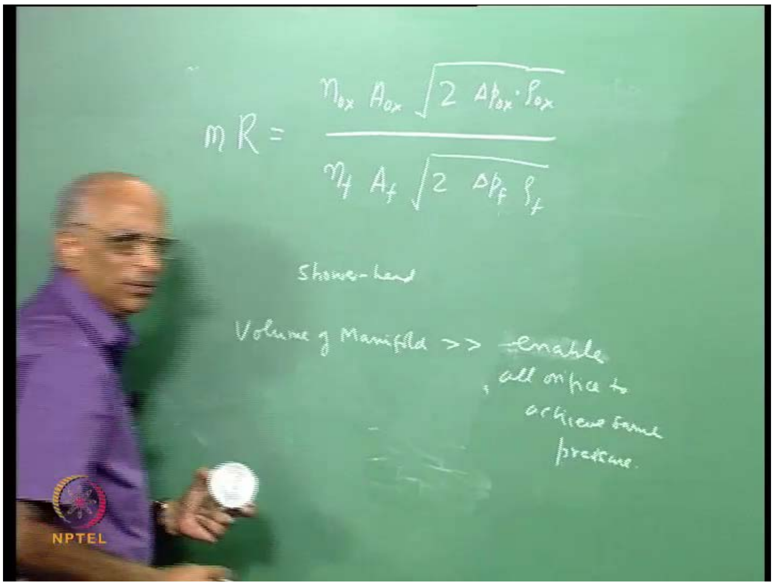

Let us say R mixer ratio is equal to the number of oxidizer orifices, into the area of each oxidizer orifice, into 2 into delta p across the oxidizer orifice, into the density of the oxidizer orifice divided by number of fuel orifices, area of the each fuel orifice into 2 of delta p across the fuel orifice into rho of this. If I have a shower head which has common delta p f is equal to delta p oxidizer and of course, 2 cancels and this is how you get a mixer ratio.

This is all about the simple way of injecting fuel in a rocket chamber using what we call as a shower head, but this shower head teaches us one more lesson. I told you this is the manifold and this is the orifice and this is where it is. I have a particular manifold volume what should be this volume in a rocket chamber should it be large or small. From fluid mechanical considerations if the volume of manifold is large then I will have the same pressure for all the holes over here. If I have a very small manifold volume the holes which are at the center near the tube inlet will get the high pressure the others will get a low pressure.

Therefore, from fluid mechanical considerations I should have a volume of manifold which is let us say large, to get all all orifices in order to enable all to let us say enable all orifices to achieve same pressure. What is it I am talking of now let us let us light slightly deviate from the topic.

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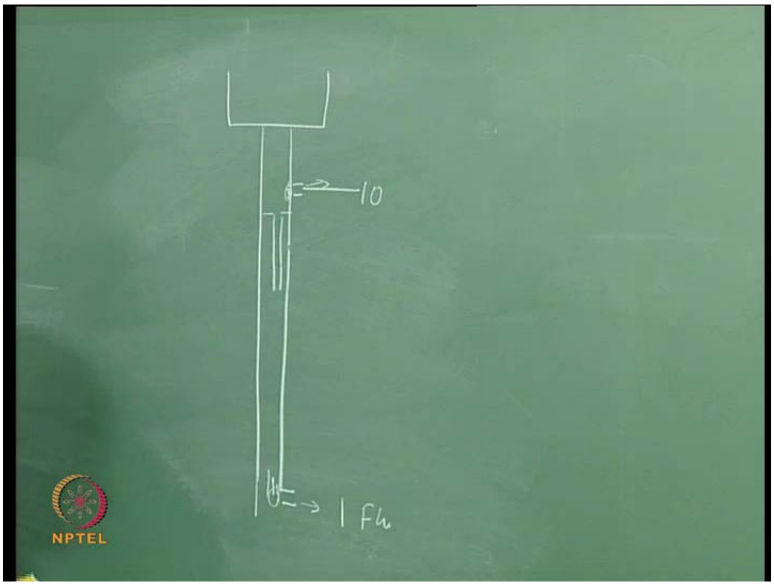

Supposing I have a multi story building I want to supply water from the top which is 10th floor. And I want to supply uniform I want to ensure water is supplied uniformly to all the flats. What do I do let us say I have a tank on top and I have to supply to the 10th floor I have to supply to the first floor. If I put a common manifold tube or a tube which is supplying water to the 10th floor may be to the first floor you know this fellow will get a good supply whereas, this fellow will not get a supply how do I ensure uniform supply and this is the same thing what we use in our manifolds. See may be if I were to say if I size this in such a way, such that I may be I increase this then I decrease this then again I decrease this. And such that by the time it comes here, it has more resistance then may be here the supply here pressure and the supply pressure could be the same this is 1.

Or else I could put some filter here, or I use a large whole filter here. I put something like a small filter here, such that I introduce some pressure drop here such that my supply pressure is same. And so also in rocket injectors whenever I have a manifold I cannot have a large manifold for the simple reason.

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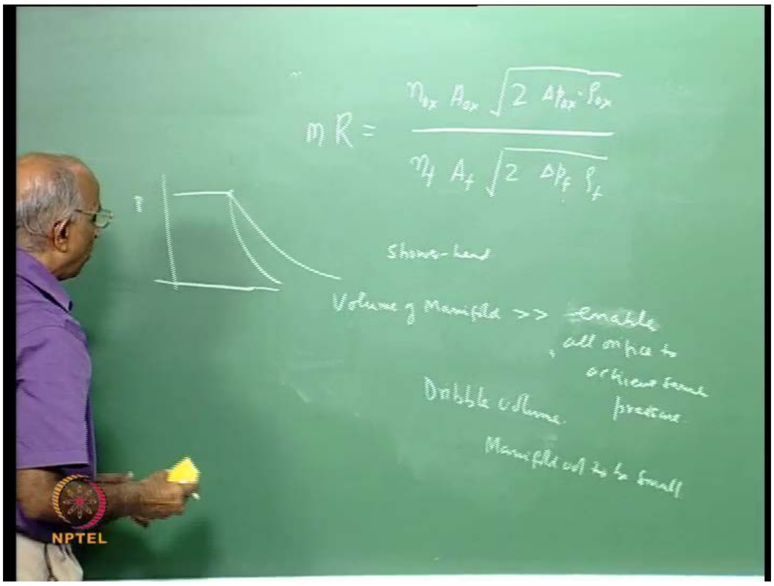

If I have a large manifold lot of propellant collects before it can be injected. And therefore, I have when I stop the flow of the propellant into the chamber still lot of propellant is there it continues to dribble. That means, what is going to happen I i I have my thrust or I have the chamber pressure I stop my experiment here, or I terminate the rocket here it will continue to burn for a long time, because all these things will keep on falling. And you would have seen this you close your valve and the shower and the keep keeps continuing for some time, because your dribble volume or the volume of your manifold is high.

Whereas, if I have a very small manifold then immediately it will come down, because there is nothing much over here therefore, even though I would like to have a large volume of the manifold such that, I can supply to all the orifices at constant pressure from the considerations of dribble volume. I would like to keep my manifold volume to be small, but if I have to keep my manifold volume small then what is it I have to do.

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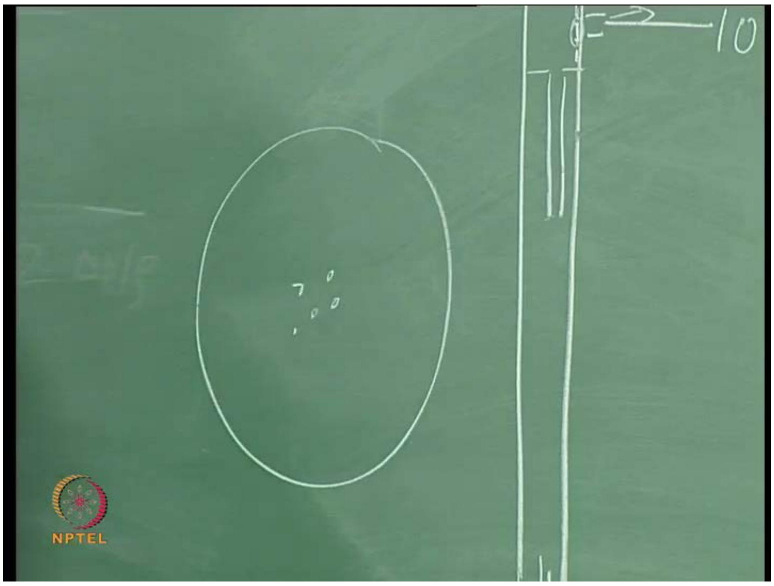

I have to put something like a sieve or something over here, such that may be the holes which are over here, are covered with a sieve such that there is more pressure drop and there is less pressure drop on the outside such that all the holes can have equal flow. And these are some common things which we use in the design of shower head injector.

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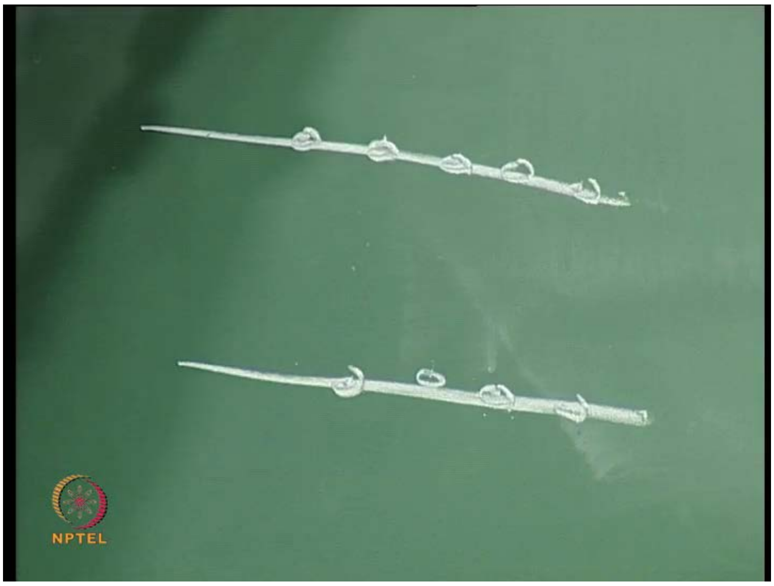

But shower head injector is something like a weak injector, because as you know if I have a jet coming like this as a jet coming like this, it takes some definite time for it to atomize and and form droplets, but you want droplets as early as possible. And though some of the earlier designs in rockets liquid propellant rockets use shower head injectors at present point in time we never use the shower head injector.

What is it we do we get the same thing like let us say one stream of jet coming like this the other stream of jet coming like this, instead of having these jets coming like this we make them interact with each other. That means, we have impinging jets and once you impinge the jet. You have something like a fan which is being formed over here and that becomes a thin fan, and that is what what begins to burn; may be we will look at the different injection devices in the next class, and at that in during that class we will also look at some of the problems which we face in the combustion chamber.

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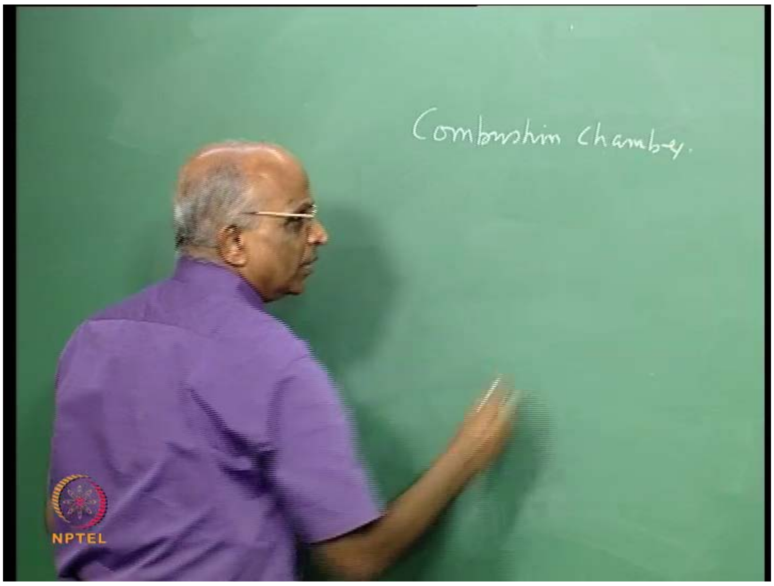

Therefore, in in this class what is it we have done we started with the gas generator cycle. We looked at the deficiencies of a gas generator cycle. Namely some propellant gets wasted which is not fully utilized therefore, a stage combustion cycle and expanded cycle are preferred especially at high pressures. Then we just started with the injectors we looked at the shower head injectors, maybe we will build up on this and look at the other injectors which are used in liquid propellant rockets in the next class. thank you then I think this is about it.