

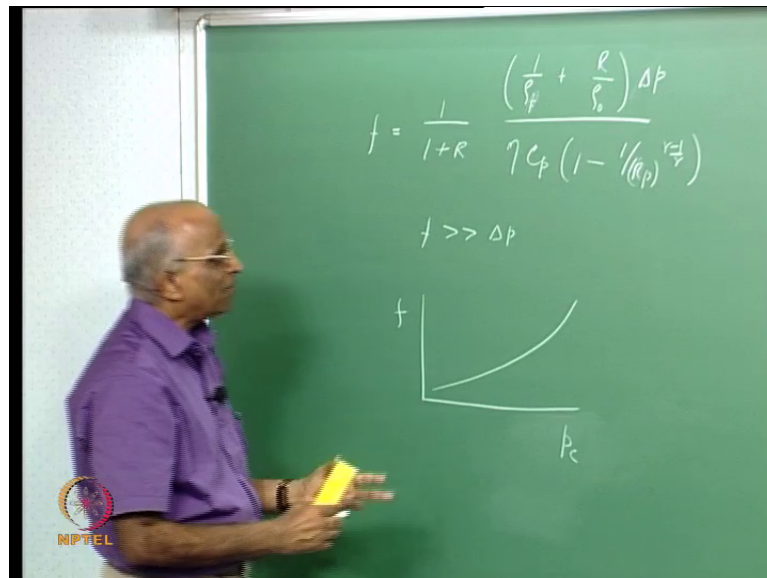
Rocket Propulsion
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Lecture No. # 28

Analysis of Gas Generator and Staged Combustion Cycles and introduction to injectors

In the last class, we derived an expression for the fraction of the total propellant flow into the gas generator as a function of R , the overall mixture ratio; the overall mixture ratio means from the tank whatever be the oxidizer, which is being supplied to the fuel, which is supplied from the tank. We also had the other parameters viz., the temperature in the gas generator which depends in the mixture ratio in the gas generator, the density of the fuel, which we called ρ_f , density of the oxidizer ρ_o , the pressure increase across the pump Δp so many Newton per meter², the value of C_p and the expansion ratio in the turbine. (Please note that T_{GG} is missing in the following slide in the denominator).

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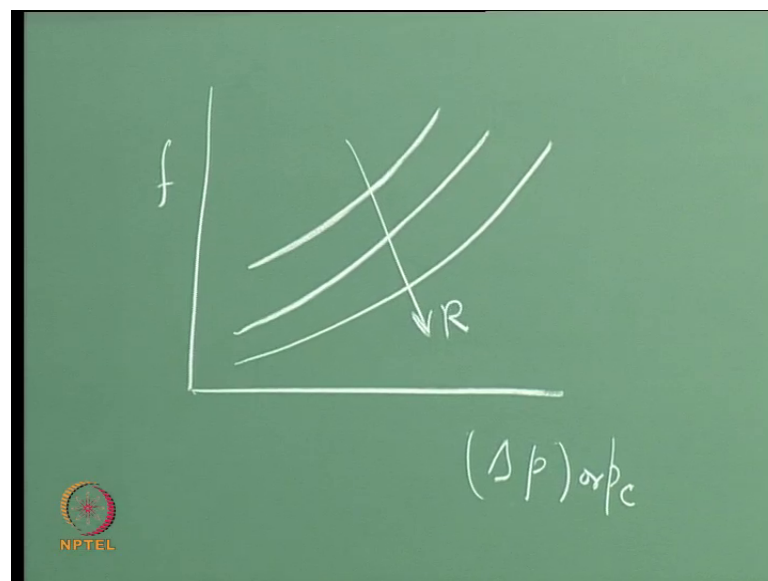
What does this expression tell us? Immediately we see f increases as Δp goes up, where Δp is the pressure increase across the pump. That means, for a high-pressure engine and a high pressure engine will demand a higher value of pressure at the inlet to the engine.

Therefore, the increase in the pressure ΔP must be high. Therefore, the fraction of the propellant f , which goes into the gas generator, must be high. If we want to plot, the value of f as a function of Δp across the pump, the trend of the change of Δp should be similar, to the trend of the change of chamber pressure.

We can write here p_c as the chamber pressure instead of Δp on the x axis. The fraction of propellant, which is required to flow through the gas generator, should increase as the chamber pressure increases; this is first observation; is this alright?

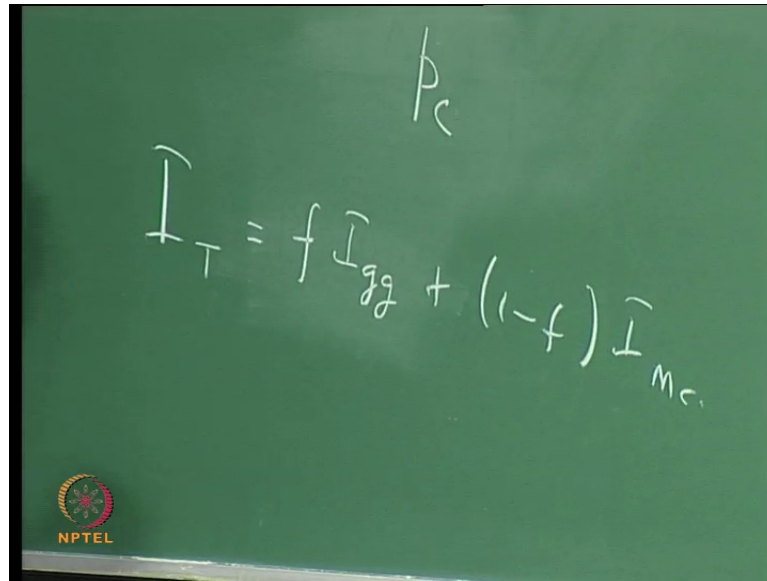
How will the fraction f change with the overall mixture ratio? If overall mixture ratio is higher that means, the value of ' f ' will be smaller, because we have R in the denominator. This R in the numerator is modulated by the density and multiplied by some number and added to a quantity; therefore, the R in the denominator tends to be stronger or rather the value of f will decrease as R increases.

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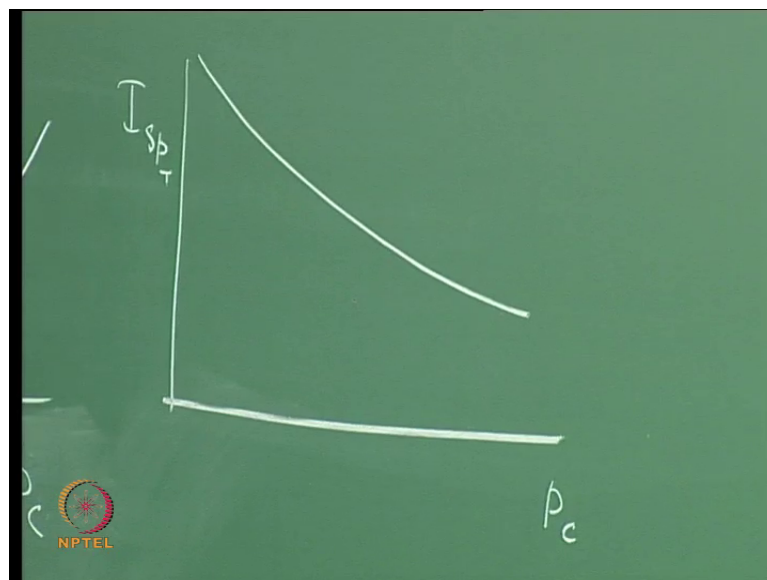
And therefore, we can represent the influence of the overall mixture ratio if we plot Δp over here or which is same as we said as p_c ; may be we will get a series of lines for different values of R and as R increases the value of f decreases. Let us try to interpret these two graphs, which I have just drawn. We find that as the pump pressure increases or equivalently the chamber pressure increases, we need more of the fraction of the propellant to be introduced through the gas generator and what is the implication.

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$$p_c$$
$$I_T = f I_{gg} + (1-f) I_{mc}$$

The total impulse now I call it is total specific impulse is equal to f through the gas generator \times specific impulse of the turbine exhaust $I_{GG} + (1 - f)$ of the specific impulse of the main chamber.

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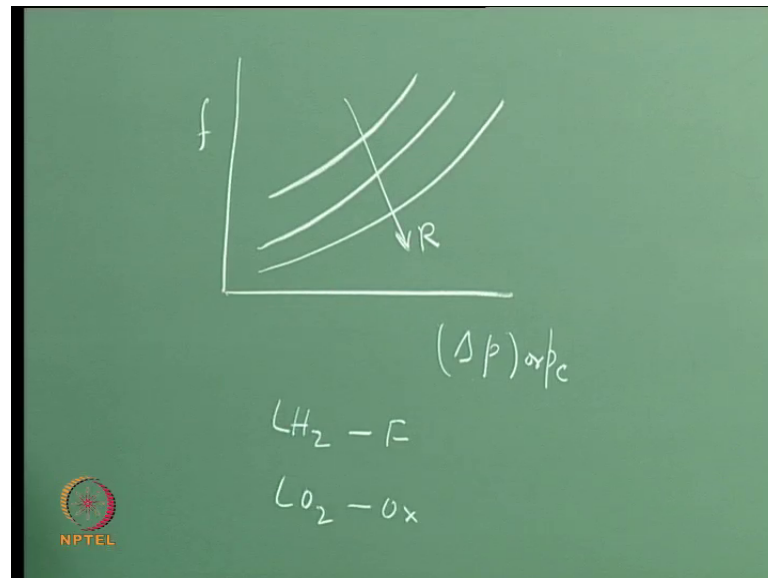
And we found in the case of a gas generator cycle, if we increase this f the $I_{sp,T}$ will decrease. In the gas generator cycle, if we plot the total specific impulse of the total engine system as a function of let us say the value of p_c , in the case of the gas generator cycle net I_{sp} will fall with pressure if the specific impulse of an engine will not increase

with chamber pressure.

The net effect of the increased fraction 'f' is such that the net specific impulse decreases.

Why should the fraction of the propellant which flows through the gas generator decrease with increase of mixture ratio?

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

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

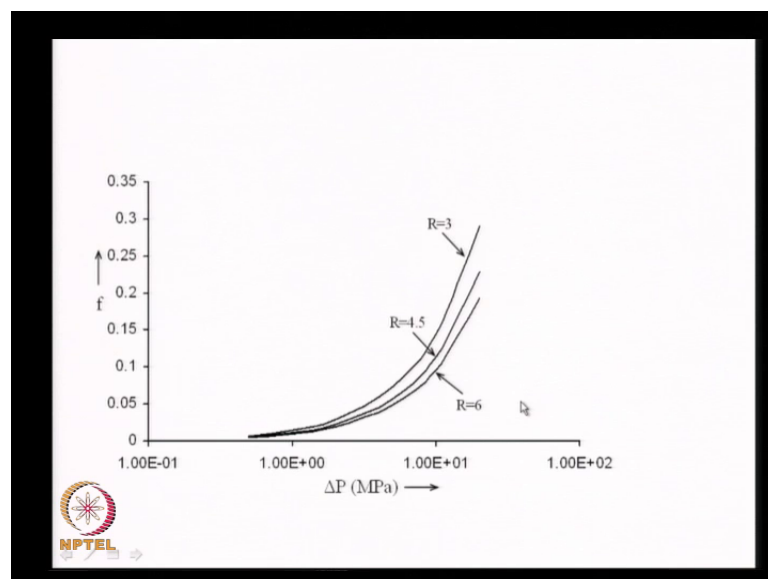
$$\frac{\dot{m}_H}{\dot{m}_{H,GG}} \left(\frac{1}{\rho_H} + \frac{R}{\rho_O} \right) \Delta p = \eta C_p T_{GG} (1 + R_{GG}) \left(1 - \frac{T_{OT}}{T_{GG}} \right)$$

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

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


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 expression, which I had written on the board earlier.

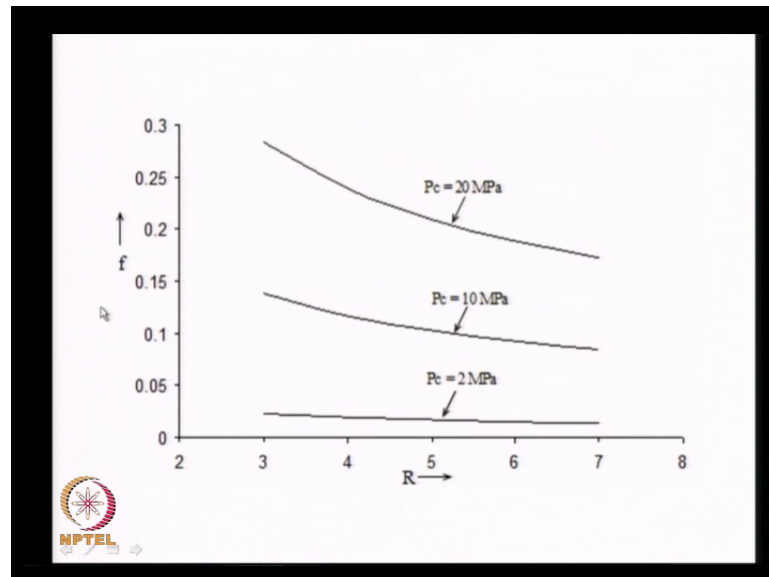
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And we said as 'f', the fraction of the propellant, which flows through the gas generator, as a function of p increases. We are considering the Δp as 0.1 MPa, 1 MPa, 10 MPa, 100 MPa and f increases. You know it is a linear with respect to Δp , but since we use a logarithmic scale the higher values of pressures get compressed as they increase on the X

axis and hence the curve. As R increases the value of ' f ' decreases.

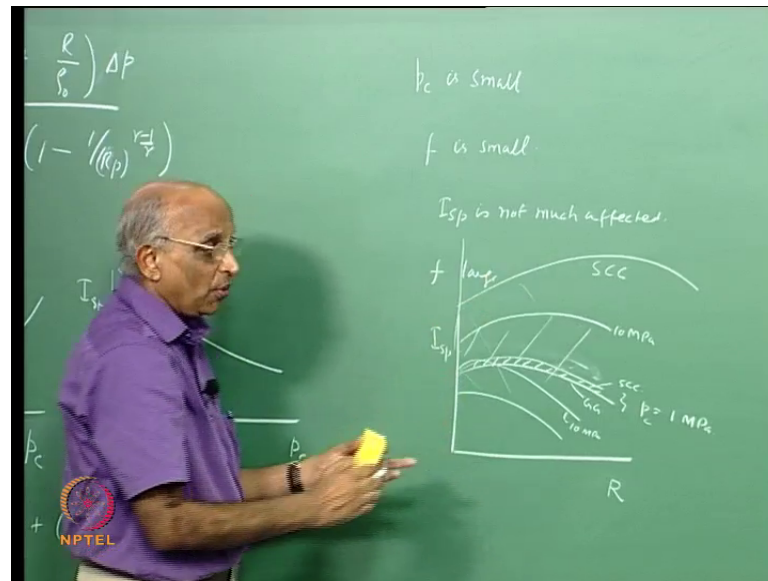
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If the chamber pressure is chosen as a parameter and we plot fraction f as a function of the overall mixture ratio, for a high chamber pressure we have a large fraction ' f '. The mixture ratio of the gas generator is assumed to be 0.6. And for η for the turbine pump system as 0.6; the temperatures of gas generator as 900 Kelvin, we find that for a high value of chamber pressure we require large flow rates through the gas generator whereas, if the chamber pressure is small we 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 we find? The value of ' f ' is negligibly small.

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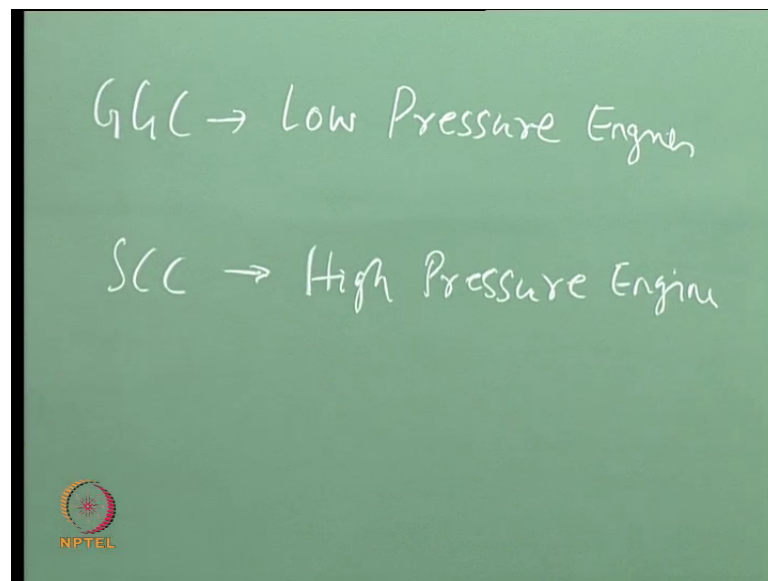


If 'f' is small you know I do not really spend so much of propellant in the gas generator and therefore, the I_{sp} is not much adversely affected. However, if the value of 'f' is going to be large, we are pumping so much fuel and oxidizer into the gas generator, that the net I_{sp} comes down. Rather if I have to make a plot now of the value of the net I_{sp} as a function of let us say the chamber pressure, I find that I_{sp} monotonically decreases with increase of pressure if the influence of pressure on specific impulse is not accounted. If I_{sp} is plotted as a function of the overall mixture ratio, we find that at low chamber pressures the I_{sp} decreases with mixture ratios. At higher pressure, we get an increase followed by a drop. This is because, though the I_{sp} is more due to the enhanced value of pressure, the large fraction of propellants used in the gas generator at the rich mixture ratio causes the I_{sp} curve to droop.

Whereas if we allow the net propellant into the main chamber like we have in a staged combustion cycle, may be in that case, we will get a small increase for the stage combustion cycle. This is value is at a chamber pressure of 1 MPa i.e., 10 bar. But if we have to operate the engine at a value of let us say 10 MPa, which is slightly higher pressure, the GG 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 increase of I_{sp} came from pressure. In fact, for the GG cycle, the performance drops off rapidly with overall mixture ratio since the mixture ratio in the main chamber becomes very much oxidizer rich. The stage combustion cycle

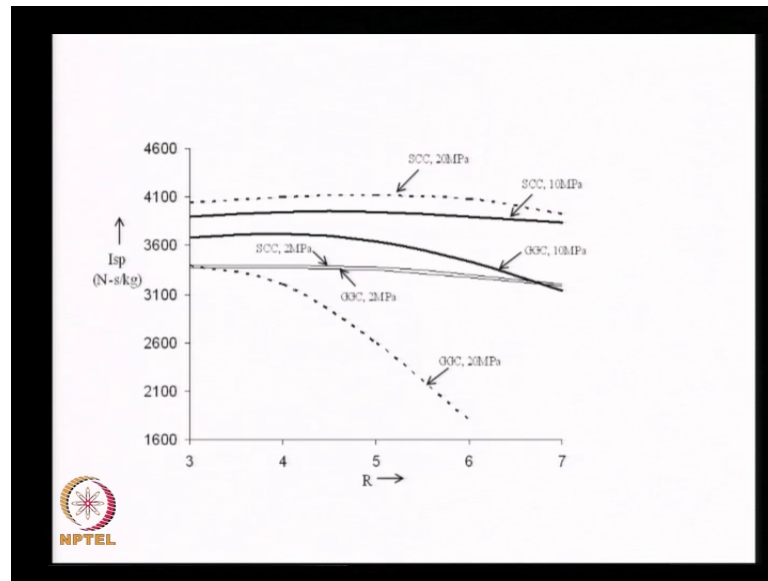
will give a high performance even at the higher mixture ratios. If we go to still higher pressures, this we are talking of 10 MPa, and if we go to something like 20 MPa or 200 bar may be the G G cycle will come down like this, because I am losing lot of lot of my impulse in the auxiliary nozzle, whereas, my stage combustion cycle will be much better. In other words at low pressures by operating a gas generator cycle we do not lose much; whereas at high pressure we keep losing more and more to the extent that the G G cycle is not competitive any more.

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

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If we operate an engine using the gas generator cycle at a small value of chamber pressure, this slide shows the net value of specific impulse that we get and if we operate the same engine on a stage combustion cycle at the same low pressure, we get a slightly better performance. This is because we have not lost very much, because f is small. I have lost something from stage combustion cycle to gas generator cycle; therefore I still find gas generator cycle is lower than stage combustion cycle, but the loss in performance or the decrease in the value of specific impulse of the gas generator cycle is small.

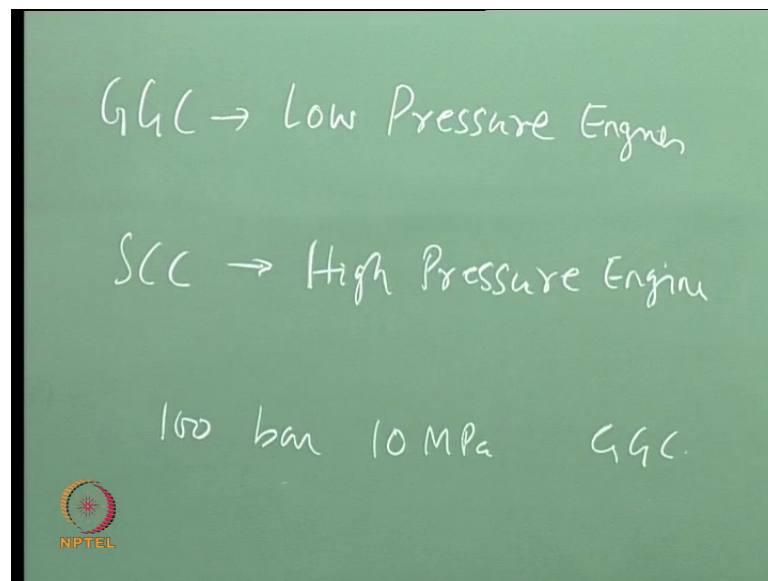
The loss is small, because f might be something like 0.01 or something of this order. If we go to higher pressure what is it we find? At higher pressure the gas generator, because the pressure is high, we get a slightly higher value of specific impulse, but at the same value the stage combustion gives me a much higher value of specific impulse. That means, by operating at something like 100 bar, I lose if I were to operate the rocket in a gas generator cycle and I will have a lower value of specific impulse whereas, if I operate it in a stage combustion 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 ' the G

G cycle has this low performance whereas, we do not lose anything in stage combustion cycle and the performance is very high in terms of specific impulse. We lose a lot by operating a liquid propellant engine in a gas generator cycle at high pressures.

If we have a low pressure engine, maybe a GG cycle is adequate while if we have a high pressure engine it is necessary to go for stage combustion cycle.

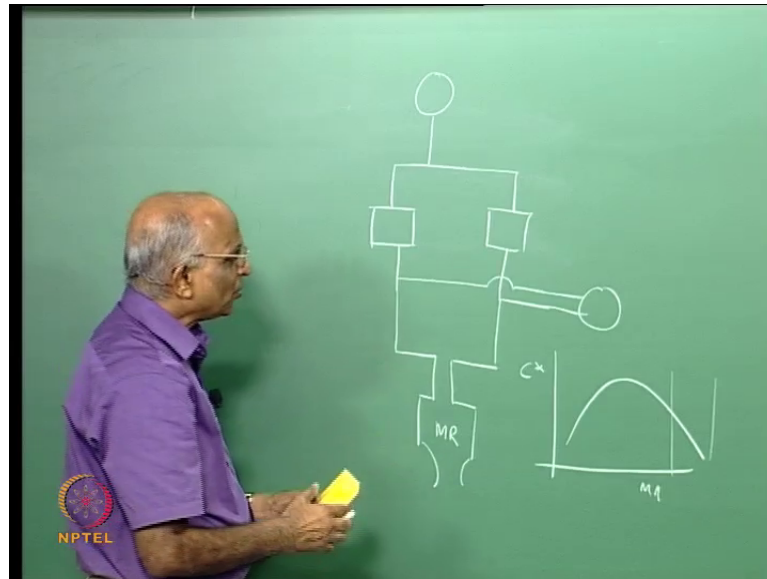
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And generally for cryo engines a chamber pressure up to about 10 MPa or 100 bar seems to be the limit for a gas generator cycle, above this to operate a gas generator cycle you will lose a lot. And this follows from a cycle analysis.

To be able to complete the cycle analysis, we must also find out why the droop or fall in I_{sp} with the overall mixture ratio happens especially for the gas generator cycle. It falls so rapidly at higher pressures. The reason is that the overall mixture ratio in the main combustion chamber becomes very oxidizer rich since the gas generator demands fuel rich mixtures.

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Like for instance we had a gas bottle; from the gas bottle, we had the tanks. What did we do? We took little bit of the oxidizer, little bit of the fuel into the gas generator, and this is mind you very fuel rich. And therefore, we are bleeding more and more of it. What happens when I bleed more and more of the fuel rich mixture, the mixture ratio of the main engine keeps increasing, because I am drawing lot of fuel into gas generator and starving the main engine of the fuel. Therefore, this becomes oxidizer rich and then again what is the dependence C star or Isp with respect to mixture ratio. It comes down after an optimum mixture ratio. And that is why the droop in the curve.

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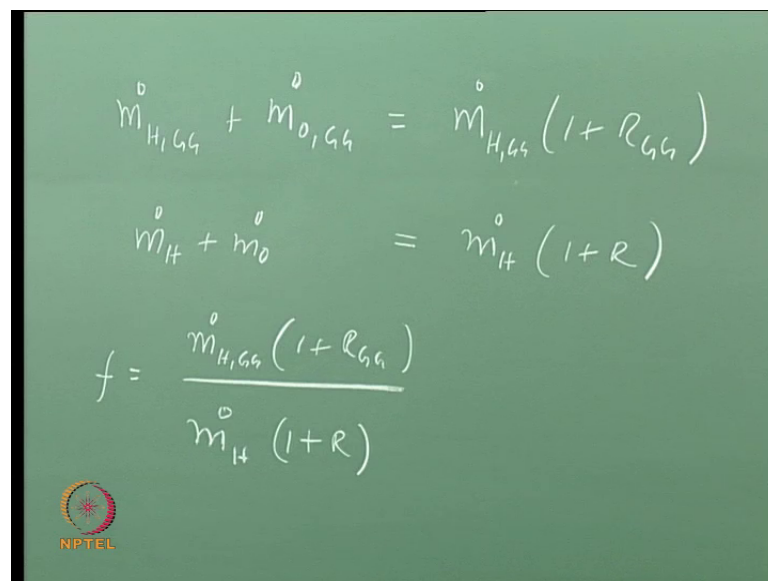
$$R_{MC} = \frac{\dot{m}_o - \dot{m}_{O,44}}{\dot{m}_H - \dot{m}_{H,44}}$$

$$= \frac{\dot{m}_o \left[1 - \frac{\dot{m}_{O,44}}{\dot{m}_o} \right]}{\dot{m}_H \left[1 - \frac{\dot{m}_{H,44}}{\dot{m}_H} \right]}$$

Therefore, let us quickly derive an expression what will be the value of the mixture ratio in the main thrust chamber for a gas generator cycle a function of R and 'f'.

The value of mixture ratio in the main chamber is required. Let us picture this gas generator cycle in our minds. We say R_{mc} , the mixture ratio in the main chamber, is equal to $\dot{m}^o_o - \dot{m}^o_o \text{ gg}$ in the gas generator which is not available in the main chamber $\div \dot{m}^o_f - \dot{m}^o_f \text{ gg}$ through the gas generator. We consider the specific case of hydrogen oxygen as propellants. And this we can now write as equal to $\dot{m}^o_o \times (1 - \dot{m}^o_o \text{ gg} / \dot{m}^o_o)$. Similarly, we express hydrogen as $\dot{m}^o_h \times (1 - \dot{m}^o_h \text{ gg through GG} / \dot{m}^o_h)$. And how do I get this value of $\dot{m}^o_o \text{ gg}$ which is going through the gas generator or $\dot{m}^o_h \text{ gg}$ which is going through the gas generator to the total oxygen and hydrogen flow. We have already done something very similar, in the last class.

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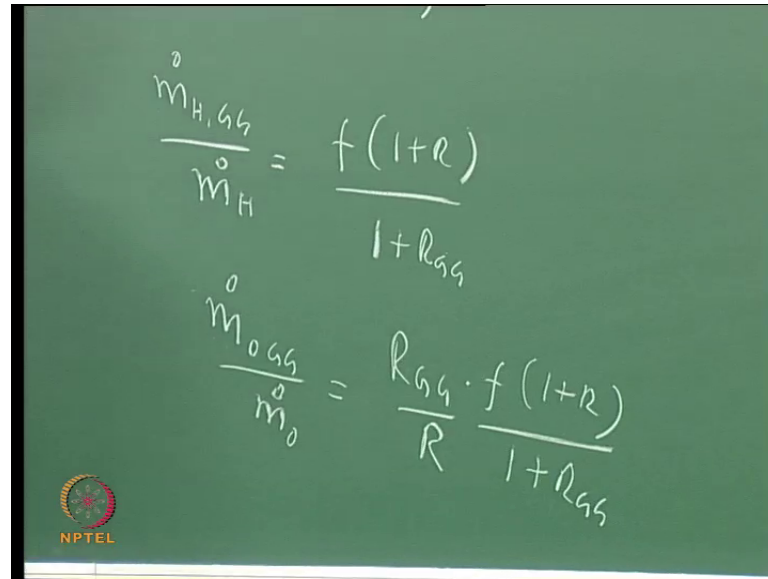
$$\dot{m}^o_{H_2, GG} + \dot{m}^o_{O_2, GG} = \dot{m}^o_{H_2, GG} (1 + R_{GG})$$

$$\dot{m}^o_H + \dot{m}^o_O = \dot{m}^o_H (1 + R)$$

$$f = \frac{\dot{m}^o_{H_2, GG} (1 + R_{GG})}{\dot{m}^o_H (1 + R)}$$

Let us take a look at $\dot{m}^o_h \text{ gg through gas generator} + \dot{m}^o_o \text{ gg through gas generator} =$ the total propellant flow in the gas generator. This is equal to \dot{m}^o_h through the gas generator $\times (1 + R_{GG})$. And similarly, we can we can write an expression for $\dot{m}^o_o + \dot{m}^o_h$, which is the total mass of propellants as equal to $\dot{m}^o_h \times (1 + R)$. And now we know what is the fraction f. Fraction $f = \dot{m}^o_h \text{ gg} \times (1 + R_{GG}) / [\dot{m}^o_h \times (1 + R)]$.

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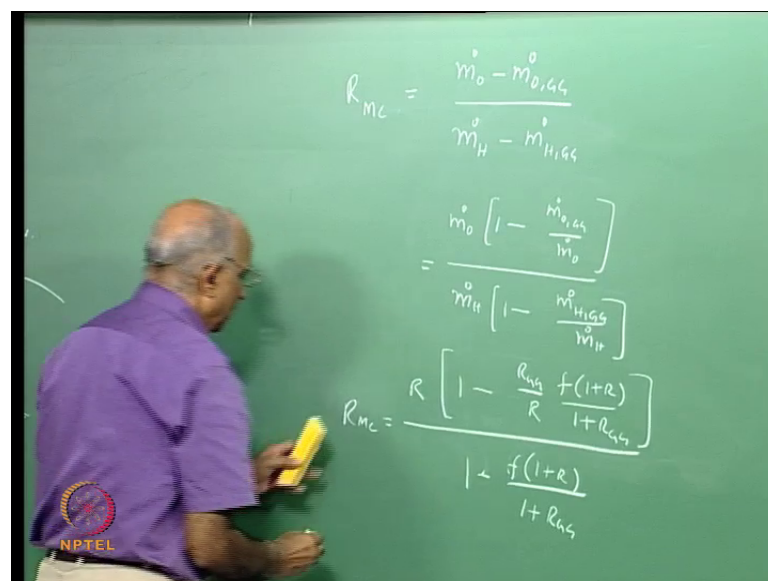


$$\frac{\dot{m}_{H,GG}^o}{\dot{m}_H^o} = \frac{f(1+R)}{1+R_{GG}}$$

$$\frac{\dot{m}_{O,GG}^o}{\dot{m}_O^o} = \frac{R_{GG} \cdot f(1+R)}{R(1+R_{GG})}$$

Or rather from this we get $\dot{m}_{H,GG}^o / \dot{m}_H^o = f \times (1 + R) / (1 + R_{GG})$. And now we can also write, if this is ok, $\dot{m}_{O,GG}^o / \dot{m}_O^o$. How do we convert $\dot{m}_{H,GG}^o$ to this $\dot{m}_{O,GG}^o$. Multiply it by R_{GG} . Therefore $\dot{m}_{O,GG}^o$ becomes equal to $\dot{m}_{H,GG}^o \times R_{GG}$. And $\dot{m}_{O,GG}^o / \dot{m}_H^o = R$ therefore, $\dot{m}_{O,GG}^o = R \times \dot{m}_{H,GG}^o$. Therefore, $\dot{m}_{O,GG}^o / \dot{m}_O^o = R_{GG} / R$ into the same value viz., $f \times (1+R) / (1+R_{GG})$. And now we substitute these values of $\dot{m}_{H,GG}^o$ by \dot{m}_H^o from the first expression, and we take $\dot{m}_{O,GG}^o / \dot{m}_O^o$ from the second expression in the expression for the mixture ratio in the main chamber.

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$$R_{mc} = \frac{\dot{m}_O^o - \dot{m}_{O,GG}^o}{\dot{m}_H^o - \dot{m}_{H,GG}^o}$$

$$= \frac{\dot{m}_O^o \left[1 - \frac{\dot{m}_{O,GG}^o}{\dot{m}_O^o} \right]}{\dot{m}_H^o \left[1 - \frac{\dot{m}_{H,GG}^o}{\dot{m}_H^o} \right]}$$

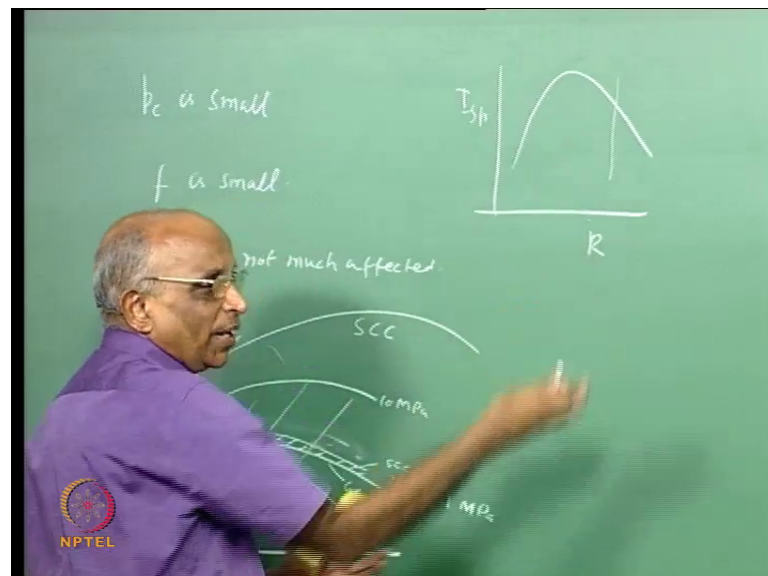
$$R_{mc} = \frac{R \left[1 - \frac{R_{GG}}{R} \frac{f(1+R)}{1+R_{GG}} \right]}{1 - \frac{f(1+R)}{1+R_{GG}}}$$

And I get the value of R for the main chamber $R_{mc} = (m^{\circ}o - m^{\circ}o_{GG}) / (m^{\circ}h - m^{\circ}h_{GG})$. This is equal to R from mass of oxidizer by fuel $\times (1 - f)$ take from the second expression, $R_{GG}/R \times f \times (1+R)/(1+R_{GG}) \div (1-f) \times (1 + R)/(1+R_{GG})$. I think we must learn to do such derivations for an analysis.

We have obtained the mixture ratio in the main engine as a function of the mixture ratio in the gas generator and the value of ' f '. And for combination of parameters like R_{GG} is being about 0.6 and for different values of R , we can plot R_{MC} as a function of f . We find as ' f ' increases the value of the mixture ratio in the main chamber keeps increasing and as the value of R increases.

If the value when f is equal to 0, the mixture ratio in the main chamber is same as the overall mixture ratio. This is the condition for the staged combustion cycle, and the expander cycle engine, wherein 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, we regain the solution. 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 cannot operate the engine.

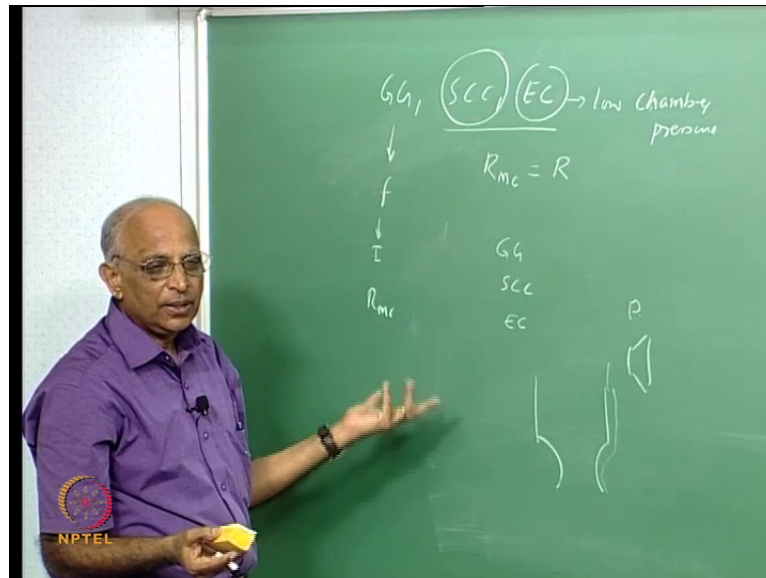
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In other words what we just now told was R versus the specific impulse or C^* goes like this. We start operating at these low values and that is why the specific impulse or equivalently C^* or the total performance keeps falling. This is how we compare the

different feed system cycles such as the gas generator cycle, the stage combustion cycle, the expander cycle, etc. We will quickly sum up by telling the following: for pump feed systems, we could operate the liquid propellant rocket as a gas generator feed system, as a stage combustion cycle or as an expander cycle or some other cycle

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We found that the stage combustion cycle is something like a topping cycle; we find the GG cycle suffers at high chamber pressures, because the value of the fraction of the propellant is used to drive the turbine is not properly utilized. And what is driven out is at a low value of expansion through an auxiliary nozzle; whereas, in the topping cycle the mixture ratio of the main chamber is same as the overall mixture ratio. In the case of the GG cycle, the mixture ratio in the main engine and the overall mixture ratio are related through f and R_{GG} .

For high pressure of operation, the staged combustion cycle is particularly useful because we gain the advantages of high pressure, but we will have to take a look at the design of pumps after two or three classes. I think this is all about the gas generator and the stage combustion cycle and the expander cycle. We cannot operate the expander cycle at high values of pressure, because we use only a vapor that is generated by heating with the chamber, but this also has some powerful implications. Maybe we will take a look at some examples on why we cannot operate the expander cycle at high pressure.

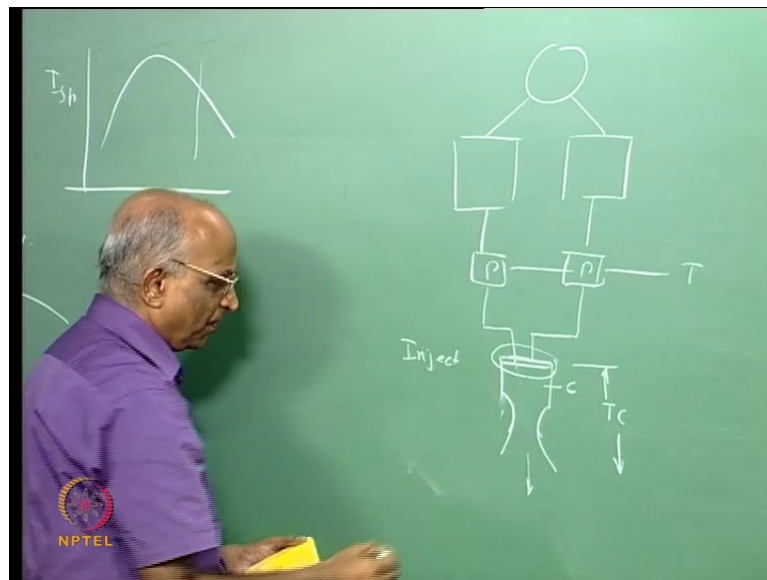
In an expander cycle, we are using a chamber which runs hot. We have limited amount

of heat transfer possible in a chamber. And therefore, we cannot have very high power and since I cannot have very high power. The expander cycle operates at low chamber pressures.

But, its performance will be very much higher than the gas generator cycle, because we 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.

Let us go to the next element of our discussion namely the thrust chamber.

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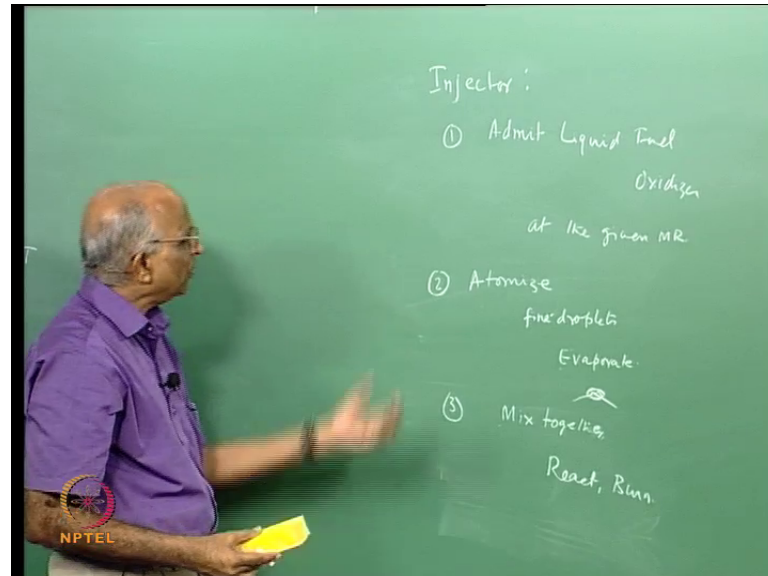


We need a gas bottle and we could find out how much mass of gas is required. We said well propellants are stored in tanks, then we said we need something like a pump for fuel, we need a pump for oxidizer, which is driven by the turbine and we still have to cover this part on pumps. We come to the chamber wherein fuel and oxidizer are injected into the chamber. That means, we have a fuel to be injected into the chamber, similarly the oxidizer. We need to know how combustion takes place in a chamber and of course, we have considered the nozzle expansion earlier.

We would like to concentrate on this thrust chamber in this class and may be first half of the next class. What does the thrust chamber consist of? It consists of a device to inject the liquid into it into it. May be the liquid must evaporate get mixed together and burn and the products of combustion must get expanded. Therefore, let us consider the first

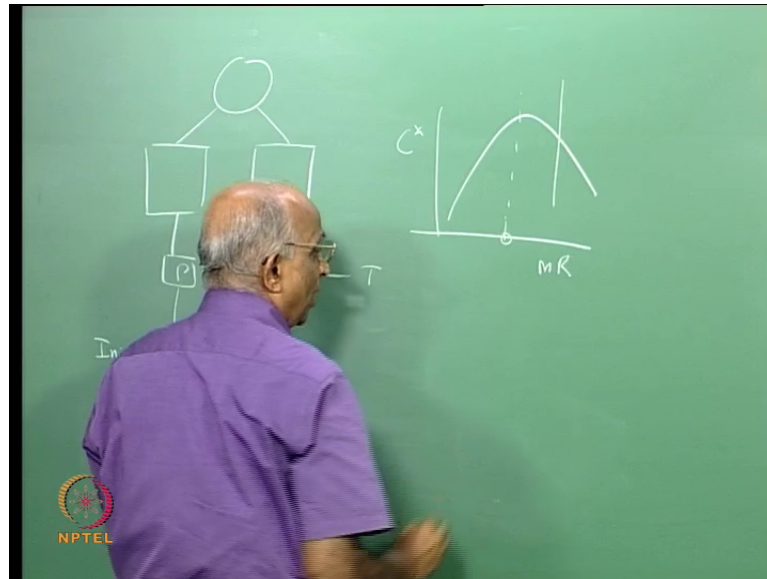
part namely the injection device. How do you inject the high pressure fuel into the chamber?

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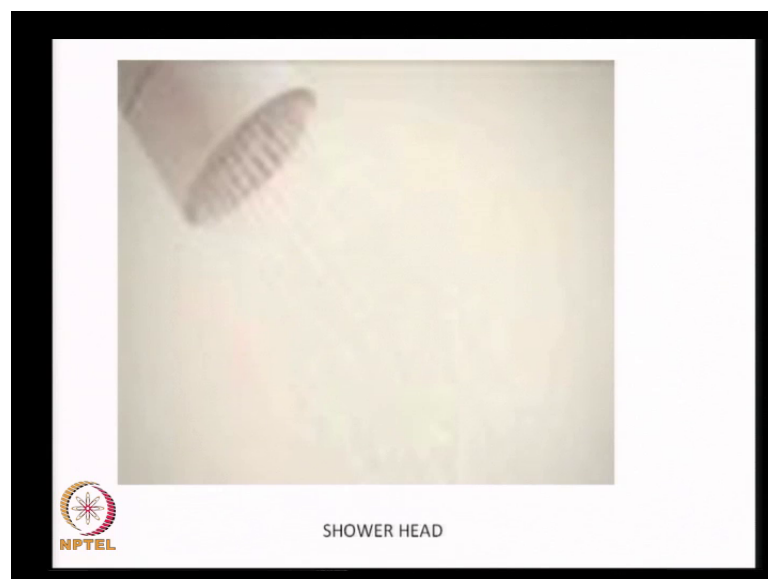
The injector admits the requisite quantities of liquid fuel and liquid oxidizer at the given mixture ratio into the chamber. That means, it must have some way of control of the mixture ratio. It must the required quantity of propellants into the chamber. Not only does it does it admit the liquid fluid at the given mixture ratio, it must also sort of increase the surface area of the liquid or it must atomize the liquids. 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 must the injector assist in vaporization, but the third point is it must help the evaporated vapor of fuel and oxidizer to mix together. It must ensure that it will push the fuel and oxidizer in some way such that the vapor of both will mix together. Once mixed, the fuel and oxidizer can chemically react and burn. In some cases you need an igniter to start the burning, but once started the hot environment can always promote the chemical reactions and the burning. Therefore, the requirement of an injector is it must admit suitable quantities to give the correct mixture ratio and mix the vapors.

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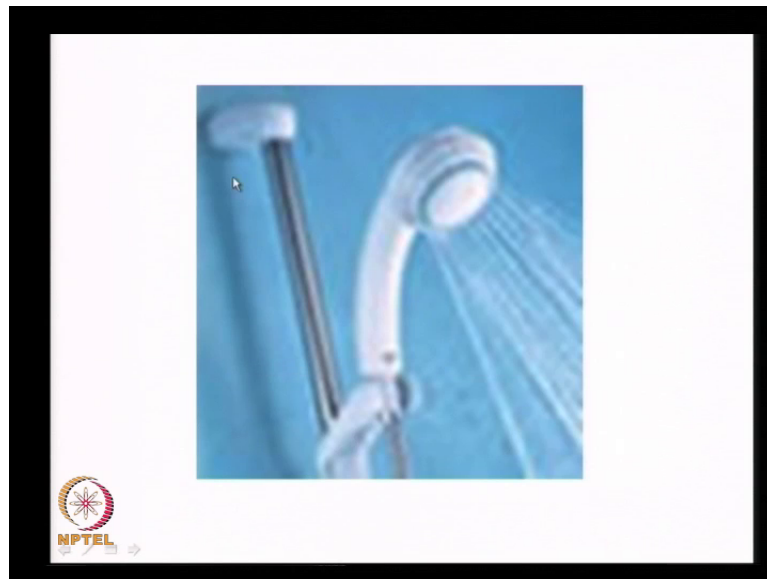
And we are interested in a given mixture ratio. Let us not forget this graph of C^* or I_{sp} as a function of mixture ratio. It is in the fuel rich region that we get a much higher specific impulse. Therefore, we are interested in this value of mixture ratio. The injector must also admit the required amount of fuel oxidizer and fuel such that we get the thrust as desired, get this mixture ratio and 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 are familiar and let us let us build up on it.

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In the figure, I show a shower head. We use it daily for bathing..

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Let us take a look at the streams of water generated. The streams get broken into drops later on.

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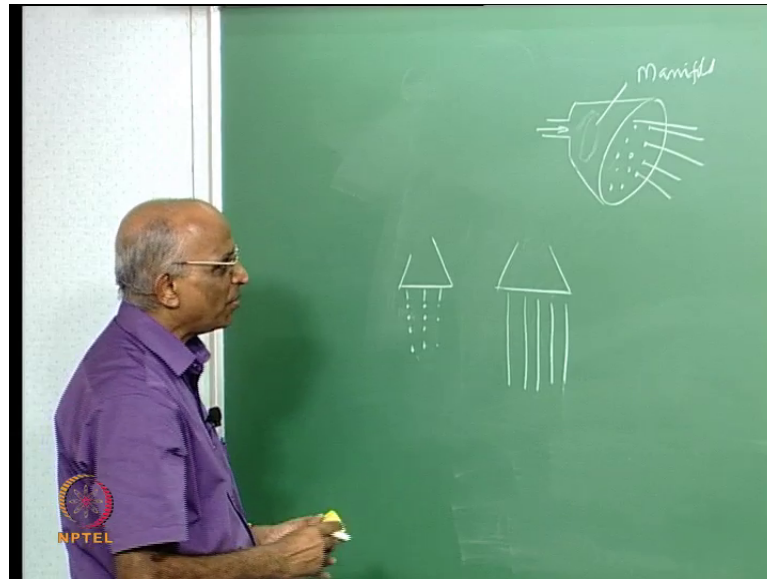


We have something like a head and a number of holes or orifices. I brought a shower head and take a look at it.

You know this is something like what we use in our shower you know you have the

water coming from the water line, water collects in this region known as manifold and then you have a series of holes or orifices. And this is what we called as a manifold in which water collects. The pressure in the manifold is higher than the ambient pressure and water is forced through these orifices. Let me just sketch this shower head on the board. It tends to be very illustrative of the different types of injectors, which we use.

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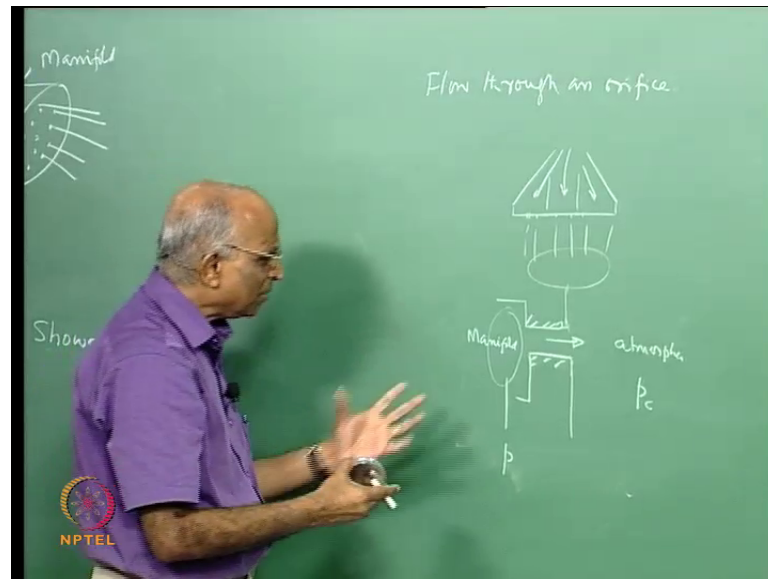


I have a surface with a number of fine holes. This is what was said to be a head, which has lot of orifices. You have something like a place through which the liquid is admitted. And we have spacing between these two holes or streams. And this is where we admit the water and this is what we called as a manifold. What does the manifold do? It admits and maintains the pressure over here such that water squirts out through these holes here. And you know that very often you find if your shower head is not properly designed and you are taking a bath let us say, you do not get the streams of water hitting you. If your shower head is very well designed you find the jets of water come like this as laminar streams.

If it is not very well designed, you find some drop drops of water coming like this, may be at the same value of velocity. We would like to have 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 is known as a shower head injector. Let us again go through a shower head injector. We have manifold in which the water collects and forces through

the orifices.

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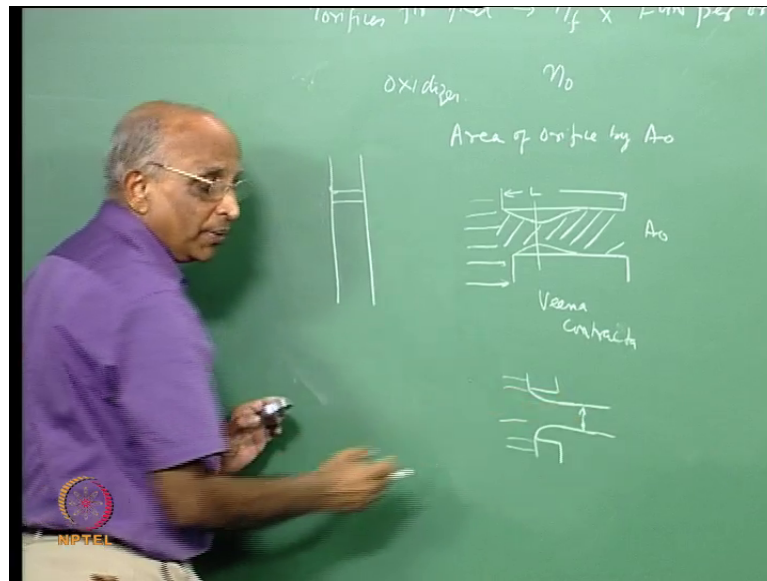
Therefore, we are looking for something like flow through an orifice or a hole. The shower head consists of a lot of these holes through which water may be pushed through when we are taking a bath. And a similar scheme can be used in case of liquid propellants. You have the manifold here. We have the set of orifices here. We could divide the manifold into partitions and admit the fuel in some region and admit the oxidizer in the other portions. We allow them to mix in this region and evaporate and burn. This becomes the shower head injector. Now, we would like to find out about the flow through the orifices?

We show one such hole or orifice, this is the manifold here and we have a lot of such holes. This is the manifold; since its volume is large, the liquid as such collects in this manifold here. That is in the region in the chamber preceding the orifices therefore, the pressure in the chamber is the supply pressure to the hole or orifice. The velocity is almost zero here considering the larger volume. And the water squirts out through these particular holes.

Therefore, we have the manifold; in the manifold the pressure is p and the velocity is almost zero. And in the case of rockets, the liquid gets supplied into the chamber wherein the pressure corresponds to the chamber pressure from these orifices. We have the chamber pressure downstream of the orifice and the supply pressure ahead of it in the

manifold. We are interested in finding out the flow through the orifices.

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If we have let us say n_f orifices for fuel and I have n_o orifices for oxidizer, we want to find the flow rate through the orifices and the mixture ratio. We would like to find out the flow per orifice and multiply by the number of orifices to determine the net flow rates.

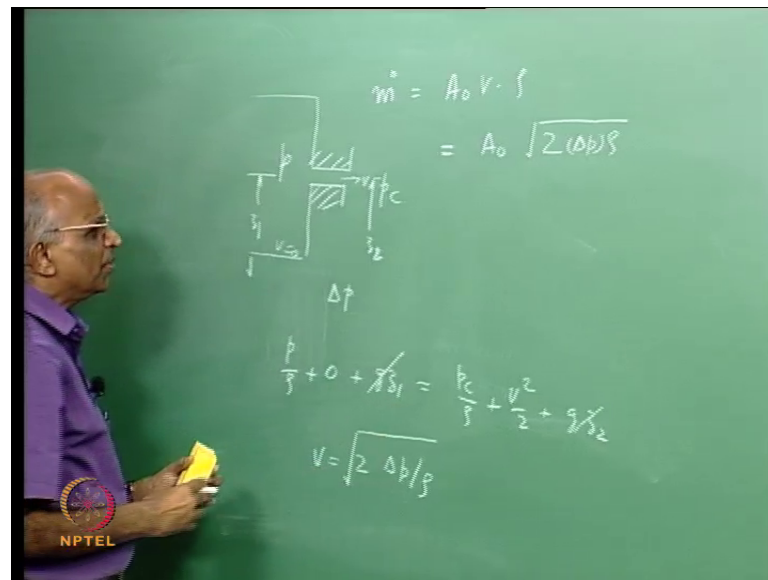
How do we find the flow through the orifices. We look at this scheme again. We find that there is lot of science even in a small orifice flow, which we need to understand. We have an orifice whose edges are sharp. We call it as a sharp edged orifice. How do we make an orifice for the particular shower head? Each of the holes is drilled on a plate.

If we drill a hole and remove the burs at the edges, we get the sharp-edged orifice. When the fluid enters the sharp edge from the manifold wherein the velocity is almost zero, it accelerates and sort of contracts; The liquid separates from the walls of the orifice, contracts to a minimum and then reattaches later to the walls. The minimum contracted area is called as vena 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 a very thin plate instead of having a given length of the orifice. The separated flow leaves the orifice.

The flow is coming from the manifold contracts and goes straight out. That means, the flow does not reattach back to the wall of the orifice. In fact, the flow is separated and

the effective area of flow is going to be much lower than the area of the orifice. If we denote the area of orifice by A_0 , the area of flow is going to be much lower. How do we write out the expression for the mass flow through the orifice. Let us try to derive a simple expression.

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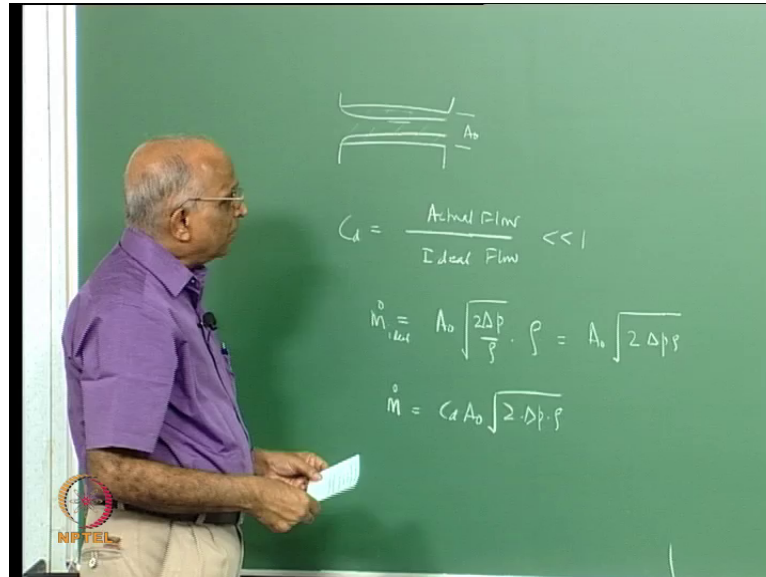
You would have done this in your fluid mechanics class; but let us just do it again. We have a manifold and we are considering the case of a single orifice. The pressure in the manifold is higher than the chamber pressure. The difference in pressure is equal to Δp . We want to write an equation for the velocity here at the exit of the orifice when the entrance velocity at the manifold is zero. We denote the exit velocity by V . We use the Bernoulli equation; the flow is liquid at small values of velocities therefore it is incompressible and its density ρ is a constant. Therefore, we have $p/\rho + V_1^2/2 + gz_1$, where z_1 is height above datum at the entry to the orifice. $V_1 = 0$. The value of pressure at the exit is p_c and the expression becomes $p_c/\rho + V^2/2 + gz_2$ where z_2 is the height above datum over here. Since the orifice is small in length, we can take gz_1 is equal to gz_2 , because there is not much change between z_1 and z_2 . And therefore, we immediately get the square of the velocity of the stream leaving the orifice equal to $\sqrt{2 \Delta p/\rho}$. That is V is $\sqrt{2(p-p_c)/\rho}$.

The mass flow rate is equal to the above velocity multiplied by the area of the orifice into density. If the orifice cross sectional area is A_0 , and we get the mass flow rate as A_0

$\times \sqrt{2} \Delta p \times \rho$. This is the mass flow rate for a simple sharp edge orifice.

But we just saw that the orifice sometimes flows full like it is attached over here, there is some friction over here and sometimes it flows separated from the walls of the orifice.

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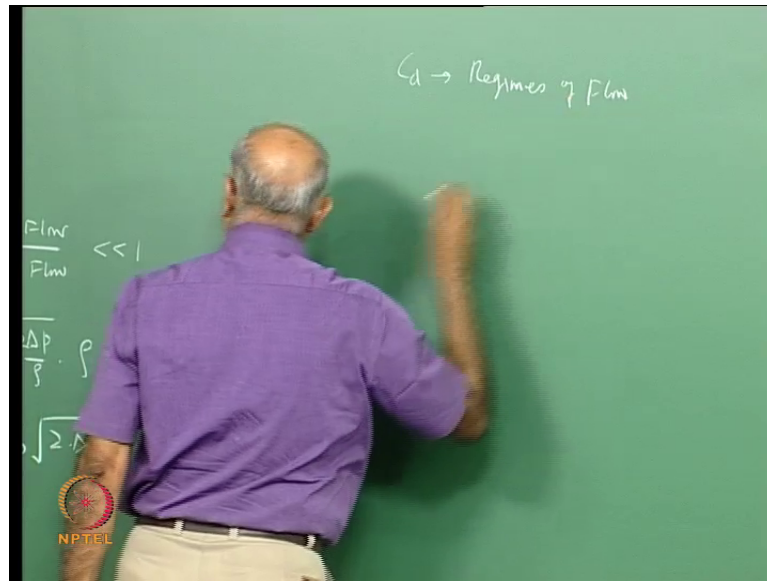


Therefore, there are different regimes of flow. Depending on the type of flow through the orifice, whether attached in which case it runs full or whether it is detached in which case it does not run full, the cross sectional area of the flow will change. We find that based on the orifice area, which is A_0 , we can define a coefficient namely a discharge coefficient as equal to flow based on the ideal flow or ideal mass flow what we could have and the actual flow. We 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 Δp . In practice we have friction at the wall, sometimes the flow is separated and the flow may not be totally axial. The actual flow will be less than ideal flow and therefore, we have a discharge coefficient C_d which will always be less than one.

To be able to arrive at this value of discharge coefficient we write in terms of mass flow rate m° in the ideal case. What is the value of the ideal mass flow rate? We have flow runs full through the area A_0 , the velocity of flow depends on the pressure drop namely $\sqrt{2} \Delta p / \rho$. And therefore, we get the ideal flow rate as equal to $A_0 \times \sqrt{2} \Delta p \times \rho$. In practice since you do get separated flow and we have frictional effects you do not know

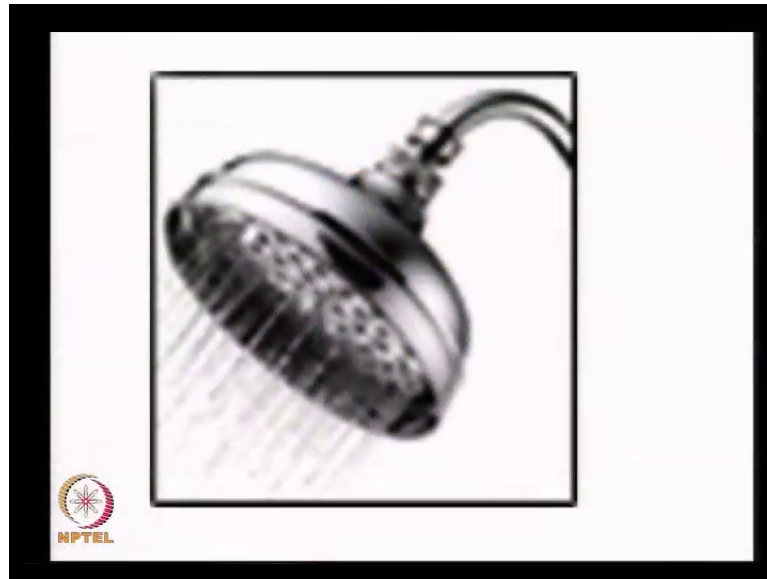
what this area of this separated flow, you base your total flow on the total area A_0 . The actual flow would therefore be equal to $m^o = C_d \times A_0 \times \sqrt{2 \Delta p \times \rho}$. The flow is incompressible and therefore the density is constant. This is the value of the flow, which takes place, is given by this particular expression. Let us again recall that A_0 is the area of the orifice through which flow is taking place, C_d is the discharge coefficient, ρ is the density of the liquid, and Δp is the pressure drop across the particular orifice or hole.

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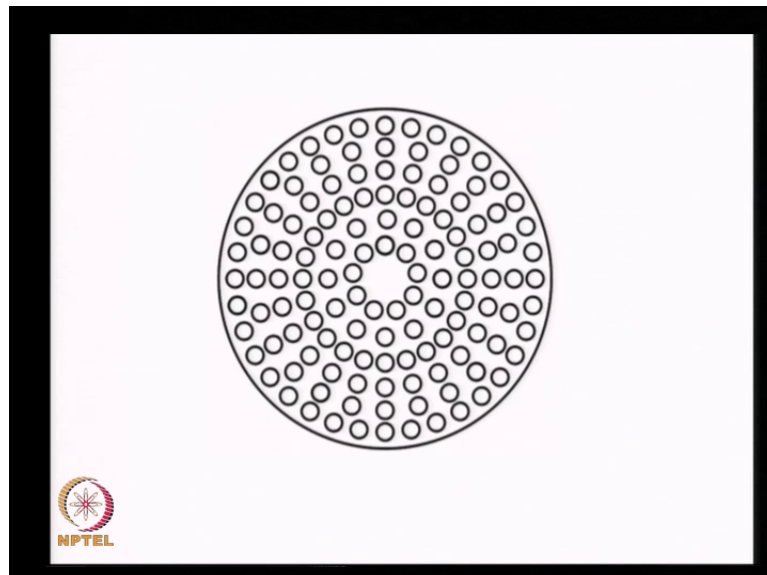
It must be remembered that the value of the discharge coefficient C_d depends on the regimes of flow through the orifice. What do we mean by regimes of flow? The flow sometimes runs full such as it happens when the orifice is large, sometimes with cavitation it gets separated or when the orifice is very very thin, the flow cannot reattach. And for the different conditions we would like to examine the value of C_d .

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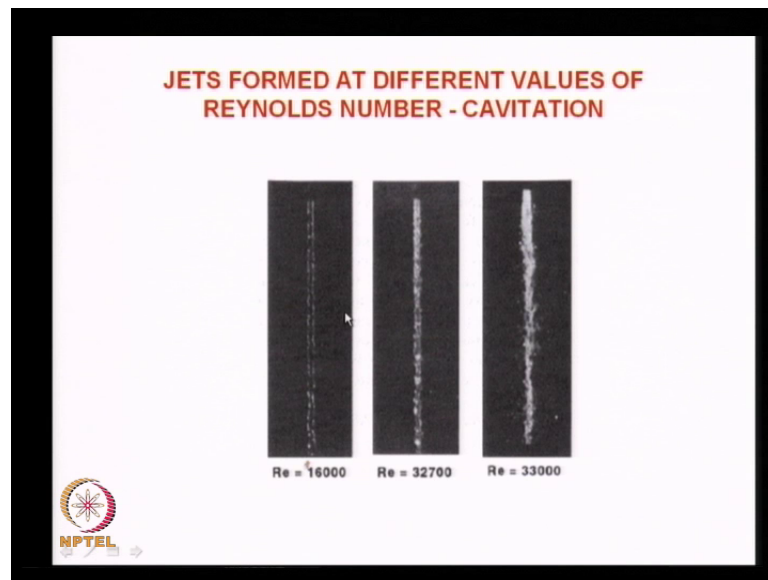


We should not spend too much time on it, because we are shifting the topic from liquid propellant rockets to once particular element of it. This shows your injector head or shower head wherein you have lot of these small holes through which flow is taking place.

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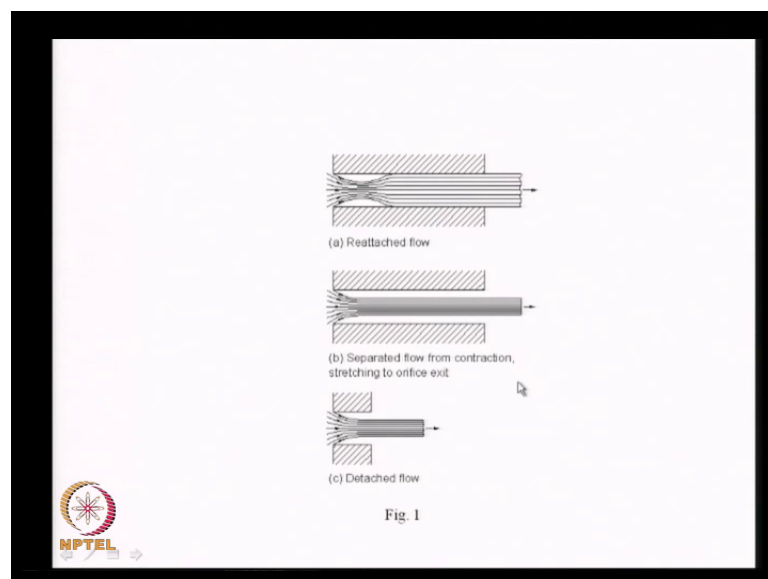


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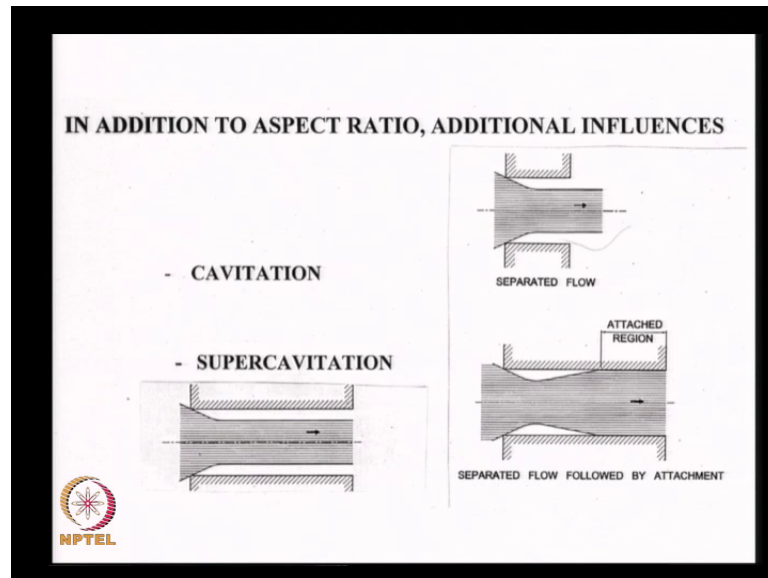
If we do experiments and allow flow at different values of Reynolds number, we have as flow rate increases, an increase of the Reynolds number. We see in the figure the jet issuing from an orifice at Reynolds number of about 16,000, 32,000 and 33,000. You find that at smaller values of Reynolds number the texture of the jet is quite smooth; like you stand under a shower you can see silvery water coming down. At some Reynolds number it tends to become a little turbulent and rough. At yet higher values of Reynolds number it becomes violently rough. Let us examine the flow further.

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When we have a long orifice the veena contracta is followed by the flow subsequently attaching to the orifice walls. Sometimes even for the same length the flow goes straight through; it does not attach. Whereas for a small length the separation is understandable, because if we were to cut the orifice much before it attached, well there is no way of reattachment. What could be the reason for flow not attaching for the longer orifices?

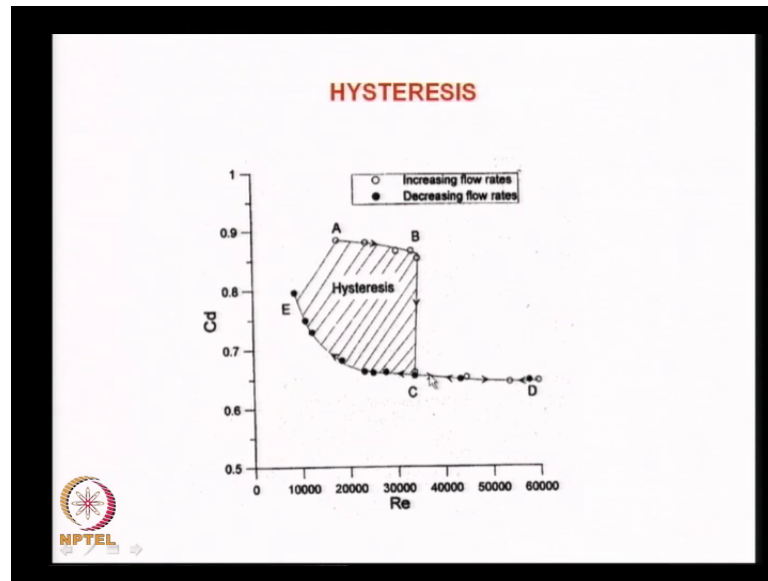
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When flow is taking place at high velocities, and we further enhance the velocity by increase of the pressure drop, the static pressure of the liquid in the orifice decreases. If the pressure decreases to a value equal to or less than the vapor pressure of the liquid itself then cavities begin to form in the liquid. Once cavities begin to form in the liquid, a reattachment like this is not possible and the flow separates out even for the longer orifices. Such type of flow is known as cavitated flow, and some books call it as super cavitation. Though the flow should have reattached, the pressure here has gone to a low level wherein the pressure of the liquid is equal to or less than the vapor pressure of the liquid and vapor gets generated and the flow separates.

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

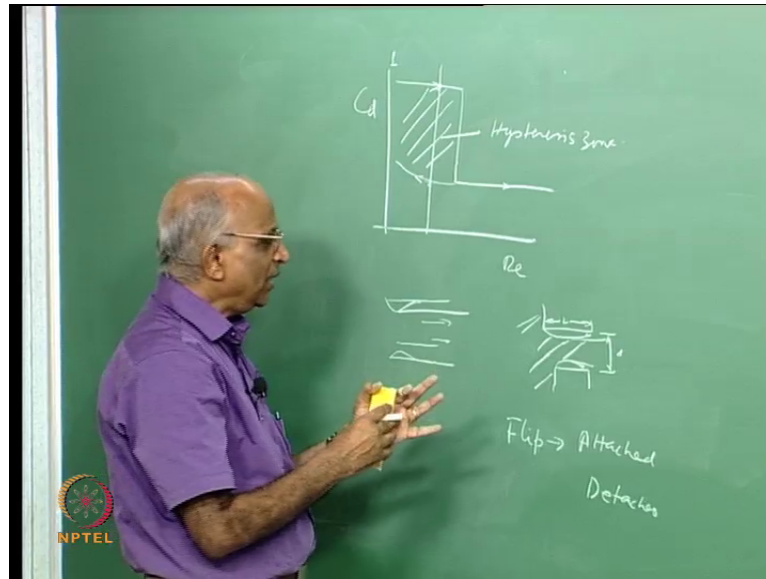
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And if we do an experiment starting at low value of Reynolds number wherein we get an attached flow, we get a high value of discharge coefficient since the flow is the attached and the whole flow area is contributing to the flow. Thereafter the discharge coefficient decreases as the Reynolds number increases because of the frictional losses and losses due to turbulence. At some value of Reynolds number cavitation starts and the flow separates to give a smaller discharge coefficient. The small discharge coefficient persists at still larger Reynolds numbers.

And now if we start reducing the pressure or reducing the velocity from the high Reynolds numbers, the discharge coefficient does not increase in the same way it decreased with increased Reynolds numbers. The flow retains the memory of the separated flow and continues to be separated and abruptly jumps back to give high values of discharge coefficients. That means, even a sharp edged orifice which makes the shower head injector can give a multitude of discharge coefficients.

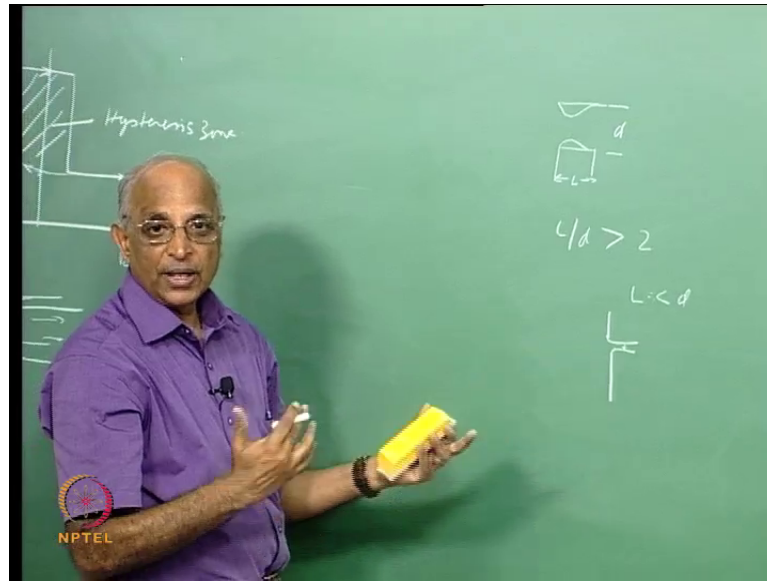
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When we start the experiment and measure the C_d as the function of Reynolds number we initially get attached flow for which C_d is near to 1. This is because the flow comes and gets attached and the fully attached flow gives discharge coefficients with losses due to friction drop and turbulence. But when cavitation starts, the flow separates. The flow separates giving low C_d when in the forward direction of increasing Reynolds number. When we reduce the pressure the discharge coefficient does not trace back the original values and we have a zone for which we get two values of discharge coefficients. This zone is known as the hysteresis zone.

If we have the length of the orifice to the diameter of some value wherein it is just near the attachment, the jet issuing from it would have certain characteristics. At the threshold value the flow attaches and reattaches with the result that there is a flip in the jet and change in the discharge coefficient. The flip is between attached region and detached regions of flow.

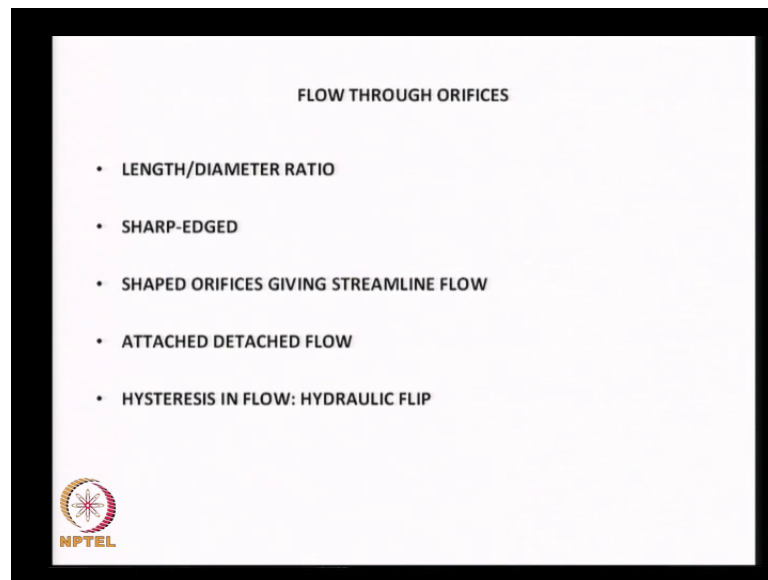
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Therefore, even to choose a shower head we need to understand the mechanics of flow. Normally the shower heads are such that the length of your orifice is greater than the diameter so as to get the attached flow. The orifice length L to the diameter of the orifice D is known as aspect ratio of the orifice and is about 2.

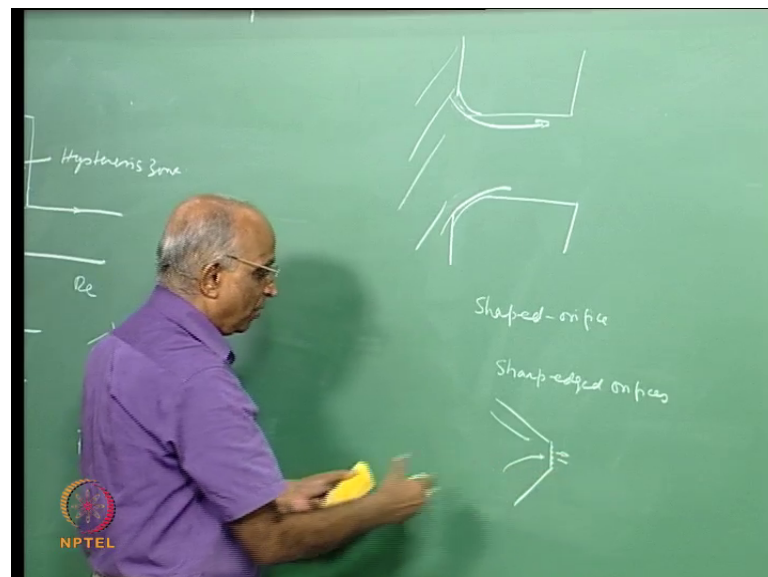
For control purposes whenever you want a controlled flow experiment we use a very thin orifice with razor type of blade in which the length is a very small number compared to the diameter. And the flow in this case is always detached. Therefore, you must choose whether you want detached flow or attached flow and accordingly choose the dimensions. 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 normally choose sharp edged orifices. If you go to the market and you want to buy a shower head for bathing, why not choose a shaped orifice which provided streamline flow? This could provide attached flow without any flow separation compared to the sharp edged orifices.

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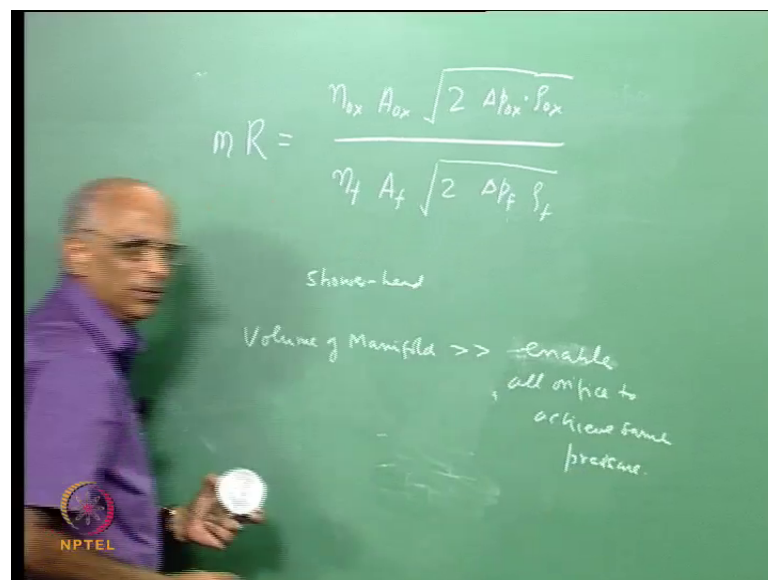


Let say an orifice at the exit of the manifold could be shaped for a smooth entry. Why not make such orifice which provides smooth streamline along the flow. This will give full flow. But to fabricate such orifices is difficult especially in large numbers. We could

have an orifice which is like this; however, the next one would be different and to obtain reproducibility in something like a shaped orifice is more difficult. And we are going to have 40 holes in a rocket we may have 80 holes or 100 holes or 200 holes. To get so many shaped holes drilled with shaped orifices is difficult and therefore, we normally use sharp edged orifices.

We have a manifold in which we fuel and oxidizer. We have a series of orifices through which oxidizer flows and fuel flows, and that is how we make a shower head injector. We would like to calculate the mixture ratio formed by the injector.

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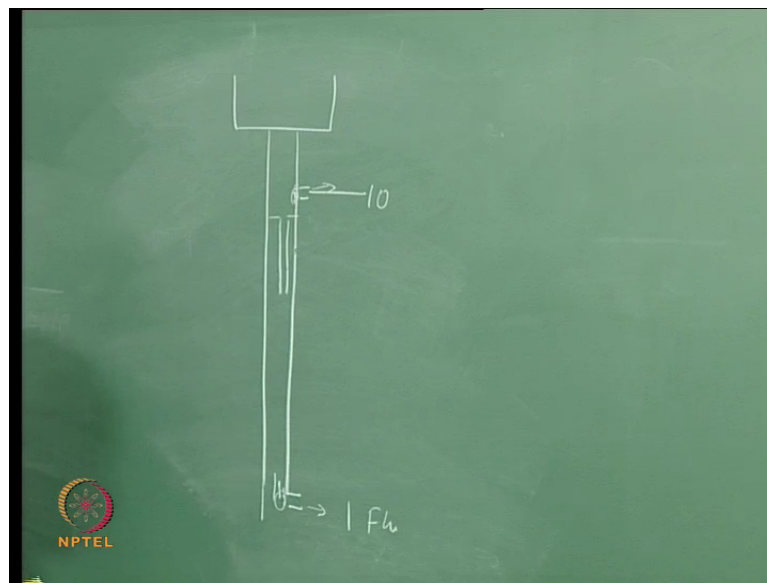
The mixture ratio R is equal to the mass flow rate of oxidizer to the mass flow rate of fuel. Therefore the value of R is equal to C_d for the orifice \times the number of oxidizer orifices \times the area of each oxidizer orifice $\times \sqrt{2 \times \Delta p \times \rho_{ox}} \div C_d$ of the fuel orifice \times number of fuel orifices \times area of the each fuel orifice $\times \sqrt{2 \times \Delta p \times \rho_f}$. If we have a shower head which has common Δp and C_d for both the fuel and oxidizer orifices, the terms cancel out. This is how we obtain the mixture ratio.

This is all about the simple way of injecting fuel in a rocket chamber using what we call as a shower head. This shower head teaches us one more lesson. We had said that this is the manifold and this is the orifice. We have a particular manifold volume. What should be this volume in a liquid propellant rocket. Should it be large or small? From fluid mechanical considerations if the volume of manifold is large then we will have the same

pressure for all the holes over here. If we 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 we should have a volume of manifold which is let us say large in order to get all orifices achieve same inlet pressure and form similar jets. Let us take an example.

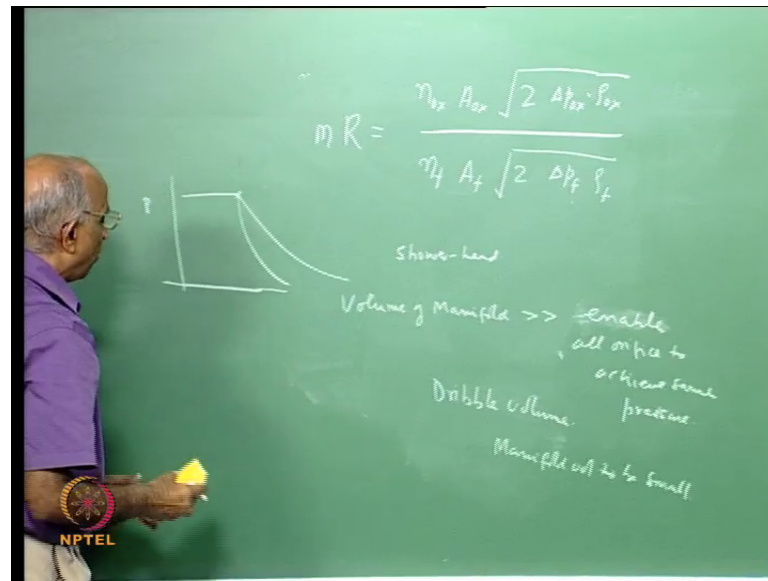
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Supposing we have a multi-story building and we want to supply water from the top which is on the 10th floor. And we want to supply water uniformly to all the floors i.e. to all the apartments. If we put a common manifold tube or a tube for supplying water, a person on the 1st floor will get water at high pressure while a person on the top floor will hardly get water. How do we ensure uniform supply and this is the same problem for the different orifices in the injector. How to configure the manifold? The flow resistance for the lower floors has to be increased by reducing the diameter of the pipe conveying water to the lower floors.

Or else we could introduce resistance by placing filters or gauges. We place a filter with larger holes on the top floors. At the bottom floors we place finer filter such that we introduce some pressure drop such that the supply pressure is same. And so also in rocket injectors whenever we have a manifold we cannot have a large manifold for the simple reason that lot of propellant collects before it can be injected.

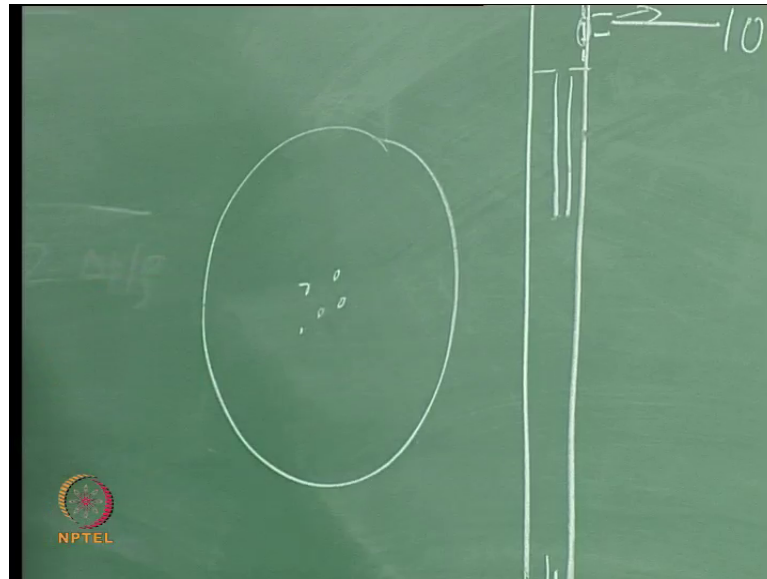
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And when we stop the flow of the propellant into the chamber, the huge quantity of propellant will continue to dribble. What is going to happen? We have the thrust or we have the chamber pressure and when the propellant flow is terminated the dribbling of propellants will continue to burn for a long time. And you would have seen this when you close the valve of the shower and the water continues to dribble. This is because of the large dribble volume or the volume of your manifold is high.

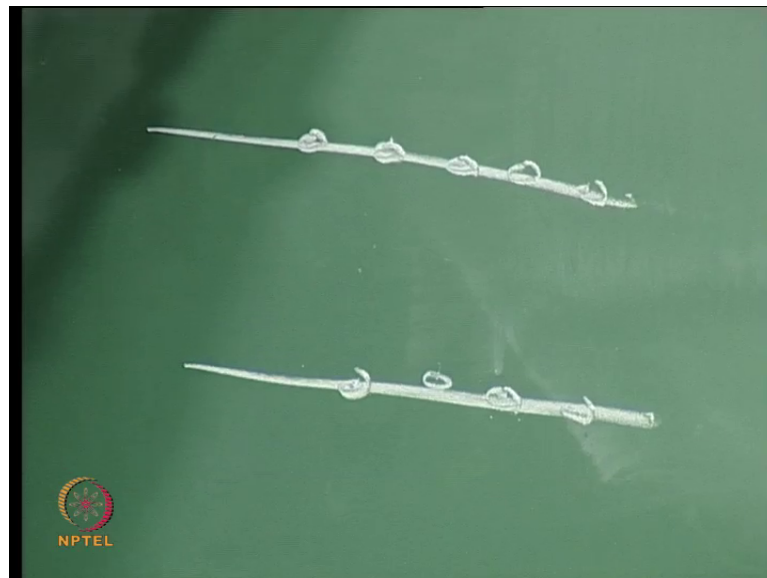
Whereas, if we have a very small manifold then immediately the thrust terminates because there is nothing left to burn. Even though we would like to have a large volume of the manifold such that we can supply to all the orifices at constant pressure, from considerations of dribble volume it becomes essential to keep the manifold volume to be small. But if we have to keep the manifold volume small, then how do we ensure uniform flow in all the orifices?

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We place something like a sieve over the holes near the inlet and decrease the pressure at the inlet to the orifices and in regions away on the periphery we communicate the pressure without any obstruction. These are some common methods used 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 the jets formed are all parallel. It takes some definite time for it to atomize and form droplets, but you want droplets as early as possible. Mixing of the fuel and oxidizer is also difficult.

And though some of the earlier designs in rockets liquid propellant rockets use shower head injectors, at the present point in time we never use the shower head injector.

What is it that we do to improve it? Instead of jets being parallel we make them interact with each other. That means we have impinging jets. And once you impinge jets we form something like a fan. We will look at the different injection devices in the next class and also look at some of the problems which we face in the combustion chamber.

In today's class, 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. A staged 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. We will build up on this and look at the other injectors, which are used in liquid propellant rockets in the next class.