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Aerospace Propulsion

Liquid Rocket-Pump Fed System

Lecture 36

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In the last class we had looked at pressure effect system let us look at turbo comfort systems in this class before we go there just to refresh the required volume.

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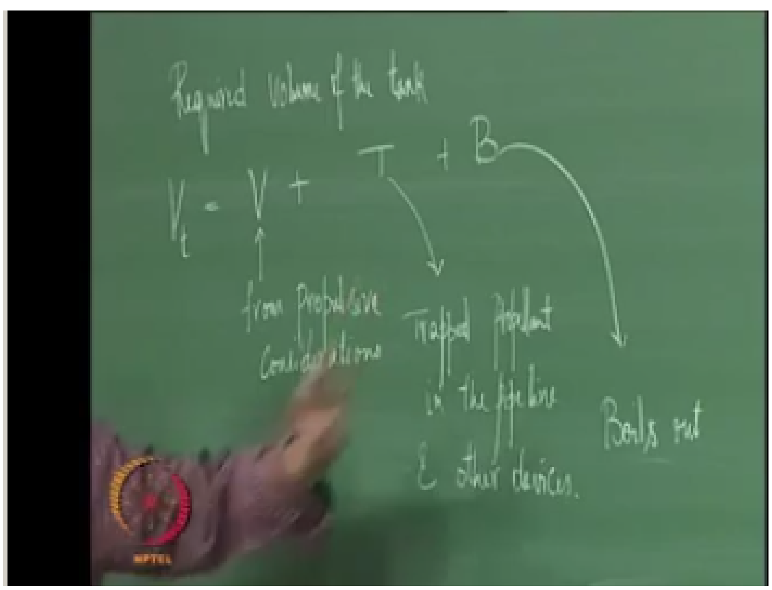

Required volume of the tank this will have to include of the volume calculated from propulsive considerations that is if you are looking at what is the mass flow rate from thrust calculate knowing is P calculate mass flow rate and then knowing density of the propellants and the burn time you can calculate volume right and in addition to this there will be some trap propellant in the pipeline.

And also in devices even in the tank you will not be able to expel out all the propellant there will be a small fraction of it that will be left unexpected so this is that then a certain portion of the propellant boils out that is depending on whether it is a cryogenic this fraction will be a lot larger fraction because the ambient temperature is much higher than the propellant temperature.

So this boiling will be higher in a cryogenic propellant and lastly there is something called eulogy alma okay now if you fill the time to the brim there is a problem if there is boiling then the pressure tends to buildup very rapidly and the tank may not be designed for a high pressure if you are particularly if you are looking at a comfort system right because Pomfret system most of the pressurized is given by the pump.

So the tank might be able to withstand only a few bar pressure so if you fill the entire tank with liquid then the pressure as it boils the liquid boils will build up and therefore that might create a problem so you give it a small extra space so that the pressure end can also act right so this is known as you love all um-- this is typically something like 2.5 percent of okay.

That is volume arrived from propulsive considerations plus trap propellant two-point-five percent of that this is some kind of a thumb rule that people use to calculate voters should be the village volume okay so this will give us the overall tank volume okay now in the earlier case when we were talking of pressure effect systems what we used to do was we used to have a gas bottle.

And we are try to size the gas bottle right here what we need to also calculate is what is the pressure that is required at the end of the or after pumping at the end of the pump what should be the pressure required one as we know volume flow rate the other one is pressure required is to be calculated.

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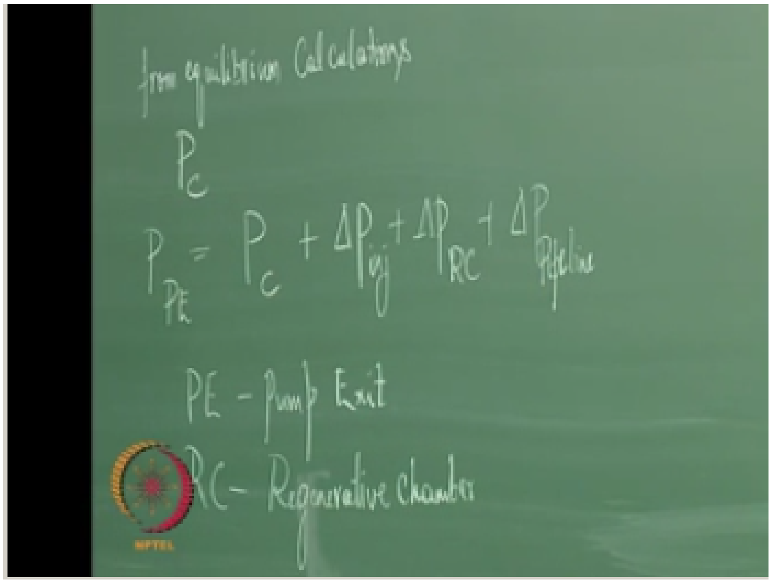

Now from equilibrium calculations we will know what is the chamber pressure PC right so if we know the chamber pressure then how do we go about calculating the pressure at the pump exit okay PE indicates pump exit so this pressure at the pump exit will be the chamber pressure right plus the pressure drop in the injector fine and then there is pressure drop in the re circulating chamber right it is a coolant jacket with very fine tubes.

So there is a large pressure drop in this in this coolant jacket so there will be a pressure drop RC is recirculation thing or regenerative chamber then in addition to this there is other pipeline through which there can be pressure loss so there is a Δ p.

Okay so if we know all this then we can calculate what is the pressure required at the pump exit now this we will be able to calculate from equilibrium considerations what about this Δ P across the injector we will know the mass flow rate right mass flow rate through the injector that is to be given so how do we calculate this ΔP across the injector.

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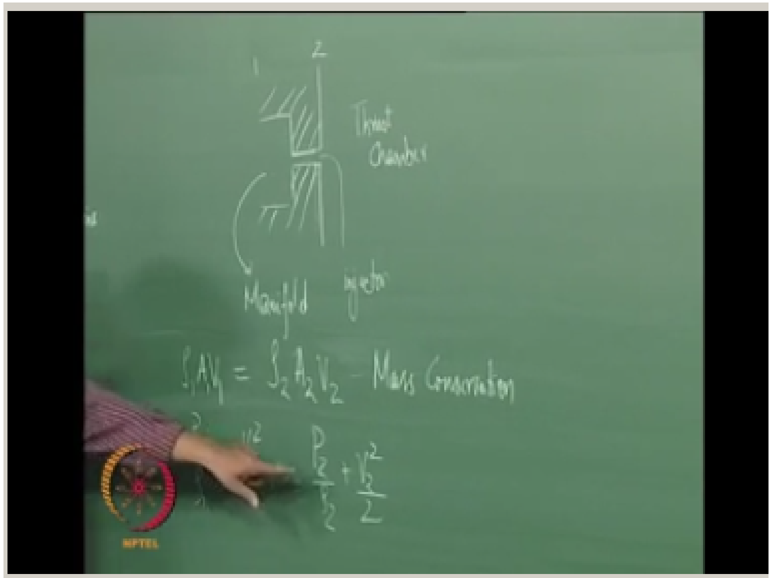

So if you look closely at the injector will be something like this, this is injector and this is the manifold and here is the thrust chamber or combustion chamber right so there is a manifold that is upstream of the injector now it is so designed that this area is very, very small compared to the manifold area and if that happens what can we say about the velocity of the liquids remember firstly most of the fluids that we are dealing with our incompressible liquids in this case.

So if you are having incompressible liquids then what are the things that you need to consider equations of mass conservation and momentum conservation momentum conservation in this case because density is constant you can use Bernoulli's equation right so let me call this as one this point s to so ρ1 a 1 V 1 = √2 a2 v2 right this is mass conservation then momentum conservation is p 1 / ρ1 right.

So now if you look at this term the square of the velocity in comparison to square of the velocity here what can we say about it because we made the areas in such a way that this is very small compared to this so I can neglect this in comparison to this okay so we will get for pressure drop across the injector you need to calculate the mass flow rate you need to calculate the mass flow rate so you need the velocity v2.

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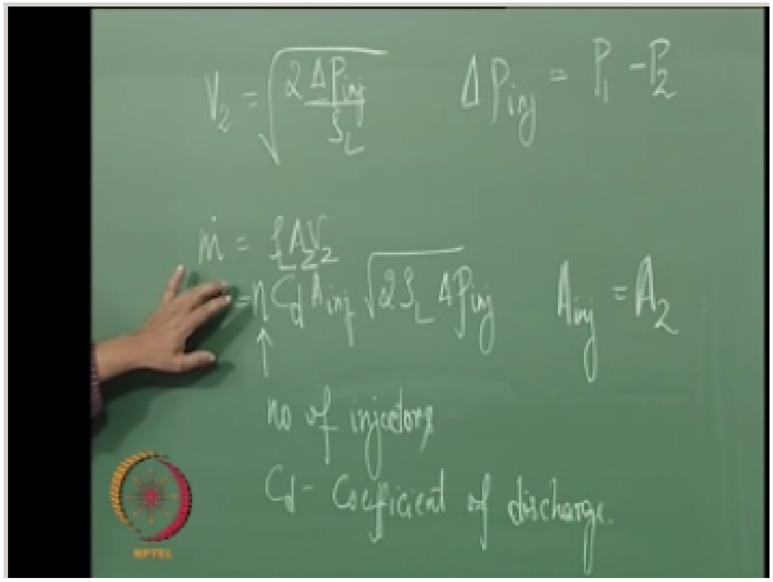

So v2 would be ρ p injector √ b =p1- p2 fine so ρ is the same anyway it is a incompressible liquid so therefore this Row 1 and Row two do not change so you will get that equation now we know the velocity we need to calculate the mass flow rate so mass flow rate is given by m dot is equal to ρ AV right in this case a row 2 a2 v2fine but what can you say about this, this is if the actual area is this one only.

But because the very narrow construction through which you are forcing the liquid to go through it and because of boundary layer effects the actual area will be smaller than this so therefore you need to consider a coefficient of discharge so you will have CD into a injector okay now if I take the row inside there is one row already right under the square root so you will get under root right this is for mass flow through one injector right in a rocket motor they are going to be a number of injectors.

So you need to multiply it by n this is nothing but number of injectors and CD is coefficient of discharge make also call this as ρ L okay so we know now in if you look at this equation if we know what is the mass flow rate that should go through the injector we can back calculate what should be the Δ P across the injector okay.

So then coming back to this equation we know this we know this right now how do we calculate this part Δ P across the injector sorry regenerative chamber if you remember we were doing we are dealt with how to calculate the heat transfer coefficients and other things right there if you know the mass flow rate and again mass flow rate you will know so you can use a similar relationship to calculate.

The pressure drop across the injector anyway the density is going to be the same a areas might change right but you can calculate what is the pressure drop across the injector right oh sorry regenerative chamber fine so this part is we can do and similarly ΔP across pipeline is again you will know the diameters so you can calculate what is the ΔP in the pipeline fine so overall you will get what is the pressure at the exit of the pump that you will be needing.

So we know the mass flow rate of the propellants we know the pressure at which they need to be delivered so what can we calculate if we know these two things we can calculate the pump power required right and then based on efficiencies we can again calculate what is the turbine power that needs to be given to it okay yes if you are using liquid hydrogen it will be mostly a gas.

So these things will have to take into account compressibility effects okay you will have to take compressible fluids into consideration and rework these numbers right these are for liquids if you have liquid hydrogen that is the only case wherein it will become a gas probably so you need to rework this for a gas.

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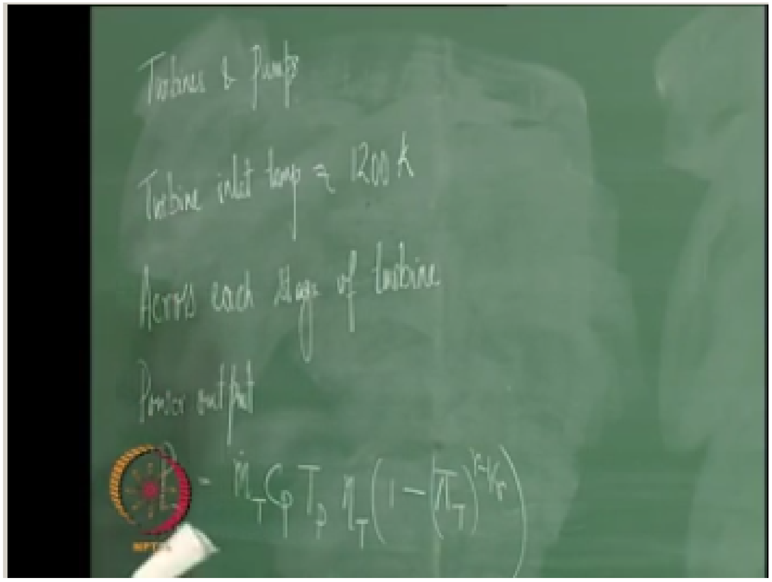

Now we know what is the exit pressure at the end of something that is required right we have just calculated that then what are the other things that we need to calculate turbine power required the inlet temperature to the turbine is a very critical parameter right turbine you must have studied this in the jet engines or gas turbine engines that that Inlet temperature cannot be very high and usually in this case.

It is also restricted to something like 1200 is approximately around 1,200 Kelvin okay you might argue it little differently here if you remember gas turbine engines need to run a long duration they are long haul engines right but the turbine that is used here is probably going to be used for a few minutes not in terms of ours right but then therefore you can argue this way that probably you can go in for an increase in the turbine.

In let temperature but in that case you do not want to do something wherein you jeopardize the mission right although it is for a very short time and for a single use if you remember gas turbine engines they have to have number of hours of operation without overhaul and they will be used multiple types which is what makes the design.

And the construction of a gas turbine engine much more challenging than rocket engines rocket engines is always going to be one time used so therefore it is a lot easier to do this than the other one right so even with this we are restricting the turbine Inlet temperature to something like 1200 km okay and you can have a number of stages of turbine right so across each stage we can calculate the power output this is by energy consideration.

So PT the pump power can be written as CP where this is efficiency TP is nothing but turbine Inlet temperature which is why I said we need to know this if we have to calculate the, the power that can be extracted from the turbine this is nothing but turbine Inlet temperature empty is the mass flow rate through the turbine.

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And this π t here is nothing but pressure ratio across the turbine stage okay this is what is the power we can extract from the turbine okay now this must be equal to the pump power right so how do we calculate pump power so you will have something like pump turbine power balance so PT must be also equal to what is the power that is required to run the two pumps remember if you have a bye propellant system we will have two pumps 14 pl14 oxidizer so ETA mechanical into m dot F yes this is the mass flow rate of fuel.

This is the mass flow rate of oxidizer and the equations that we derived here Δ P across the injector right this has to be Δ P for oxidizer Delta P for fuel so it is not that Δ P I am sorry I will this is nothing but this Δ p f is nothing but p at pump exit minus p in fuel tank okay what is the pump exit pressure that we want minus what was the pressure that was there in the tank will give this ΔP Δ P by density.

This will give the head rise right and similarly for oxidizer you have let me put a fuel subscript here and an oxidizer subscript here simply because the exit pressure of fuel and oxidizer need not be the same especially if you are only going to take one fluid through the regenerative chambers right you are only going to use one of the fluids for regenerative cooling that one will have to have a higher pumping seat pressure.

So these two are not the same okay and this ETA pump fuel is efficiency of the pump and this is the efficiency of the oxidizer okay so by using this we can now calculate we will know what is the mass flow rate of the feel that we need what is the pressure rise that we will need in the pump so we can calculate this part power that is required by the pump and if you equate it to the power delivered by the turbine right.

Then you can calculate what is the mass flow rate through the turbine that you will need this will be known to you turbine Inlet temperature because that is a constraint and what is the pressure ratio across the turbine will also be known so you will be able to calculate what is the mass flow rate through the turbine that will be needed fine now there are various designs that are possible for arranging this pumps and sometimes you can do away with out the turbine also we look at a few of these designs that are listed here.

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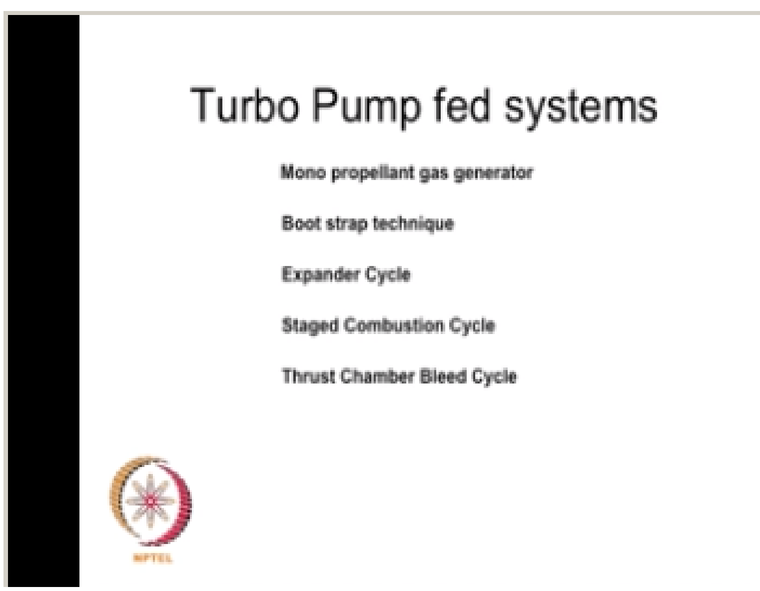

There are there is something called as monopropellant gas generator boot strap technique and then you have an expander cycle stage combustion cycle and thrust chamber bleed cycle let us look at the individual designs a little more in detail.

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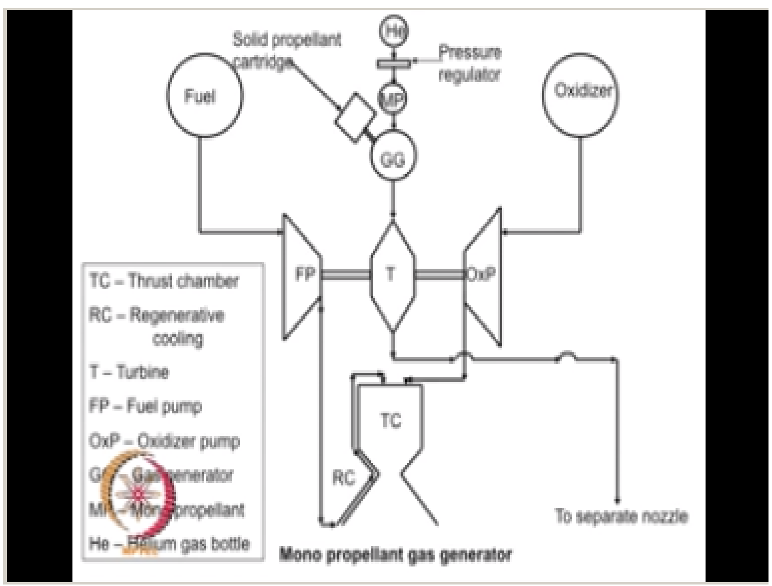

This is the schematic of monopropellant gas generator now if you look at this you have you have a fuel tank and an oxidizer tank which feeds into the pump and the pump exit of the fuel is given to the regenerative cooling chamber which moves up the region rate of cooling chamber and then enters the thrust chamber ok now the oxidizer the liquid flows into the oxidizer pump gets pressurized okay.

And the high-pressure ox oxidizer will flow into the thrust chamber the turbine is run entirely by amino propellant system okay that is you use another liquid monopropellant to run this that is you either use a hydrazine or hydrogen peroxide which needs to be again pressurized with a helium gas bottle and then you will have a pressure regulator than the mono propellant tank.

And then you will have what is known as the gas generator of the combustion chamber for the turbine right the temperature at the end of GG will have to be something like thousand two hundred Kelvin right you can also have a solid propellant cartridge to initially start up this system so the monopropellant system drives the turbine which then runs the fuel and oxidizer pump.

And the exhaust of the turbine is fed to a separate nozzle now if you remember controlling the rocket motor that we discussed earlier in the course there we talked about ways in which we can control the orientation of the rocket motor one of them was through a separate nozzle so this is the separate nozzle you will have and it will be a very small trust so you can use this to control the rocket motor.

This is about a mono propellant gas generator in this case if you notice the gas generator is not coupled with either the fuel or the oxidizer so it is an independent system so you can control it a lot better but on the flip side it will have excess weight and you will need to carry one more fluid on board right.

So this has greater control but it also means that it is going to be a lot more heavier then see that is used to start up the system probably monopropellant systems can start on their own but if you are looking at any other design okay you need some initial gas generation to drive the pump right if you do not have any fluid going through the turbine then it will be very difficult to start them so you have this so that the turbines are started in the other system also it is given as a redundant feature okay.

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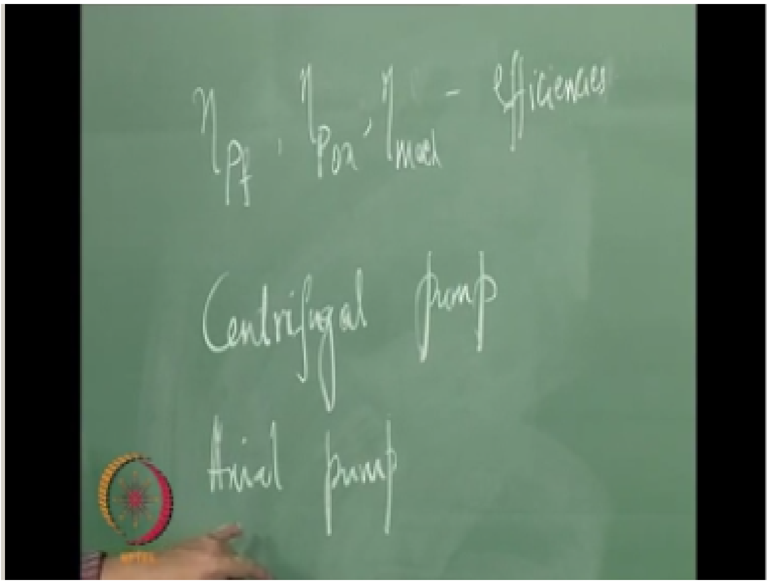

So the next technique that is used is something known as bootstrap technique as opposed to the mono propellant system here you will use a part of the fuel and oxidizer okay to drive this gas generator so you have fuel coming in through the fuel tank and the fuel pump and the region rate of cooling jacket and it will not directly go into the first chamber okay it will go to the gas generator.

All the fuel will go into the gas generator apart of the oxidizer will also go to the gas generator remember if you use this fuel and oxidizer compose combination and if you use something around let us say you are using liquid oxygen and liquid hydrogen and if you use somewhere around oh by f of six in the chamber you are going to get something like 3300 color right but you do not want that in the gas generator.

Because the turbine Inlet temperature we want to restrict it to somewhere around 1200 and not more than that so therefore what you do is you only use a part of the oxygen okay part of the oxidizer is used the rest of it goes directly into the thrust chamber only a part of the oxidizer is used so that it becomes a fuel rich system okay and then that drives the turbine.

And the exhaust of the turbine is given to a separate nozzle you also have a small solid propellant cartridge to start this system this is about bootstrap passes technique this is used in was used in Space Shuttle main engine and also in the cryogenic upper stage of ISRO the GSLV a cryogenic apostate engine this is expander cycle now expander cycle you can use only if you have a LOX a hydrogen engine primarily.

Because if you look at hydrogen, hydrogen if you pass it through the regenerative cooling jacket the temperatures at the end of the cooling after it passes through the cooling jacket will be so high that hydrogen will not be liquid anymore and it will be a gas at high pressure so if you have a low thrust engine right then you can use this and expand it through the turbine right and then feed it back into the thrust chamber.

So it is just expansion of this heated hydrogen right only with hydrogen this can work the expansion of this heated hydrogen is used to pass through the turbine and this will give you the required power to run the two pumps okay mind you this is only for a low thrust system that it is possible for high thrust systems you will also need to use fuel and oxidizer composition because if you look at this system.

And if you look at the equations here this is very low TP is very low you are trying to make it up with a larger flow rate of hydrogen okay this will be the entire flow rate of hydrogen but still there is a limitation on how much of power you can get okay the next cycle is the stage combustion cycle in this case you have fuel coming through the pump and the regenerative cooling.

And all of it goes through to the gas generator right and part of the oxidizer comes here and the other part goes through to the gas generator right after combustion here the products of combustion are directly fed to the thrust chamber so this is this can give you very high turbine power so therefore this is typically used in very high thrust and long duration engines okay.

So this is bootstrap technique or this will have a separate nozzle stage combustion is one then lastly you have something known as thrust chamber bleed here you take a part of the exhaust from the thrust chamber itself and as it goes through the pipeline from the thrust chamber to the turbine Inlet there will be a long pipeline and as it goes through it is will get cooled and the turbine Inlet temperatures probably is going to be higher than what we had set out here as thousand two hundred.

Okay it will be higher which would mean that you will only need a very small bleed okay you could also look at in some sense you can cool the turbine feed with either the few or the oxidizer so that the temperatures do not exceed some limiting value for the turbine Inlet okay so you can do that and feed it to the turbine and then this exhaust is given to a separate nozzle so as to this could be used for controlling the rocket motor now we had learnt that top how do we balance the turbine.

And pump power balance now there are various ways in which you can have or the essentially two designs of pump that you can have one is axial and the other one is centrifugal when do you use an axial pump and when you use you use the centrifugal pump when you lead a very large head when head is high you will go in for a centrifugal pump if mass flow rate is high and head is medium then you go in for an axial pump okay so Δ H or head this nothing but Δ P/ρ into G so if head required is high then you go in for a centrifugal pump.

But if head required is not so high whereas your flow rates are very, very high then you go for a axial pump the advantage with an axial pump is it is pretty much amenable to multi staging whereas the losses if you are using the centrifugal pump and if you are having a large number of stages the losses could be larger because it will have to go through a volume chamber onto the periphery.

And then again comeback to the center it a centrifugal pump you always have axial inlet and radial outlet right so the flow turning induces a higher amount of losses now let us look at what are the values of head and what are the values of flow rates that are they are going to be there in these some of the rocket motors.

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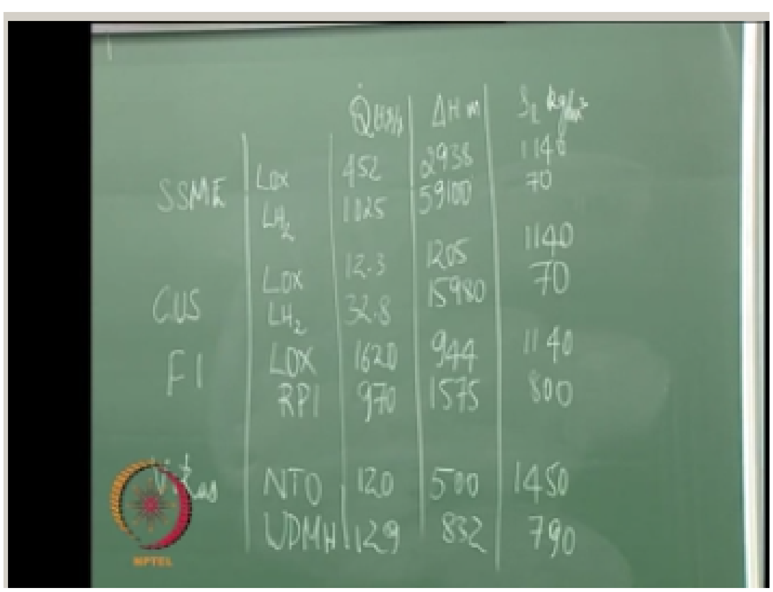

So some uses liquid oxygen and liquid hydrogen cryogenic upper stage is also liquid oxygen and liquid hydrogen f1engine this was the engine that took man to moon this uses kerosene and LOX kerosene is also indicated as rp-1rocket propellant one okay then visas engine is nitrogen tetra oxide and you dumdum symmetric diethyl hydrazine so the Q dot in liters per second and then Δ H if you look at this table this flow rate.

And head of liquid hydrogen these are very, very high simply because if you look at the density of liquid hydrogen it has got a very, very low density of 70kg per meter cube so therefore if you look at flow rate even though the mass flow rates will be very small the flow rate will be very, very high volumetric flow rate will be very high and also the head rice that is required will also be very high simply.

Because head rise is nothing but a $\Delta p / \rho$ because ρ is low, low you will have a very high head rise the same is the case for both same and cuss because both of them use liquid hydrogen in addition to this the head drives will have to be more for liquid hydrogen because it is passed through the regenerative cooling chamber okay now if you look at locks and RP one you will see a substantial difference in the head rise n flow rate although there is a much larger thrust the engine.

This engine produces a much larger crust the head rise that is required for hydrogen is much higher than RP one that is primarily because of the difference in densities okay and here again the head rise is nearly the same for both kind of both fuel and oxidizer for the because engine okay we will stop here in the next class look at what implications does this have if you have a very high head rise what are the implications that it is going to have it let us look at that in the next class thank you.

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