Rocket Propulsion

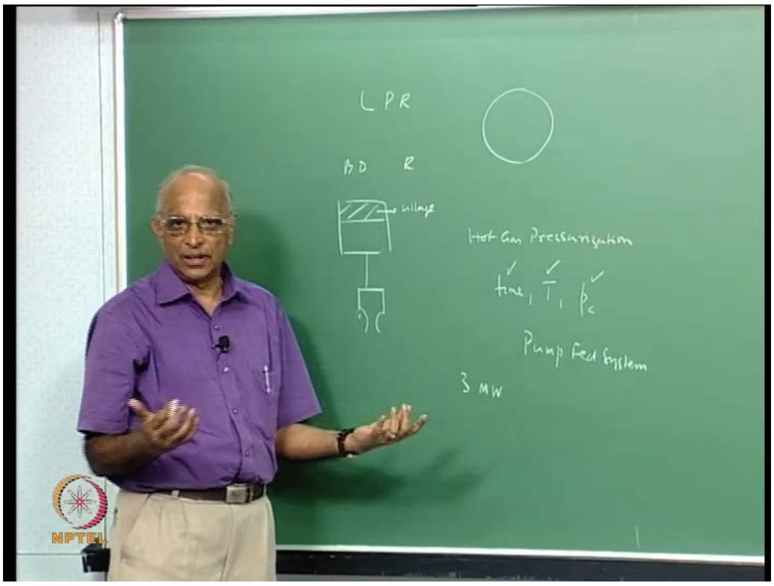
Prof. K. Ramamurthi
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture No. # 29

Feed System Cycles for Pump Fed Liquid Propellant Rockets

Well good morning, we continue with liquid propellant rockets.

(Refer Slide Time: 00:14)

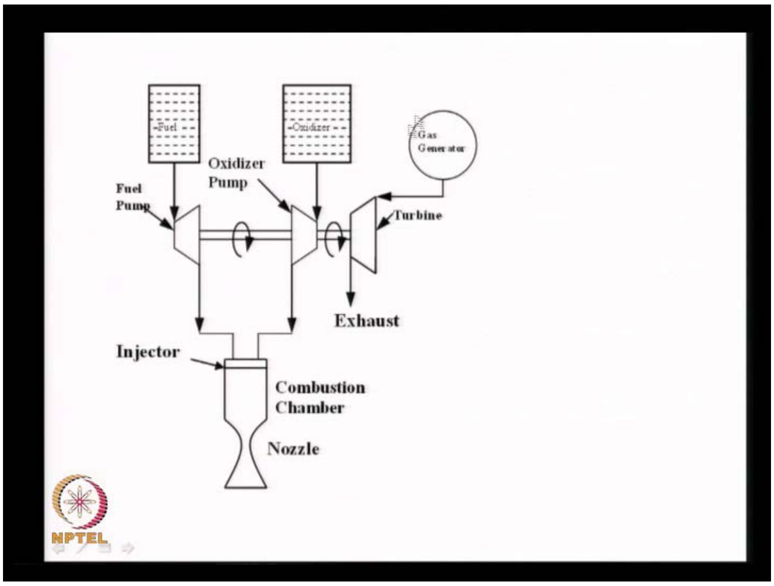


Let us quickly recap, where we were last time we said feeding of liquid propellants can be done in different ways, one was we said using a cold gas. Cold gas could be used either in the blow-down mode or in a regulated mode. The difference is in a regulated mode, we draw gas at a high pressure, maintain a constant low pressure on the propellant and push it out. In the blow-down mode, in the tank itself, we have some volume of gas which is known as ullage volume, which is pressurized initially and you allow this pressure to gradually push the propellant; in which case the pressure of the pressure at which propellant is supplied into the thrust chamber will keep decreasing with time right.

While deriving an equation for the mass of gas required in the gas bottle, we found if the temperature of the gas is higher it is better therefore, we also talked in terms of hot gas pressurization. But we told, even though it is advantageous, it has not been implemented so far and it will be worthwhile, in fact there was one of the French engines which tried this, but they did not follow it up, but I think it is a strong contender. We also found out that when the time of operation of a rocket is small or when the thrust is small or when the chamber pressure is small. We can go for something like cold gas pressurization in either the blow-down mode or a regulated mode or even a hot gas pressurization mode. But the moment the pressure of the chamber is large or the thrust is large or the time is large, we necessarily have to go for a pump fed system right.

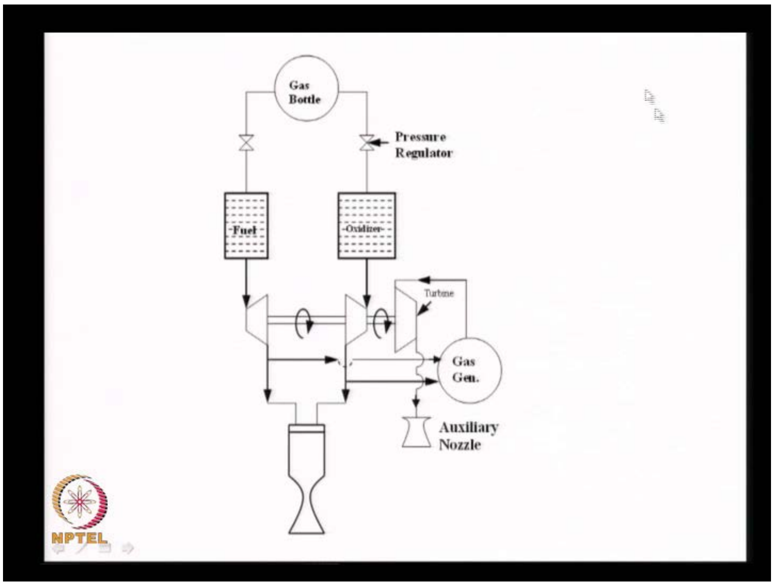
We also found that the amount of power required for the pump is enormous something like for a 600 kilo Newton engine we found that pressure required is or the power required is something like 2.4 or almost 3 kilowatt, 3 megawatt. And we said even a large power plant like the anode power plant has only something like we said something like 450 megawatts of power therefore, we are talking of huge power. And therefore, we cannot drive the pump using a battery, or an electrical supply.

(Refer Slide Time: 02:56)



And let us quickly therefore, go through what where we were; therefore, we said in order to drive the pumps, we looked at this figure in the last class also you have a fuel tank, you have a oxidizer tank both are liquids. You sort of push this into the pump maybe we need a gas bottle which pressurizes it to a small value, pushes it into the pump. I need to rotate these two pumps for which I require a turbine, that turbine generates power and it pushes this to drive that turbine. I need something like a gas generator or a hot gas source which powers the turbine and the hot gases exhausted out. The pressure built in these two pumps pushes the liquid oxidizer, pushes the liquid fuel into what we said was the thrust chamber, what I am circling now is the thrust chamber. Now, you know to have an additional thing for a generating gas is difficult because I need another set of fuels or another set of substances which can generate the gas.

(Refer Slide Time: 03:56)

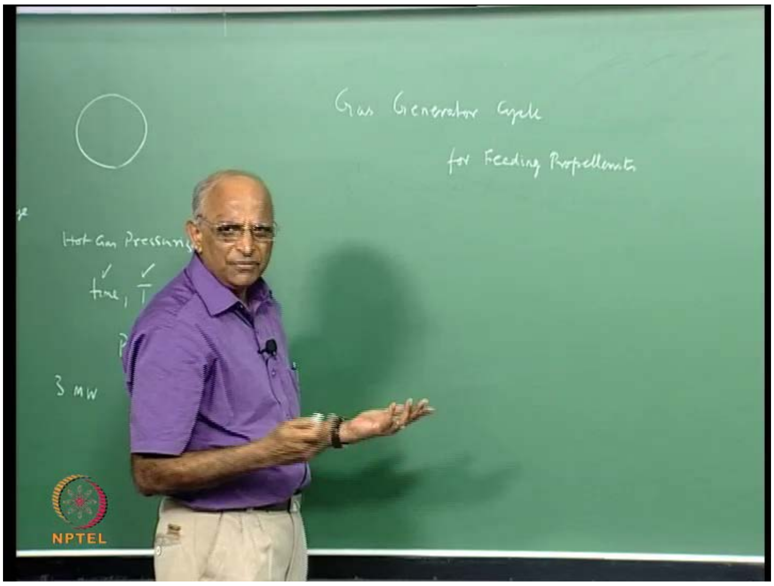


And the normal practice therefore, is to make use of the existing fuel and oxidizer itself. How do we do that, we also looked at it in the last class maybe after you are pressurizing the liquid fuel. You take a little bit of the liquid fuel into something like a pre burner or a burner over here which we call as a gas generator. You take the oxidizer also mix the two together over here generate hot gases, push the hot gases into the turbine and exhaust the output from the turbine into the ambient. Therefore, you have something like a gas generator which is driving the turbine, which intern drives the fuel pump and the oxidizer pump and supplies, the fuel and oxidizer into the engine.

Such a fed system being essentially configured around the gas generator and how does the generator get the fuel, maybe part of the fuel is blood, part of the oxidizer is blood from the lines and it is used to generate hot gases. There is a problem in all this you know, the turbines consist of blades and it could be impulse turbine, reaction turbine maybe we have to look at it, but whatever set and done. If I put very hot gases into the turbine and we (( )) stoichiometric the fuel and oxidizer generate gases at a temperature around three thousand, three thousand six hundred degrees Kelvin.

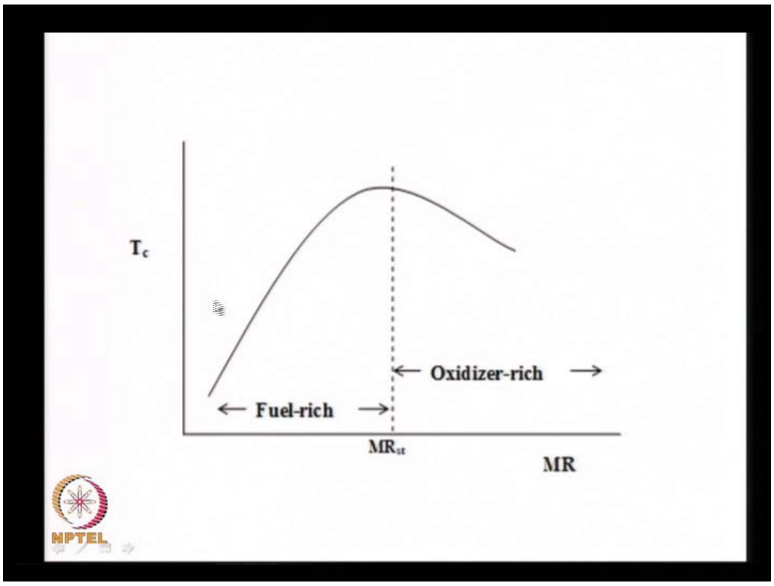
And therefore, I cannot supply these hot gases therefore the output of the gases from the gas generator must essentially be a small number maybe around upper limit is around 900 Kelvin. Therefore, how do I do that maybe I use a very fuel rich mixture or a very oxidizer rich mixer in this gas generator and supply it and the work done by the turbine is equal to the work done by the two pumps. This cycle is what we called as the gas generator fed, gas generator cycle for feeding propellants.

(Refer Slide Time: 05:54)



(No audio from 06:05 to 06:12) See unfortunately, you know when we learn thermodynamics we say cycle is something where in things come back to the initial state we call as cycle. But this is just something like what we are saying is, it is a using a gas generator, we are feeding propellants (( )) unfortunately the word cycle has got come over here. It is not related to the thermodynamics cycle (( )) auto cycle or a joule cycle or a Brayton cycle, no it is just a gas generator fed system, but in conventionally it is known as a gas generator cycle for feeding propellants and I use the same terminology.

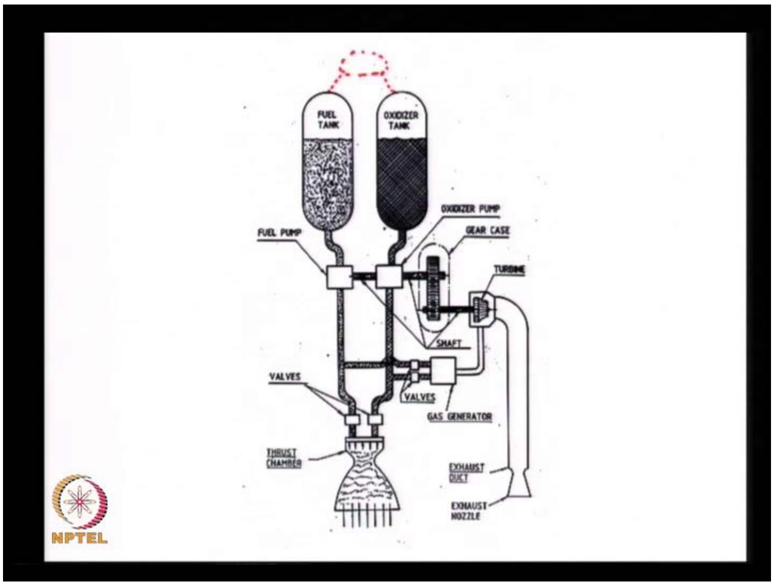
(Refer Slide Time: 06:51)



We also told ourselves in the last class well this is what I had in mind, see we said that the temperature of the gases as a function of mixture ratio is such that the maximum temperature occurs just below the stoichiometric. And therefore, you had a slight shift instead of maximum temperature occurring at stoichiometric it is slightly fuel-rich. But when we need a much lower temperature maybe I have to operate the gas generator in a very fuel-rich regions such that I get only around eight hundred to nine hundred Kelvin or maybe a very oxidizer-rich region wherein I get a low temperature.

Oxidizer-rich region is seldom use, but many of the Russian engines do use oxidizer-rich, what the reason? Why oxidizer-rich is not conventionally used this? If you have something rich in oxygen, it can always oxidize a metal. Whereas, if it is fuel-rich it cannot oxidize a metal therefore, maybe the trend is to use a fuel-rich mixture. Therefore, this was in the context of the choice of the mixture ratio for the gas generator, we tell ourselves I use a fuel-rich mixture, which has a maximum outlet temperature from the gas turbine or the inlet to the turbine around nine hundred Kelvin.

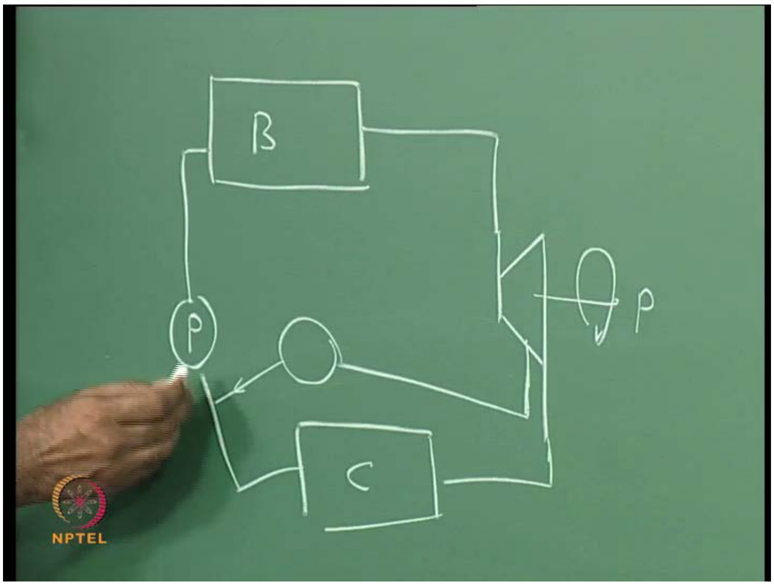
(Refer Slide Time: 08:05)



Well this shows an example of it, I have a small gas bottle which pressurizes the; let say the fuel and the oxidizer, it is spread into the pumps. I also bleed a little bit of fuel, a little bit of oxidizer burn it in a gas generator, I generate hot gases and these hot gases drive the turbine. And when they drive the turbine in this particular schematic you have a gear train changes, the speed and hence the top required for the pumps and these two pumps supply the propellant to the engine and the same thing is bleed of here. You may ask me how do I start the engine, after all I need high pressure over here maybe I need another bottle of high pressure gas or maybe some slug somewhere.

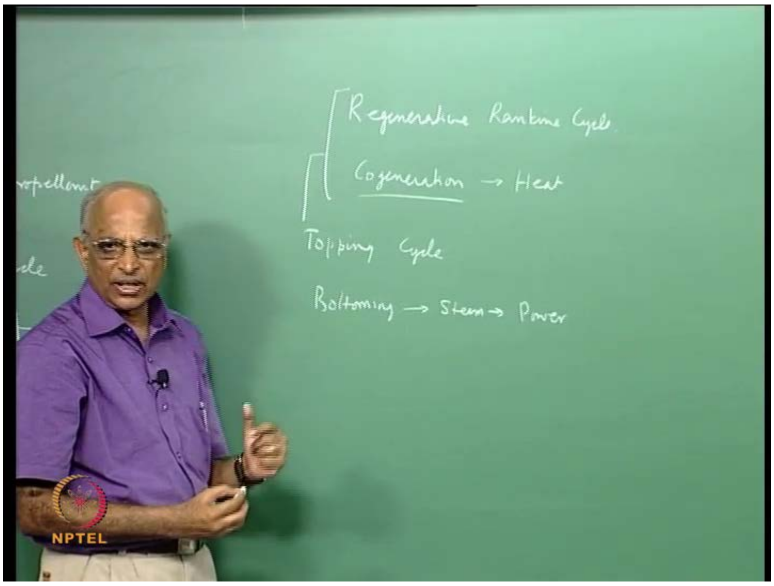
Which I initially use to rotate the turbine and once it rotates, maybe it starts pumping and then I shift to this that is during the initial transient. Well this is all about the gas generator cycle, we will get back into it in some detail to find out what is it is performance, we have discussed the fed system cycles in the last class. And said that the term cycle which usually refers to a thermodynamics cycle is really not valid, there is how over a cycle known as stopping cycle used in power plants.

(Refer Slide Time: 09:23)



Let say the Rankine cycle, which is used in power plants, what is it we have; we have a boiler which generates steam, the boiler runs a turbine that is the high pressure steam runs a turbine and that is what generates your particular power over here. And then the outlet from the turbine is fed into the condenser, wherein water is condensed and then you have a pump, which pushes back the water into the boiler, boiler heat, this is what is the Rankine cycle. Now, very often what is done is to improve the efficiency, we know Carnot efficiency is when the temperature is a maximum now, I am talking the cold water increasing the temperature then supplying heat and then I am doing the cycle. If I were to bleed part of the after a part of the expansion, I bleed some of the gases, I take it into something like a fed water heater. And use this fed water heater, that is heated water into the boiler, well my efficiency will increase because my net temperature is higher.

(Refer Slide Time: 10:42)

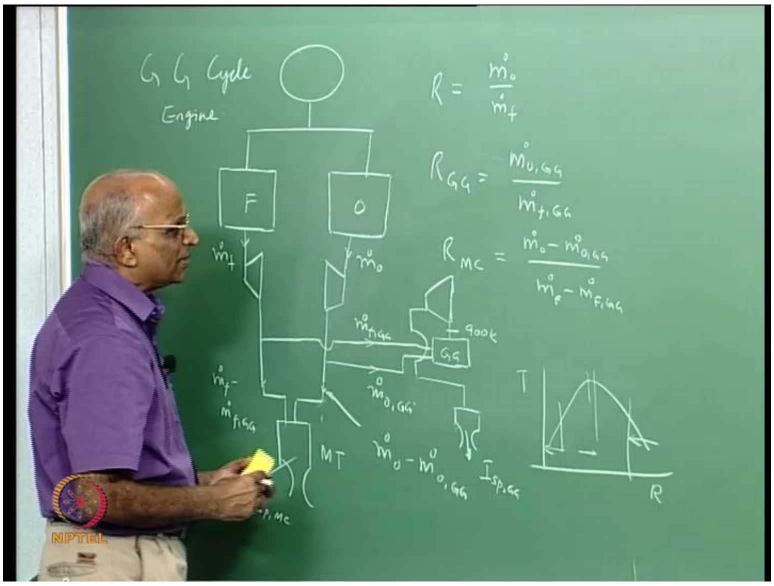


And this came is what we know as what we call as the regenerative Rankine cycle rate. Just like you have regenerate a cycle say essentially what you do is, you heat the water before you do this and how do you heat, you bleed some of the partially expanded gases in the first turbine, allow it to heat the fed water and then you pump the fed water and anyway this part of the cycle also continues. Therefore, you are essentially able to get a higher efficiency and these cycles are known as regenerative cycles. We also learnt in terms of cogeneration cycles and what do you mean by cogeneration, maybe I bleed some of the hot gases from of steam coming over here. Maybe at saturated level, use it to heat houses heat it, use it for some other purposes and that is what is known as cogeneration that means, instead of allowing the heat.

And how do we dissipate heat in a in a condenser maybe I have something like a tower, in which I allow the water to drip, I allow the hot gases to go it the hot gases transfer the heat I mean the hot steam condenses over here, it heats the environment that means it heats the water. Instead of doing that you know, what we could probably do is instead of heating the environment, I allow the steam to go and be usefully used for a heating houses, for heating some places maybe some industry for heating and that is known as cogeneration. These two cycles are also known as the topping cycle why we say topping because, you use some of the heat for topping up your processes rather for heating the houses or for improving your efficiency and this is known as the topping cycle.

Well if you talk of topping cycle, we should also talk in terms of bottoming cycle. What is that, maybe if I have a furnace which is generating very high temperatures and I use this furnace to heat some product tempering steel or maybe for steel making or whatever it is. And instead of allowing the exhaust gases from the steel making plant to be dissipated into the environment, I use it to generate steam then it is a bottoming process, it is just the opposite of your generation. But I use the waste heat from your furnace to generate steam and therefore, to generate power or to generate electricity and this is known as the bottoming cycle. Therefore, when I considered topping cycle, can I use some element of topping cycle in the gas generating; gas generator cycle which I just talked of, let us just try to put it together again. We must be very clear about it because this feed system cycles are important, I have something like a gas bottle.

(Refer Slide Time: 13:42)



From the gas bottle I have these two tanks fuel tank, oxidizer tank let say fuel oxidizer. I take the fuel into the pump, I take the oxidizer into the oxidizer pump and then I push it out why is this gas bottle required? I need some minimum pressure to push it out. Therefore, now my requirement of gas is much smaller because my pressure is going to be smaller. And then before I take this fuel pump over here, I take the pressurized fuel into something like a gas generator over here or a pre-burner, or something which generates hot gases at a mixture ratio which produces not a very high temperature. Similarly, I take the oxidizer into it I make it react and generate the required temperature gases over here and the balance, I sort of put into my main combustion chamber, which I call as the main combustion chamber or main thrush chamber over here.

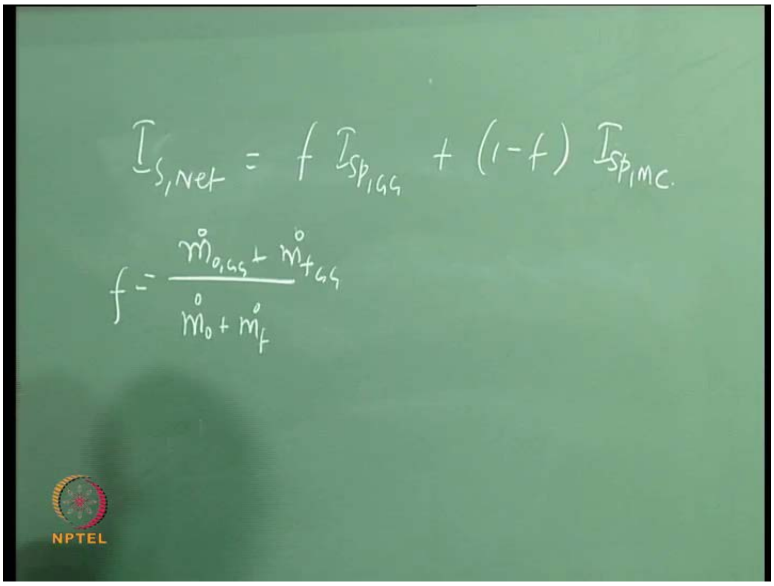
Therefore, what is it we did, we have something like mass of fuel which is supplied by the tank, mass of oxidizer which is supplied by the tank. Part of it I bleed into this namely, part of the fuel I bleed into the gas generator, part of the oxidizer I call it as M O I put into the gas generator. Now, the balance what comes over here is M dot f minus M dot f into what has been supplied to the gas generator, what comes over here is M dot O that is the main which is coming, something has gone out minus M dot O into the gas generator. Therefore, what is it, I am talking of? I am talking of when the overall mixture ratio is the overall fuel and oxidizer. Which is supplied to your system or to your overall rocket engine is something like a mixture ratio, I call as mixture ratio R which is equal to M dot O by M dot f, mass of oxidizer divided by mass of fuel.

What is the mixture ratio of your gas generator, R gas generator is equal to M dot of O which gets into your gas generator divided by M dot f which gets into your gas generator. Then, we said this mixture ratio must be terribly on the fuel side because we told ourselves, well the temperature versus mixture ratio. If I were to plot instead of M R I am writing R is something, this is something like stoichiometry, this is the peak temperature maybe I want a reduced temperature. I operate on a fuel-rich region or I have to operate somewhere over here which is the oxidizer-rich region. Therefore, now I write the value of mixture ratio in your main chamber, which generates the thrust. Or let say I call it in the main chamber R M C is equal to M dot O minus M dot O corresponding to the gas generator divided by M dot F minus M dot F, which goes into the gas generator.

Therefore, you have three mixture ratios to content with, I would like this mixture ratios such that I get maximum specific impulse, but if I by to overall look at it I would like to choose this mixture ratio such that I get a good performance. Maybe we have to calculate this a little (( )) more carefully, lets finish the topping cycle and come back to it what is; therefore, this topping cycle and this; what we are just now said is what we call as the GG cycle engine gas generator fed engine. I now ask myself see after all what did this gas generator do, it draw something like a turbine and what was this turbine? In the turbine I have high pressure gases. I reduce the pressure of gases to low value and then, I take the gases out I exhaust it out through a nozzle (No Audio From: 18:33 to 18:41) this is auxiliary.

The temperature at the inlet to the turbine or outlet of the gas generator we said is typically less than nine hundred Kelvin therefore, the temperature at the outlet of your turbine will be even less maybe around four hundred or so. And therefore, the type of specific impulse which this expansion can give is going to be a small number, let us call it as specific impulse from the gas generator, which comes from the exhaust of your turbine which is expanded through a nozzle. Whereas, the specific impulse corresponding to the main chamber, we call it as specific impulse of your main chamber therefore, what will be the total impulse what I get, it will be the fraction of propellant at this specific impulse plus fraction of the propellant at this impulse. And therefore, now I say if I by to find out, what is the value of the total impulse, what I get from this gas generator cycle or total specific impulse.

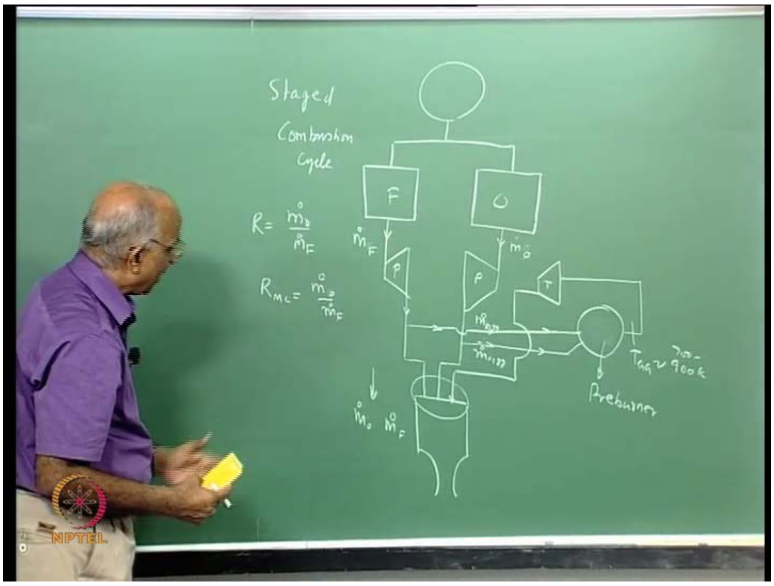
(Refer Slide Time: 19:41)



I call it as net value is going to be fraction of the gases f of the total that means, I have M dot O plus M dot f which is the total supply divided by I have M dot corresponding to the gas generator plus M dot fuel corresponding to the gas generator I define as the fraction f. And therefore, this fraction into the I S P of expansion in your gas generator exit from the turbine plus I have may be one minus f that is the part of the propellant which flows through the main engine is equal to I S P of the main chamber. We told our self this fellow whose is slightly weak, because it get the supply temperature is small have expanded the gases pressure is small therefore, the I S P of this will be very much lower than this. And therefore, the net specific impulse of this that means the total specific impulse of this gas generator fed engine is going to be less than the specific impulse what I would have otherwise got had I not done this.

Therefore, the question is can I get this heat, which is being wasted in a poor way can I get it come into the chamber, in other words it is very similar to the regenerative process in a rankine cycle. Therefore, and that is what we say is a topping cycle and let us put that together, maybe I leave this space for analysis of the GG let us put it together.

(Refer Slide Time: 21:26)



I again have a gas bottle, it supplies the two tanks a fuel tank may be an oxidizer tank. And then, I take the things out to over here and here I have a fuel pump increases the pressure I have an oxidizer pump which again increases the pressure. I take the lines how now this is high pressure, I have pump here pump here for fuel for oxidizer. And then what is it I will do, I take the some of the fuel at high pressure over here take it into the gas generator over here. And then what I do is I use this to drive a pump turbine, I bring the turbine here high pressure becoming low pressure, let us keep the directions very clear, I also take a little of this little of the oxidizer allow it to come into the gas generator over here.

Now, the temperature of your gas generator is typically around nine hundred, eight hundred to nine hundred Kelvin. Nine hundred is the upper limit let say seven hundred to nine hundred Kelvin and this drives your turbine. And what do you do with the turbine exhaust now, let us see how to regenerate it and these two, the balance of the fuel and oxidizer come into your main chamber. Now, what do you do with this turbine exhaust, you bring the turbine exhaust out over here and I also admit it into the injector over here. That means the heat which is left out in the turbine is again re generatively used here and this is what constitutes the topping cycle used for a feed system.

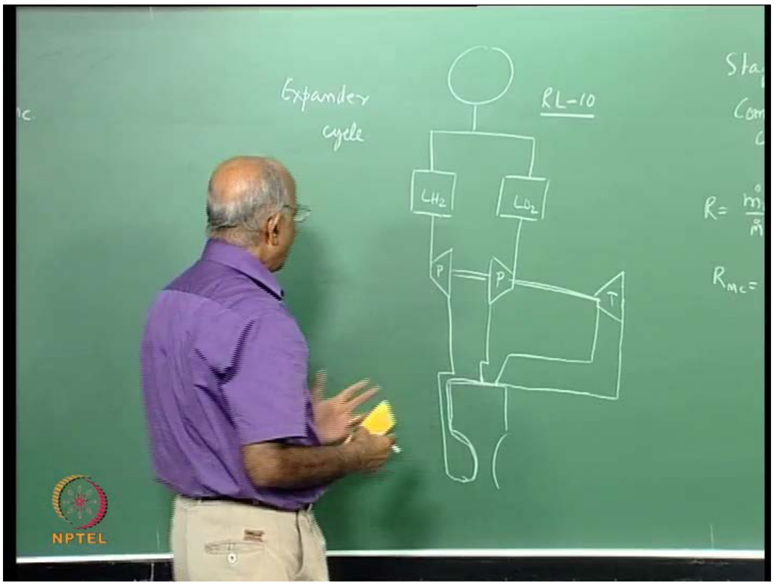
In other words the exhaust it is not wasted with low impulse as in a gas generators cycle, but it is fed back into the main chamber for secondary combustion. First combustion takes place here at low temperature then turbine expander and then that is mixed with the other part of the process here. And therefore, it the combustion now takes place in two stages and therefore, this topping cycle is also referred to as combustion taking place in stages, or something like staged combustion cycle. Now, I will try to find out, what is the value of mixture over all mixture ratio? What is the value of mixture ratio of the gas generator? What is the value of the mixture ratio in the main engine? Just like we did for gas generator, let us do it for the stage combustion cycle.

Therefore, stage combustion cycle again we say M dot oxidizer M dot of the fuel, I supply something like M dot O corresponding to the GG, I take; this (( )) fuel a line therefore, I say may be this should have been f, this should have been O therefore, I take M dot f into GG, I take M dot O into GG. And then here I had M dot f minus M dot f GG, here I had M dot O minus M dot O GG all this is coming back here and therefore, the net value what enters here is still M dot O and M dot f. Or rather the overall mixture ratio if it is going to be M dot O by M dot f, the mixture ratio in your main engine or main chamber is again the same value of M dot O by M dot f in this case. And what is the gas generator? Gas generator is equal to like what we had earlier M dot O GG by M dot f GG.

This is the main distinction between a gas generator cycle and what we call as a stage combustion cycle or topping cycle. And when we use the gas generator in the stage combustion cycle, very often it is referred to as a pre-burner because it first burns and again we have a second burn, the cycle is also known as a this the gas generator is called as a pre-burner. Well we need not even have something like a stage combustion cycle.

When we talk of volatile fuels, volatile fuels means liquid hydrogen or let say liquid methane or liquid propane, it is also possible for us to have a another cycle let us quickly plot that out.

(Refer Slide Time: 26:30)



May be I have a gas bottles, let say I have volatile fuel, let say liquid hydrogen or liquid methane or something like this may be I have oxidizer like liquid oxygen. In this case what I could probably do and which is also workable is maybe I have a pump over here I have another pump over here for the oxygen. Now, what I do is this particular liquid hydrogen I have to supply to the chamber, combustion chamber, the combustion chamber takes place in a chamber it runs hot. And therefore, I connected to the chamber like this, the hydrogen flows along the chamber gets heated. And this heated hydrogen, I take it out over here I run my turbine using this hot gases, hot hydrogen vapor or hot volatile liquid whatever is generated.

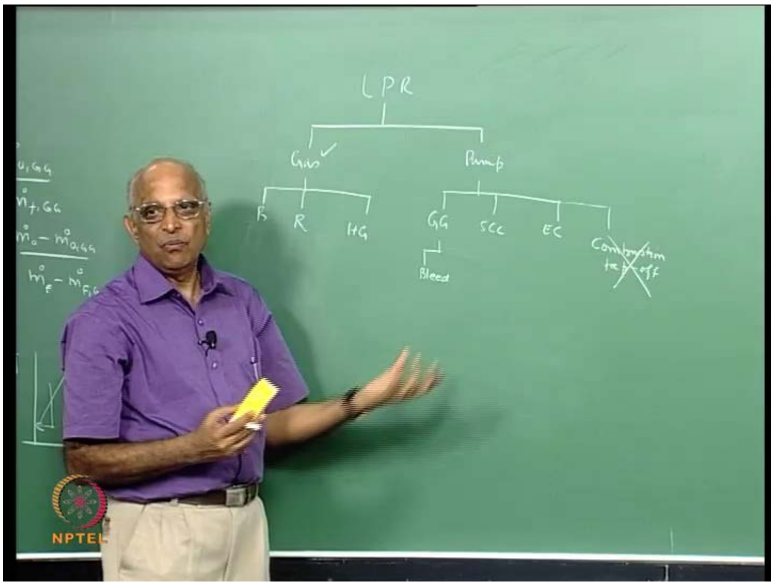
And then I drive the turbine and then, I take the exhaust gases put it into the chamber, I take the oxidizer put it into the chamber. And in other words what is it I have done, I have turbine which is run by the heated fuel or heated oxidizer, whatever be, it is possible to generate a vapor. I generate the pump I drive the pump, I drive the pump of the fuel, I drive the pump of the oxidizer. And in other words just by using the hot chamber, I expand the gases in a turbine and I run the pumps and such a cycle is a derivation of stage combustion cycle, but without a pre-burner and this is known as an expander cycle.

Therefore, the pump fed systems are basically classified as belonging to gas generator cycle in which case I allow the exhaust from the turbine to go into the environment. May be second is stage combustion cycle wherein I put a pre-burner and take the combustion to occur in two stages. Or I just use the hot vapor generated on the outside of the engine may in the next class I will do the regenerative cooling and we will; it will become little more clear at that time. I use the vapor form during cooling of the chamber to run a turbine this vapor runs the turbine and this turbine then runs these two pumps which is known as an expander cycle.

We could have combinations of some of these cycles, like we could also have may be instead of allowing the exhaust from the gas turbine to come through this may be I can feed into the nozzle divergent and try to generate little more thrust. In which case the cycle known as gas generator with bleed, what is bleed I allow some of the output gases to come and generate little more thrust by injecting it into the nozzle here. You could keep on devising cycles or maybe I could have something like a combustion taking place in the chamber. I allow the gases to come and drive the turbine and this known as the combustion tap of cycle, but it has never been used in practice. What has been used in practices expander cycle this is I; you will recall I showed a cycle, I showed an engine R L 10, I said this was the first engine, first cryogenic engine developed in U S.

This uses an expander cycle, most of the cycles use the gas generator cycle but the stage combustion cycles are extremely powerful have very high performance, as we shall be seeing subsequently and this is what is normally preferred. I think we will take a look at it, what is to be preferred when and why is; what we must address.

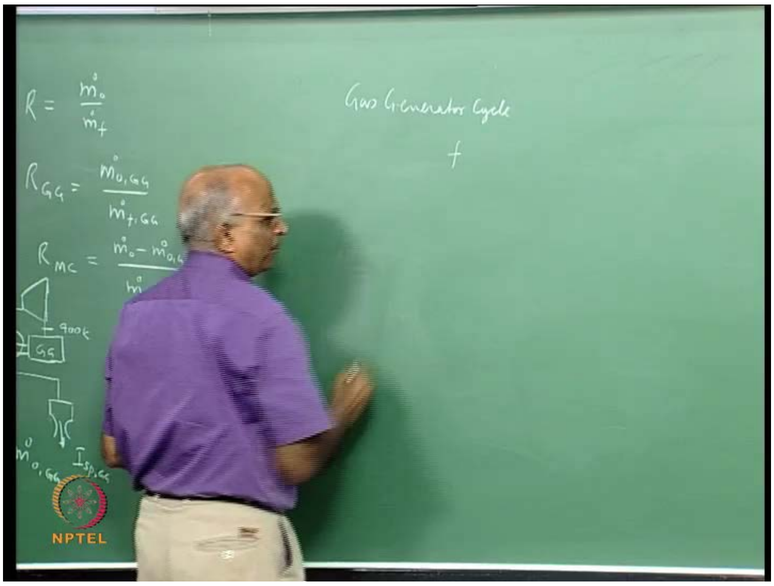
(Refer Slide Time: 30:46)



But, to be able to do that, let us therefore, now summarize whatever I have been telling so far in the following language, namely we said a liquid propellant rocket could either be pump fed or be gas fed. For gas fed we know how to calculate the amount of gas either in the blow-down mode, regulated mode or in the hot gas mode. When we talk of pump fed we told ourselves well gas generator cycle, stage combustion cycle or topping cycle and the expander cycle. You would like to know under what conditions do I use this cycle, when do I should I use this, when should I use this. Well we could have derivatives gas generator with bleed, which wherein instead of allowing the gas to; go to the exist I allow it to the ambient through an auxiliary nozzle.

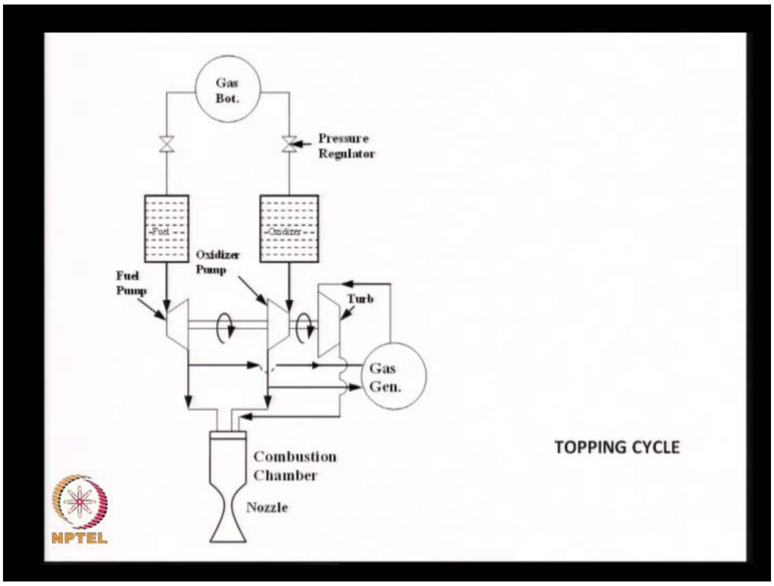
I allow it to get into my nozzle and generate little more thrust or I could also have something like a combustion tap off. I use the instead of having a separate pre-burner I tap up some of the products from the combustion, but you know to be able to tap off. The same consistent mixture ratio is difficult and that is the reason why such things are not used. We have several other cycles which are not of interest, but I think we must keep our minds open and try to see how best we can improve these cycles. If this part is clear, I can go back and analyze what cycle should I use when; what is it? Let us do this exercise.

(Refer Slide Time: 32:20)



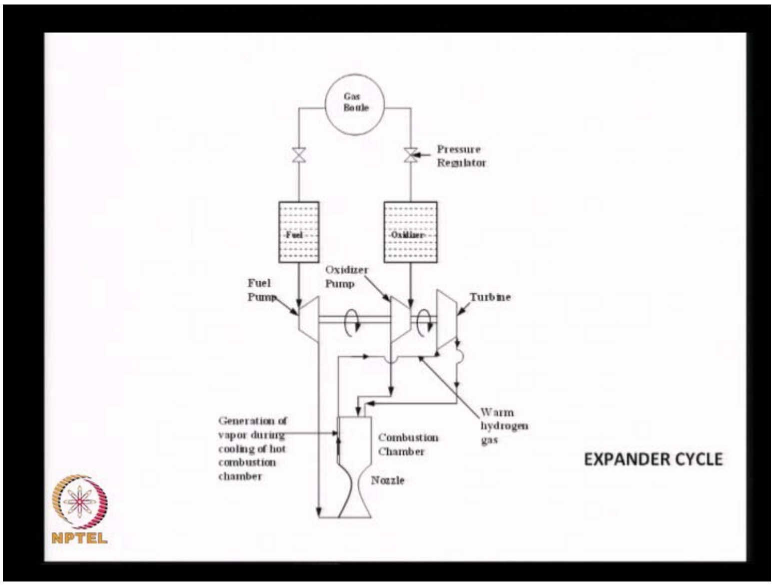
We find that the gas generator cycle, a fraction f is not very usefully used, can I calculate that value of f is the first question.

(Refer Slide Time: 32:39)



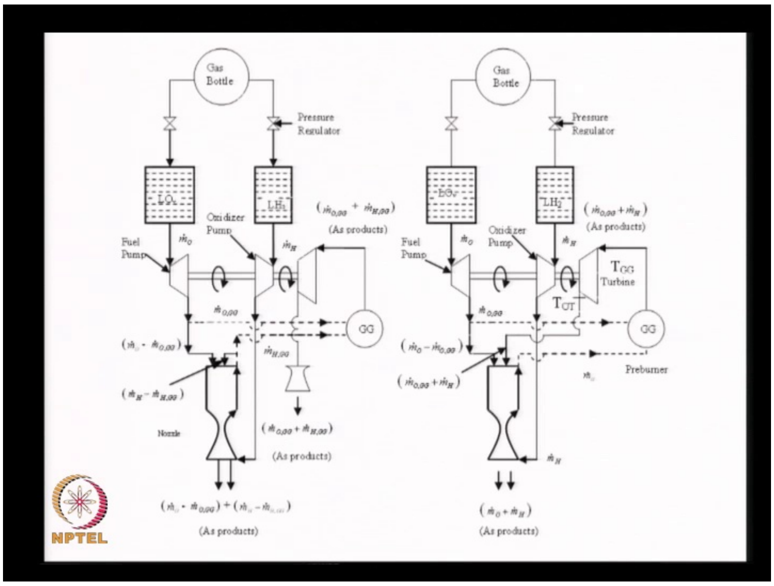
But, before I do this let us quickly run through what little I have been doing, I think this is whatever we are doing is related to the feed system and it is important is the topping cycle well.

(Refer Slide Time: 32:45)



This is the expander cycle, in the expander cycle you have fuel and oxidizer. The oxidizer is pumped with this pump this is pumped over here the fuel is the volatile fuel. Therefore, it comes cools the chamber, the hot vapor so generated runs the turbine exhaust from the turbine is fed back and that is, why we call it as the expander cycle? The vapor is generated during cooling of the particular thrust chamber. Well this is gas generator with bleed, the exhaust instead of being expanded through an auxiliary nozzle. Comes back into the nozzle at the; in the divergent portion and it use to develop some more I S P for this or some more specific impulse of your rocket, I think this is all about it.

(Refer Slide Time: 33:36)

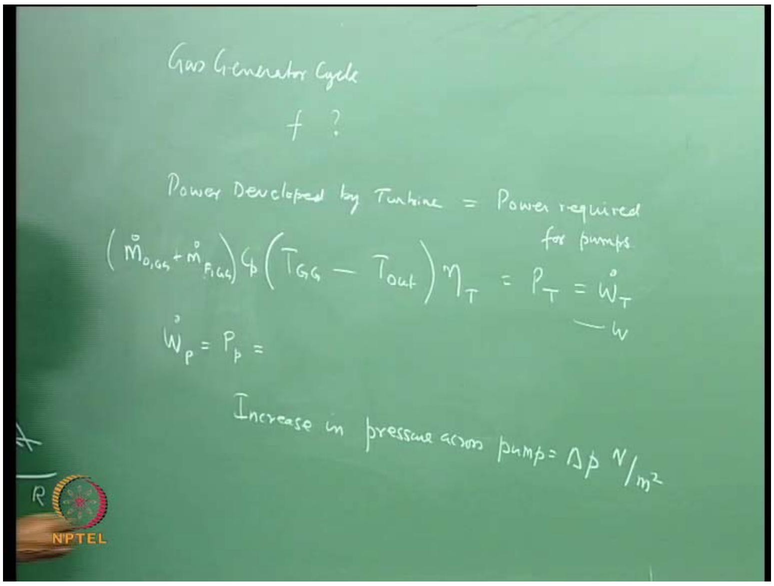


Let us now, put things together this looks clumsy, but it is exactly what I have been writing on the board you have mass of fuel, mass of oxidizer, mass of this and all that is all what is shown in this particular figure. This I show for the gas generator cycle on this side you have mass of oxidizer coming into the turbine, the part is taken to the gas generator. In this case I consider this specific case of liquid oxygen, liquid hydrogen, mass of hydrogen coming into the pump over here. This is taken into the gas generator burns here drives the turbine, the balance what comes in here is only fuel that is M dot hydrogen minus M dot which goes into your gas generator. Similarly, you have oxygen which comes in here which is equal to M dot of oxygen minus M dot which goes into the gas generator.

Therefore, in this case, in the GG cycle to repeat again you have three mixture ratios and over all mixture ratio, mixture ratio for your gas generator and a separate mixture ratio for the engine or your main chamber. Whereas, in your stage combustion cycle the overall mixture ratio is same as the mixture ratio for your engine, the R the mixture ratio for your gas generator is bound to be different, is this part clear? If this part is clear, let us quickly do this exercise of finding out what will be the value of f. See what is done over here you know, I forgot to draw this line over here you should have reminded on this. What is this line? I say that the turbine is rotating the turbine rotates the oxidizer pump the turbine rotates this pump, because mechanically the power generated in the turbine is running these two pumps.

Therefore, let us to be able to find out how much fuel is required or what is the fraction of propellant which is required to drive the turbine here I need to be able to find out how much pump power is required. Therefore, let us put it down.

(Refer Slide Time: 35:41)

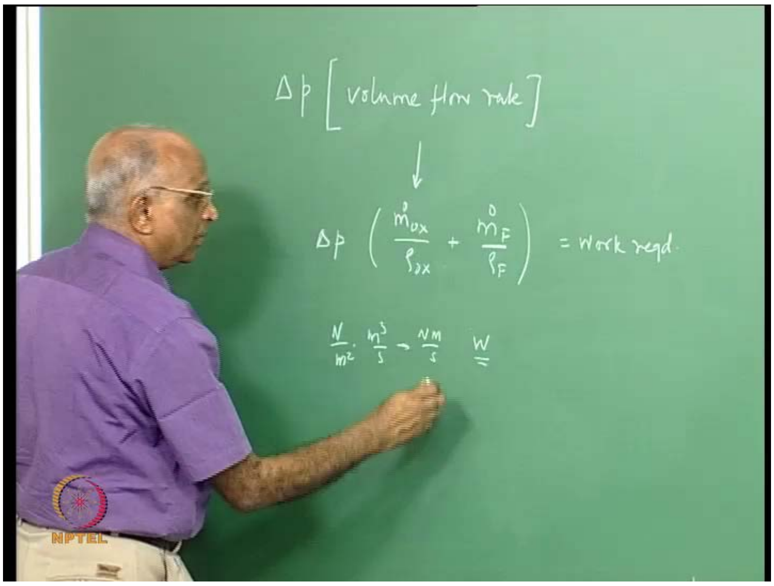


What is the power developed by the turbine (No Audio From: 35:33 to 35:53) and where does the power developed by the turbine go it runs these two pumps. Let us say pump for fuel pump for the oxidizer and this must be equal to the power required for the two pumps. Now, what is the power developed by the turbine these are very clear, we told ourselves the out let temperature from the GG is let us say eight hundred, nine hundred Kelvin. We call the outlet temperature as T GG and this temperature of gases is what enters into turbine let us say that the outlet temperature from the turbine is temperature outlet, let say T outlet. I again repeat T GG is the temperature at which the hot gases from the gas generator enter your turbine, some power is generated in the turbine there is some expansion may be an impulse turbine, you are expanding the gases and at the outlet the temperature is T outlet.

Therefore, what is the work which is done by the turbine, rate of work is equal to M dot O GG the mass of oxidizer, mass of fuel into the GG that is the total propellant flow into the GG. Which is the total propellant flow into this, into the value of C P that is your enthalpy and therefore, this is going to be so much watts of so much M dot C P into temperature difference is the work done. And since, we are talking of mass flow rates the rate of work done is so much of course, your turbine has some efficiency let us say efficiency of the turbine and therefore, this is the power of the particular turbine. Let us satisfy ourselves, let us make sure whatever we are writing total mass flow M C P into delta T is the enthalpy.

Enthalpy which is drop in your turbine, which is the work done by the turbine and how did we say, but we are not talking of mass, but we are talking of mass flow rate. Therefore, this is the power of the turbine rate at which work is being done or this is I can also write as W dot T right. Can you tell me what is a work done by two pumps? We have been doing it in the last class also. Rate at which work is done by the two pumps which is equal to the power of your two pumps is watt, let say the unit is watts joule per second. How do I write it, let us take a look at this it takes fuel increases the pressure from this value to this value, let us say that the increase in pressure is delta P (No Audio From: 38:58 to 39:12) Newton per meter square let us say Pascal. And what is the work done by this two pumps?

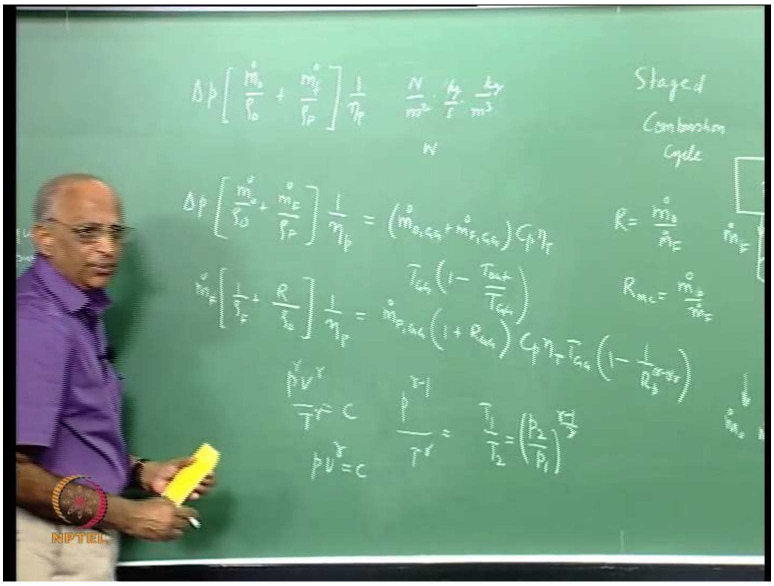
(Refer Slide Time: 39:28)



Now, the work done by a pump can be written as delta P in to the volume flow rate, where delta P is the pressurize across the pump and volume flow rate means, the volume the rate at which flow takes place through the pumps. The volume flow rate through the pump corresponds to the flow of the oxidizer and the flow of fuel namely, M dot oxidizer in terms of so much kilograms per second divided by the density of the oxidizer plus M dot of the fuel divided by density of the fuel. This is the volume flow rate of the fuel, this is the volume flow rate of the oxidizer and this therefore, multiplied by delta P across the pump is equal to the work required to run the pumps. If I look at the units delta P has the units of Newton per meter square and these have units of kilogram per second, kilogram per meter cube.

That means, meter cube per second which is equal to Newton meter per second or something like joules per second or it is equal to something like watts, this is the rate of work required for the pumps. See for the present to have a simple analysis, I have assumed that the pressure increase in the two pumps is the same otherwise I have to have a separate expression for this a separate expression for this. I am just trying to illustrate the method yes I have assumed that the pressure increase across the two pumps are the same, which need not be the case it is whatever you are saying is true.

(Refer Slide Time: 41:31)



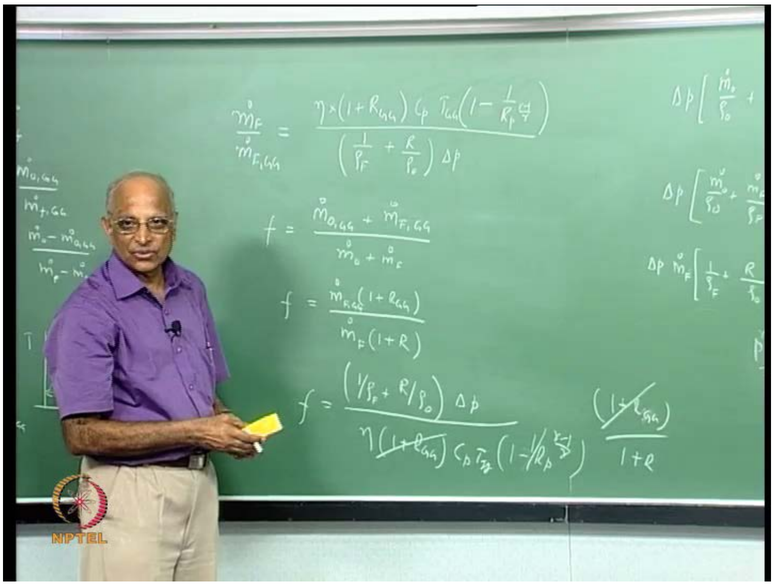
Now, if this is so; I now, say that my efficiency of the pumps is eta P and therefore, the total work done is so much work required is so much, because my efficiency of my pump is small therefore, I have to divided it. And therefore, now I equate the rate of power required for the pump with what is the work which is available. And therefore, now I write delta P into I write this as equal to M dot O by rho not plus M dot fuel divided by rho f in to 1 over eta P is equal to whatever I got over here let us simplify it and write it is equal to M dot O into your GG plus M dot f into your GG into C P eta T into whatever we have let us take T GG outside 1 minus T outlet divided by T GG.

And this becomes my expression how do I get the fuel fraction from here, fuel fraction we said was equal to the fraction which is going into your gas generator divided by the total therefore, maybe I let simplify this little bit more. Let us rewrite it in the following way M dot O into 1 over rho not plus M dot O no, let us take M dot f outside in which case it becomes a little simpler M dot f into one over rho f plus M dot by M dot f is your overall mixture ratio into the value of rho not is it all right into one over eta P is equal to same thing I use again I take M dot f going through your GG over here and now I write one plus R GG into I get the value of C P eta T T GG.

And now, I say temperature if I assume isentropic expansion in your turbine T outlet by T GG for T 1 by T 2 is equal to P 2, P 1 by P 2 pressure ratio to the power gamma minus one by gamma or rather this becomes 1 minus 1 over the pressure ratio to the power gamma minus 1 by gamma. How do we do this we know, that the value of; therefore, this becomes I can write this as P gamma V gamma by T gamma. And therefore, now I if have to substitute, if I divide one by the other and I want to eliminate I get P to the power gamma minus 1 divided by T to the power gamma is a constant or rather P 1 to the power gamma minus one by T 1 to the power gamma minus one is equal to P 2 and all that therefore, I get T 1 by T 2 is equal to; I get and this is what I said as pressure ratio.

Now, let us go slowly, but let us do things completely. Therefore, if now I have to simplify this expression what I have here, what is it I get? I get the value of M dot of the fuel.

(Refer Slide Time: 45:25)



Through your gas generator divided by M dot of the total fuel, which is going is equal to now I take eta P on this particular side, say the product of the turbine efficiency and your pump efficiency is total eta. That means, I take this by this therefore, this comes here or rather let me invert it M dot f by M dot GG is equal to so that it becomes eta over here which is equal to eta is equal to pump efficiency into your turbine efficiency, M dot f M dot G comes over here and on the hand side. I; therefore, have eta into one plus mixture ratio in your gas generator into I have whatever I have written here C P into T GG into 1 plus the pressure ratio in your particular pump divided by gamma minus 1 by gamma.

And I have to divide it by let me divided it over here which means I put this equal to over here, 1 over rho f plus overall mixture ratio divided by rho 0. (No Audio From: 46:55 to 47:08) is this please check whether we have left out any terms, yes where does delta P come M dot f into this into delta P. That means here also we should had delta P here we solve out the value of delta P over here, that means delta P over here.

(( ))

Where 1 minus?

(( ))

1 minus R gamma minus 1 by gamma, good anything else therefore, we are able to find out the value of M dot f by M dot O, but still what is it I want? I want to find out the

fraction of the fuel which is going through your particular gas generator. What is it I am after f is equal to M dot O or M dot oxidizer which is going through your gas generator plus M dot fuel which is going through your gas generator divided by M dot O plus M dot fuel that means the net value of these two is the fraction. That means, the fraction propellant is going through your gas generate divided by the total over here. Now, this I again simplify as M dot O GG into 1 plus R GG divided by M dot O M dot F into GG into 1 plus M dot O GG by M dot f GG is a mixture ratio over here M dot O GG or let us again take M dot of F into 1 plus R. Please let us be very clear about it and this is equal to your f, but what is it we have got here? We have got M dot F by M dot O over here may be I have to now convert it into some form wherein, yes.

(( ))

M dot f divided by M dot f GG correct therefore, we have this, we have M dot f divided by M dot f GG divided by M dot F over here. Let us substitute the value and what is it I get? I get the value as 1 over rho f plus the value of R divided by rho 0 into delta P divided by the value of eta into 1 plus R GG into C P T GG into 1 plus R P into gamma minus 1 by gamma 1 minus the value here. And this is equal to I have to now get the value of M dot F multiplied by 1 plus R G divided by I now find into 1 plus R is equal to the value of f. I find that 1 plus R GG and 1 plus R GG gets cancelled and therefore, f is equal to 1 plus rho 1 over the density of the fuel mixture ratio divided by density of the oxidizer into the pressure drop divided by the net efficiency of your pump and turbine C P T GG minus 1 by R into 1 over R is the net fuel value.

(( ))

1 plus R.

(( ))

C P into 1 minus 1 by R you are correct. Now, I want to discuss these results how do I do it may be we will do it in the next class before I proceed further. Therefore, what is it we have done in this class, we look we wanted to calculate what is the fraction of the propellant which flows through your gas generator and we have got an expression for this. We will quickly go through this expression and then we will see in what way to interpret the results, Thank you.