Fundamentals of Combustion for Propulsion
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Lecture - 22
Liquid propellant rockets – Part 2

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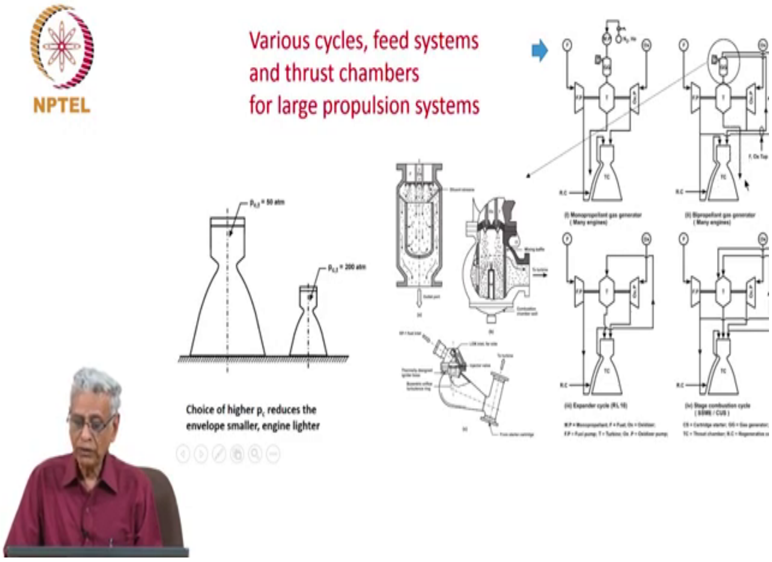

Let us shift to various cycles feed system thrust chambers for large propulsion systems. One key point I want to make to you is the following; rocket operating conditions are always at high pressure, but the question is what pressure is good and what pressure is not good.

In comparison to solid rockets, the liquid rockets have a certain advantage. In solid rockets, the propellants are carried in the chamber and the entire chamber has to be pressurized. In the case of liquid rockets it is not so; the combustion chamber of the rocket engine enjoys a pressure which is what you decide for performance. And the feed system which provides the fluids into the combustion chamber can be at lower pressure and introduce a turbo pump which raises the pressure and pumps it into the combustion chamber.

Because of that you have an advantage to reduce the possibility of reducing the weight and the system volume of the thrust chamber this is a possibility in the case of liquid rockets. I just showed you showing you here that, if you take the chamber at 50 atmospheres, the rocket motor would look like this; at 200 atmosphere it would look like this; and the largest pressure which is currently deployed is 300 atmosphere

So, you can imagine that the thrust chamber is really very small. You may be looking at a large propulsion system, we can carry liquid in tanks which are 2 meters in diameter, 4 meters long; but the actual operation of combustion and thrust generation occurs in a small volume that you see here. And you see here that that, various options for the way you can manage the whole thing. I will show you two of them, all others you can may actually do refer.

What you see here is a thrust chamber, into this you have a turbo pump which is the turbine, fuel pump, oxygen pump, you have a fuel tank, oxygen tank; because these pumps operated at high speed, there will be problems of cavitation in the pumps; to prevent cavitation, you must supply them at some pressure. So, you have to have the pressurant at whatever pressure maybe 300, 400 atmospheres.

Allow through a regulated process pressure into the tanks of the fuel or oxidizer at couple of atmosphere, 5 to 6 atmospheres; that pressure will deliver the liquids into the pumps to ensure that when these are operating at high speed, no cavitation occurs and these pumps deliver the fuels at pressures whatever is required here.

And if you take a pressure here of 200 atmospheres, you will be looking at pressure at the a turbo pump of 500 atmospheres. If you are looking at pressure here of say 300 atmospheres, you may be looking at 700 atmospheres as a pressure of the liquid after the turbo pumps.

So, these really operate in very difficult conditions if I may say so. Then these are delivering to, in fact if you have this thrust chamber like this; you have a high heat flux load coming from the combustion flowing combustion gases. To take care of that, you have to cool this chamber and to cool this chamber, it is called regenerative cooling.

The fuel are oxidizing depends on the choice to is not very clear it right away; it passes through this and they deliver it into the combustion chamber. So, this is the normal strategy for you know one class of propulsion system. Well and you have other systems here; you have fuel pump, oxidizer pump.

Now, in this case you from the turbine you are in this case, you are leaving it as an exhaust exactly as you are doing it here. This another class of systems which are used and to operate it you in both the cases, you need a gas generator. What does it mean? When you have to start the propulsion system, you have to started turbo pumps; turbo pumps have to be started through high temperature, high pressure gases and it is called a gas generator and this cycle is usually called gas generator cycle.

And for that, you have to pump the liquids normally by gravity it starts up; then you have to or you start up with a solid cartridge, spin the turbine, as a turbine spins it starts pumping and start feeding liquids back into the gas generator, gas generator starts stabilizing, and once they start stabilizes the RPM of the turbo pump increases and things like that.

So, you have a complex system arrangement here to manage the transition from starting to steady state. Typically it takes in a large system about 3, 4 second; in smaller systems about a second. There is one here which you see called stage combustion cycle, in which case nothing is let out from the turbine; all the liquids go through the only combustion chamber. And this means that, the operating pressures in many of them inside the feed system will be very high and the performance actually delivered in terms of specific impulse from the stage combustion cycle is the highest of all these options.

And in so far as the gas generator is concerned you know that, there are variety ways of doing that; you may use impinging injectors, you may use other classes of injectors, mix them. Sometimes you to maintain the temperature required for the turbine which may not be too large; you also add water as it happens in VIKAS engine and in some other systems you have other variants.

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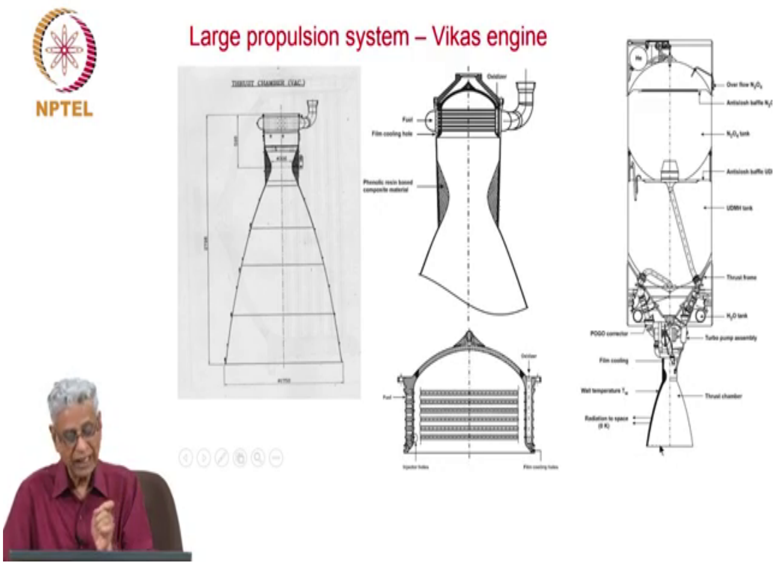

I just want to show you the large propulsion system called it Vikas engine, which is actually being deployed in ISRO. It is the interesting combustion system, you have oxidizer fuel coming in; you have six injectors as you will see here, impinging injectors, radially they are coming into the combustion chamber, combustion occurs here.

This incidentally is not a regeneratively cooled system, this original system is not regenerating a cool; and you have a material called sieve and throw out of the corridor. Some equivalent phenolic resin based composite material is used here; it is slightly ablative, not too much for the burn duration that you are looking for.

And well you will see the actual system; you have turbo pump assembly here. And well the point to notice is this becomes the very red hot when actually; if you see the system operating this becomes red hot and it radiates into the space which is taken at 0 kelvin. And you have you know containers for propellant tanks here and the liquid is stored here, gas pressure comes here; in the analyte space here the gas is delivered here, propellant pressure or the liquids, which will be drawn into the turbo pumps which are located here.

In this particular system they need water as well, as I told you in the turbo pump you need to spray water to cool it down to temperature required for operation of the turbine. And not true in every case, but in this case it is so. And inside the combustion chamber you have some interesting feature you see here.

The fuel is injected near the wall they find spray, this is true for almost every liquid engine and this keeps the wall cool, ok. So, that the heat flux which comes from the hot gases is taken care of in terms of the intensity or ferocitate which it attacks the wall. The liquid actually vaporizes some here; we have removed the throat as well in the way it is designed.

Typically about 15 percent of the fuel goes into this operation. It is contribution to performance is not very significant and the reason is the following; inside the combustion chamber, the fuel and oxidizer are delivered and they move along after impingement in this case along the axis, there is a oxidizer to fuel distribution across.

Now, near the wall, it is always fuel rich. So, when you look at the streams coming out of the nozzle, this portion which comes out with a low temperature exhaust, and hot exhaust comes from the other regions. So, when you evaluate the performance, you to take the total momentum that comes out of this m dot into U V; but different streams have different velocities temperature, so you must take that into account.

When you account for that, you will discover that this the film coolant is not contributing a whole lot to the performance. So, you must limit thick film coolant requirement and this is the objective discussion is intentionally done during the designs, ok. Now there is something called anti slosh baffle here, the liquids when they are moved flying, we find that they can be dancing inside; they want to want to prevent that, because it might have specific frequency which will affect the performance of the vehicle itself.

You also have something called POGO corrector, this you will see is a coupling between all these may be considered rigid or may be flexible depending on the stresses which are applied it turns out that you must read them as flexible elements. And if you do not design this POGO corrector properly, you will discover on occasions that there pressure fluctuations of low frequency which get coupled to the structural system and this becomes amplified and the whole vehicle can get into difficulty; does not happen with this vehicle any time, because the POGO corrector has been designed properly.

In the early part of development Saturn vehicle, it had some difficulties and they applied their mind to how to overcome that; from that point onward POGO corrector is one of the elements of design, is a combination of structures, but propulsion; a feed system coupled to the thrust chamber. The specific analysis tools which are used to understand POGO and remove it.

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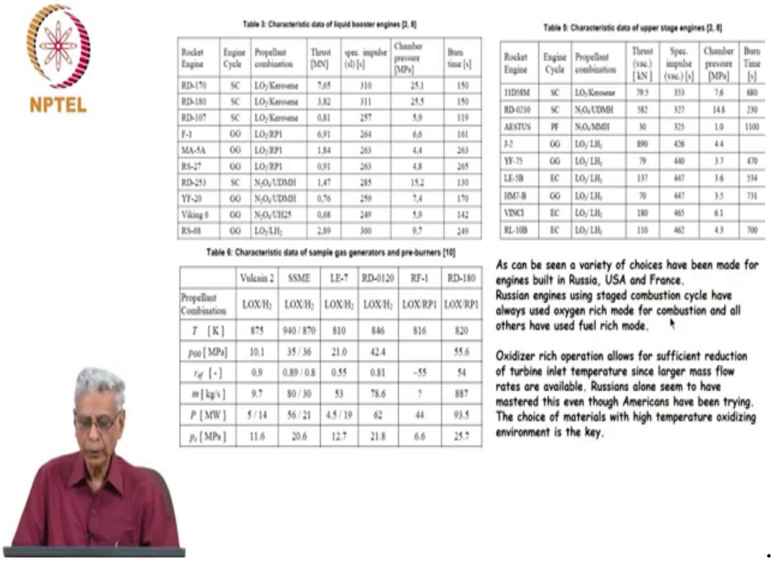

I am put together here specific details of various classes of engines, built by various countries. There are something interesting that you may want to recognize this. You see RD 170 engine, RD 180, RD 107 these are all Russian engines; these are what you see SC stage combustion cycle. As I told you the stage combustion cycle, all the propellants which are gone into turbine and others, the all go to main combustion chamber.

So, the the pressure in the feed system will always be higher than what will happen in the combustion chamber. Well it is specific impulse is a largest; it comes in a 3100 Newton seconds per k g if we will say so. Chamber pressure 250 bars, you can imagine how large it is; burn time is 150 seconds and its thrust is 7.65 million Newton's.

So, you will discover that Russian engines using LOX kerosene, F 1 LOX RP1, RP1 is the rocket propellant fuel which is also form of kerosene. Then you have variety further system, these are all some of them are American RS 27 2 27 is American, RD 253 is Russian and this is essentially the storable hypergolic combination. Viking, this Viking engine is the earlier version for Vikas which a French system N 2 O 4 in UH 25 is a mixture of N 2 O 4.

These are American engine and you will see that these are all stage combustion cycle, gas generator cycle; that means the gases which are going out of the turbine, go out of the exhaust and they do not enter remain combustion chamber. The therefore, the chamber pressures in these systems will generally be lower. You will see that the gas generator cycles here 6.6 66 atmosphere, 44 atmosphere, 48 atmospheres; stage combustion cycle they want to get the best benefit, compactness and so on. There the combustion pressures are very high, ok.

Continued more other vehicles here, we have the J 2 engine which has LOX hydrogen, they quite a famous engine went the Saturn vehicle. And vacuum thrust is 0.8 mega Newton's, very high specific impulse coming out of LOX hydrogen as you see here; both these are gas generator cycles. HM 7 is a French engine, gas generator cycle, American engine RL 10.

So, this you see this specific impulse values of LOX hydrogen are in the range of 430 plus minus 10 things like that. Chamber pressures in the ranges; because these are gas generator cycles, they have pressures of the order of 30 to 40 atmosphere. Varying burn times going up to 1000 seconds.

The gas generators, if you look at gas generators and so called pre burner; pre burner is a idea used in the case of stage combustion cycle. You see this is a French design SSME space shuttle main engine when the space shuttle, LE is a French engine, RD is a Russian design and Russian, this is essentially American design. You will see the temperature of the turbine, turbine entry temperatures are typically in this range, 800 plus minus 100 K, pressures typical of this range.

And the here the oxygen into fuel ratio is different from what happens in a main combustion chamber; it can be fuel rich as usually the case or oxidizer rich and this is speciality of Russian engines. This is what I have written here, as can be seen variety of choices have been made for engines built in Russia, USA and France. Russian engines use stage combustion cycle have always used oxygen rich mode for combustion and all others have used fuel rich mode.

The oxidizer rich operation, it allows for sufficient reduction of turbine inlet temperature; since larger mass flow of oxidizer is available. Remember the oxidative fuel ratio is in the range of 3 to 4 or 5; this is because air to fuel ratio you had kerosene 15, 16; remove the nitrogen will end up with 4 or 5.

So, these numbers are consistent whether you are using air breathing engines or rocket engines. And turbine inlet temperatures can be achieved and you can manage to run the turbine with that a larger mass flow rates available; because of the oxidizer being pushed in. Russians alone seem to have mastered this, even though Americans have been trying. The choice of materials with high temperature oxidizing environment is the key; it is not easy to develop materials which are also oxidizer compatible at high temperatures, ok.

This is not really my statement; it is stated even in American literature.

Student: Sir.

Yeah.

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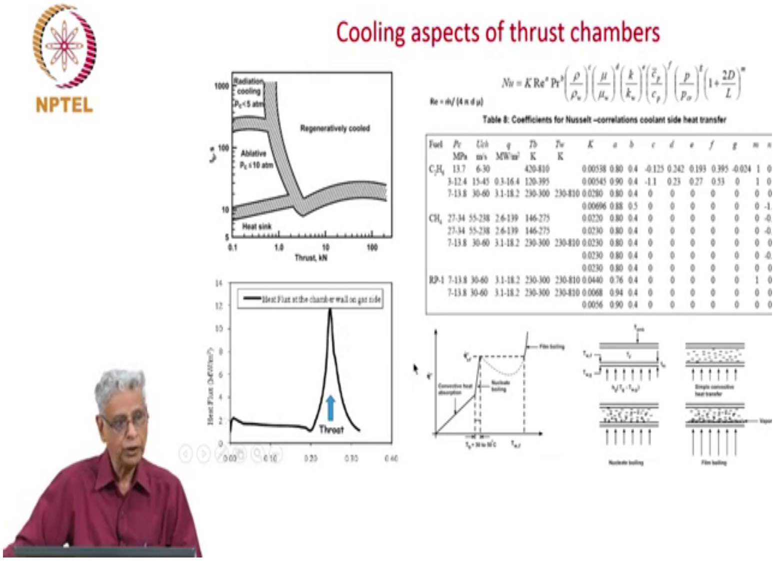

Student: This LOX hydrogen is a semi cryo engine. Student: It consist a semi cryo engine sir.

Which one?

Student: This oxygen code for conduct any other (Refer Slide Time: 16:48)

It can be used, it is used for the semi cryo in the application that they have done; but once you have the ability to do that depending and the other elements have design does not prevent you from using that. The point I am making is whether a specific design which adopts it for LOX hydrogen is a different question.

But the basic question is, if you are using oxidizer rich operation using that as a coolant and in LOX hydrogen; in the case of LOX hydrogen you still use, you can use hydrogen as a coolant also because ultimately you are going to deliver it in the form of a gas know. In even in the case of the design which is used in ISRO, your hydrogen coming as a gas and it is coming for the coolant channels and the pre burner creates products which are oxidizer rich and pushes into the core.

Student: Sir basically this is not for (Refer Slide Time: 17:50), what we have discussed is for pre burner (Refer Slide Time: 17:53) thus we will have high oxidizer which can (Refer Slide Time: 17:54)

Yeah.

Student: coming with the (Refer Slide time: 17:55) combustion.

Yeah.

Student: yeah. So, (Refer Slide Time: 17:58)

Yeah.

Now, ultimately you your ability to do one thing are there that is controlled by the fact whether we have material compatible with oxidation at high temperature; and only point I am making these Russians seems to have mastered their technology, so this is otherwise not available.

Well, I look at cooling aspects now. I wish to tell you that the subject is so vast, I can only address a few of them and I will address only select few of them; as I see it has prominently some bias from myself. So, if you have other point to make you can raise the questions, we can debate them. Cooling is an important element in all such liquid engines.

And you can do a simple analysis, your choice of ablative cooling as I saw you saw in Vikas engine. You can use regeneratively cool systems as used in other engines of LOX kerosene or LOX hydrogen. And you can use simply a heat sink for short durations are small thrusts as it happens in monopropellant systems.

So, it is a function of burn time and the thrust and short burn times and you do not have really large thrust anyway, the short burn durations; usually shot burn durations have small thrusts and you can afford not to have anything other than a heat sink. As I told you in the case of the Vikas engine, the whole thrust chamber becomes red hot and radiates heat, it is ok. For 100 seconds or 150 seconds it is perfectly reasonable to have it.

Pressures are not large this is the reason. And if you go to ablative domain, you have larger temperature range; you cannot have too much of higher pressure, because higher pressures means higher heat fluxes and it cannot stand that. And if pressures are low, you can do radiative cooling as well as I mentioned in Vikas engine

Larger thrusts and larger burn duration, you have probably no choice, but to use regeneratively cooled. In point of fact the Vikas engine, there were debates at some point of time whether to convert that into regeneratively cooled system. So, which means that is in the borderline case between one or the others.

If you had done regenerative cooling, you would have gained in terms of performance; because the liquid would have been heated, pumped into the system for gain, ok. It is a matter of design ultimately in choices you make in development of a system.

I just mentioning to you a key point here; if you look at the heat flux inside the combustion chamber. Now I what I mean is, you go along the axis, hot gases are moving transferring heat to the surface. Just remember every liquid engine has film cooling. So, that benefit of vaporizing that liquid is taken advantage off. You will see the heat flux through the thrust chamber is a firm value, near the throat it goes up to very large values. You may want to ask why? Why does it happen, that as you throw you have a very high heat fluxes?

The flow rate is the same; we are reducing the coolant diameter, why does it happen? Well I do not want this to be a discussion session, but I just want to show you the result here, the Nusselt number which is indicating heat transfer coefficient is a function of Reynolds number and the coefficient a is about 0.8. That means, R e to the power of 0.8 it shows that the flow is turbulent, that is Nusselt number going like Reynolds number to the power of 0.8 implies that the flow going past the surface is turbulent that is all it says.

So, the Nusselt number behaving with Reynolds number mean what is the question. Now if you see here, Reynolds number you can express it in rho u d by mu or you can say m dot by 4 pi d by mu. And if you follow this, you see that mass flow rate is constant through the whole system; but d changes, d comes down and increases. So, d is the lowest at the throat; that is the reason why the heat flux which is proportional to R e power 0.8 means d to the power of minus 0.8, will show you that it will be the largest the throat. This is just the elementary feature that you may have to keep in mind.

There are few tricky features in the design of a cooling systems, which actually border on heat transfer and some of you from mechanical engineering must be aware of this. What you see here is the heat flux coming from the gas and you have inner wall and you have a surface with liquid which is flowing here and you have been (Refer Slide Time: 23:09) conditioned.

So, this you have a heat flux which transfers there is a temperature which is achieved here in steady state, other temperature achieved in liquid side and you have a flow liquid flowing through it at which temperature is increasing. So, your simple convective heat transfer will just take the heat and it moves off; but you could go to a stage where you begin to nucleate boil, that is small bubbles keeps start coming out and they carry, but more heat in somewhere. So, at that the heat transfer, the heat flux which is absorbed from the system goes up substantially.

But you can only go up to some stage. If you go up to that below this stage, you are in good shape, your the heat flux that extracted from the what is delivered to it from the combustion chamber is extracted better and the temperature is not going too high. You see the liquid temperature is changes because only very small amount here. But if you are careless this goes to nucleate boiling, it goes to film boiling; which means a thin film of fluid or stream is passed and in between the temperature has to be very large, temperature gradient had to be large to extract the heat to the wall temperature shoots up dramatically.

As you see here the wall temperature has been is increased to very high values. And if this happens, it burns up there; now you have lost your hard work. So, that is why this design is a very critical feature. And to ensure that it happens in regenerating the cooling systems, they do you know many many strategies; they introduce a liquid into one place, take it downstream, take it upstream, and introduce additional liquids somewhere. In the case of the engine which is being built in ISRO also many of these strategies are deployed; just because the Russian design which for on which this is based has very similar features.