Fundamentals of Combustion for Propulsion

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Lecture - 23
Combustion in liquid rockets

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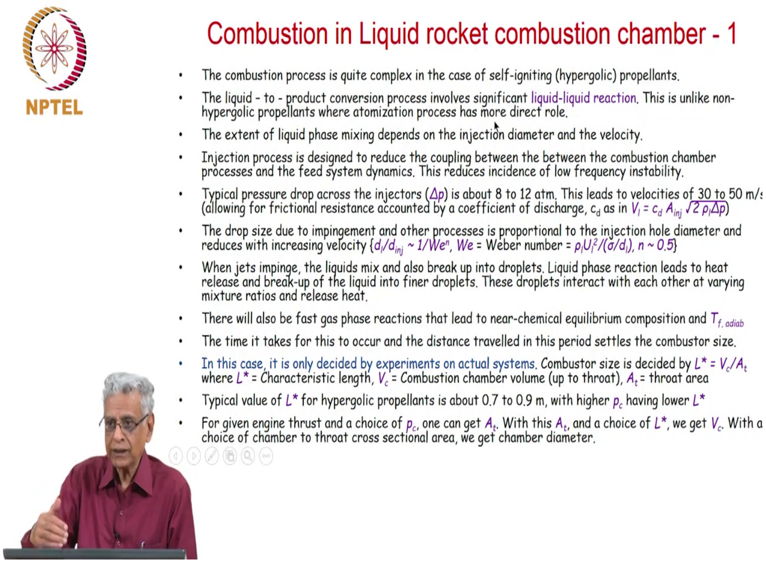

So, I think we move to Combustion Liquid Rocket engines, which is a prime subject which we need to deal with; but let us see what I have to say about the subject. I will begin by saying that combustion process is quite complex in the case of self igniting propellants. You can do this in two ways; the called like injection, which means the fuel is injected on the fuel or unlike injection fuel is injected against the oxidizer. In the case of VIKAS engine, these like injection; you have the fuel elements which impinge on each other, oxidizer elements which impinge on other. It is the droplets, this secondary atomization process is to bring fuel and oxidizer together.

If you bring the fuel and oxidizer together in the primary mode, but makes impinge one over the other; the heat release rates are very large and the cool combustion process gets completed very fast. Keep this in mind, because here the implications on the stability of the operation of the engine.

The liquid to product conversion process involves liquid-liquid reactions anyway in hypergolic systems. This is unlike non hypergolic propellants where atomization process has a more direct role. It is something which you need to keep in mind. The extent of liquid phase mixing depends on the injection diameter, injector diameter and the velocity.

The injection process is designed to reduce the coupling between the combustion chamber processes and the feed system dynamics. This reduces the incidence of low frequency instability; otherwise the pressure drops are low, any pressure fluctuation here will imply that the feed rates will change. And normally there is always a phase difference between the time at which is delivered and time which at which it feels the pressure, because of this you will find low frequency instabilities, typically in the range that are 100 Hertz or so.

And whenever if somebody gets 100 Hertz, he is not worried in design; he knows what to do, which is and this is done by essentially removed by essentially remove the coupling and you create enough pressure drop across the injector, typically 10 to 15 atmospheres. If you provide any liquids, you will discover the processes that occur in a combustion chamber or decoupled from what happens in the feed system and so low frequency instability possibilities are low.

Not only that, the injector behavior has some features. If you pressure drops, pressure drops across the injectors are low, you will find hysteresis; you will find when the flow goes in, it has got a certain coefficient of discharge; when it comes down for whatever reasons and re-injects, you find hysteresis behavior and the coefficient discharge will change and we should not experience such behaviors, because it will add to the coupling.

So, to avoid the coupling between the feed system and the combustion chamber; one must keep the pressure drops reasonably high. And I have indicated here is the 8 to 12 atmospheres. And what does they do? This leads to velocities at the injection of 30 to 50 meters per second and you allow for the frictional resistance by invoking a coefficient of discharge; you know V l is equal to C d A injector root of 2 rho l delta p.

And the drop size due to impingement with the other processes is proportional to injector hole diameter and reduces, this drop diameter reduces with increasing velocity; because the droplet diameter to inject a diameter goes like one by Weber number to the power of n and n is typically 0.5 in such cases and it is the dynamic pressure to the surface tension force, ok.

When jets impinge, the liquids mix and also break up into droplets. The liquid phase reaction leads to heat release and breakup of liquid into final droplets. These droplets interact with each other at varying mixture ratios and release heat, a complex dynamics occurring in a short domain after the injector phase. Of course, there will be very fast gas phase reactions that lead to near equilibrium composition and the achievement of the adiabatic flame temperature.

The time it takes for this to occur and the distance travelled in this period, it settles the combustor size. In this case it is only decided by experiments on actual systems. You may ask me, why. So, you may try and do a complex design of injector dynamics; the key parameter which and which it depend on the droplet diameter and there is a distribution around that. And the processes which occur to create that they are very complex; you may say I want to modelled it, yes you can model that, the ratios are around that and you have to validate it.

The only validation for such a model is the test; the test is actual performance to the engine. And well if you are good enough, you will create a sufficiently complex model; you do sufficient number of experiments including the different scale to ensure that the model is correct. Once you have done that, keep the model to yourself, do not give it to anybody else that is the typical strategy adopted by all the people.

So, it is only decided by experiments and the combustor size is decided by L star characteristic length, which is the volume of the combustion chamber divided by throat; the point which Doctor Varun talked about yesterday. And the typical value of L star for hypergolic propellants is about 0.7 to 0.9 meter and higher pressures have slightly lower L star. But the change is not too much; as you see 0.7 to 0.9 meter is you can choose 0.9, 0.8 whatever is shown.

For a given engine thrust and a choice of the chamber pressure; because you know psi star, so you can get the throat area, F is equal to C F P c 80, and so 80 you know coefficient of thrust you know, therefore, you can give me compute you know P c and one can get A t. Then you know this 80, the choice of with a choice of L star, you get the volume of the combustion chamber; with the choice of the combustion chamber to throat cross sectional area, we actually get the combustion chamber diameter as you will see next.

Student: Sir.

Yeah

Student: sir this sir somewhat I incident it, like (Refer Slide Time: 6:43) unlike igniting hypergolic propellants

Uh.

Student: The atomization process have a direct impact on the (Refer Slide Time: 6:49).

Yeah.

Student: (Refer Slide Time: 6:50).

Yeah.

Student: It is in injection.

We will discuss it on the way and if you can come back with the questions on some of them, because I am going to look at some of the other aspects as well.

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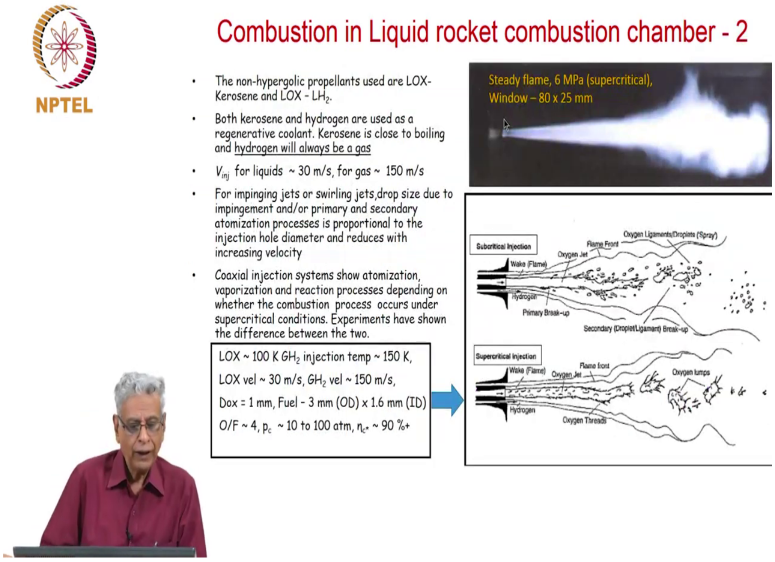

Non hypergolic propellants lox kerosene, lox hydrogen; both kerosene and hydrogen are used as a regenerative coolants. Kerosene is close to the boiling point and hydrogen will always be a gas. V inject V injector velocity of the injector a for liquids is 30 meters per second, gas around 150 meters per second; and density is low in spite of the fact at high pressure. And so, you need a cross section which is large; even if you provide further, the velocity has to be on this class.

For impinging jets or swirling jets, the drop size due to impingement or and or primary and secondary atomization process is proportional to injector hole diameter and reduces with injection velocity. This feature is general; I mean you can take that as valid all the time; whether it F 1 engine related stuff or any other engine, increasing the injection hole diameter always increases the drop diameter.

Coaxial injection system show atomization, vaporization and reaction processes; depending on whether the combustion process occurs under supercritical condition. This is the these are another parameters get introduced; experiments have shown that, there is a difference between subcritical and supercritical operations. You will see here subcritical operation of in one of the they say orifices nozzles which come up, we will find hydrogen and oxygen coming from here; we will find the liquid hydrogen breaks off into ligaments in droplets at a certain distance.

In the case of supercritical operation, I think this also brought by Varun yesterday; you will see that comes out as lumps, oxygen lumps and the use what is called thread and some. These are observations of whatever had happened in single injection hole systems. And this is also combustion that will occur at 60 atmospheres supercritical and this is window of about 80 millimeters length and 25 millimeter taken from a German research, ok. Well this particular system has a combustion efficiency of 90 percent; so it is very representative of what happens in reality, ok.

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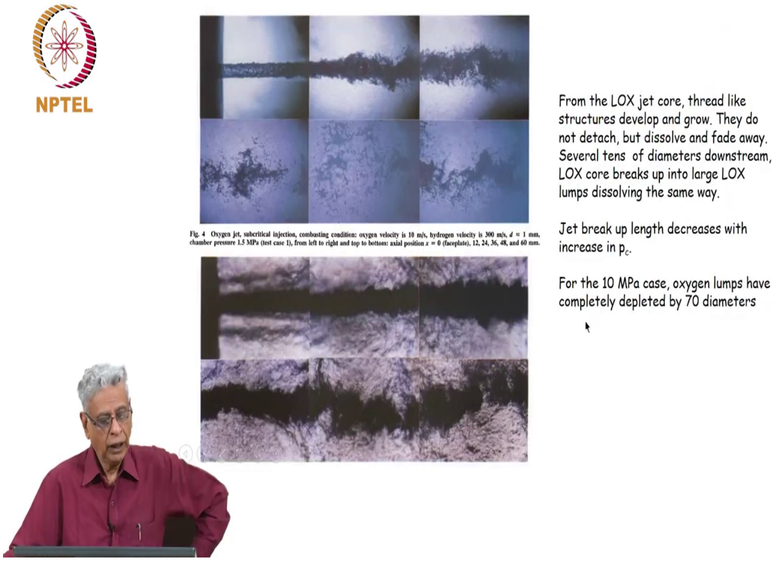

You will find more pictures of this from actual systems; this is the oxygen jet (Refer Slide Time: 9:30) subcritical injection, combusting condition, velocity of oxygen velocity 10 meters per second, hydrogen velocity is 300 meters per second, diameter 1 millimeter here. Chamber pressure is 15 atmospheres typical, left to right to bottom axial position in the faceplate and at various distances; that is this distance is the faceplate from here 12 millimeter, 24 millimeter, 36 millimeter, 48 millimeter, 60 millimetre.

You see how the developing over there, they are taking this a composite picture taken from various sections. It breaks down at some conditions around 60 mm also from the injector; then 1 mm to 60 mm you will find the whole thing has broken down, that is what I am saying here. Well from the LOX jet core, thread like structures develop and grow; they do not detach, but dissolve and fade away. Several tens of diameter downstream, LOX core breaks up into large LOX lumps dissolving the same way.

Jet breakup length decreases with increase in chamber pressure. For typical 100 atmosphere case, oxygen lumps have completely depleted by about 70 diameters. So, some of these give some insight into the way things behave inside the combustion chamber, ok.

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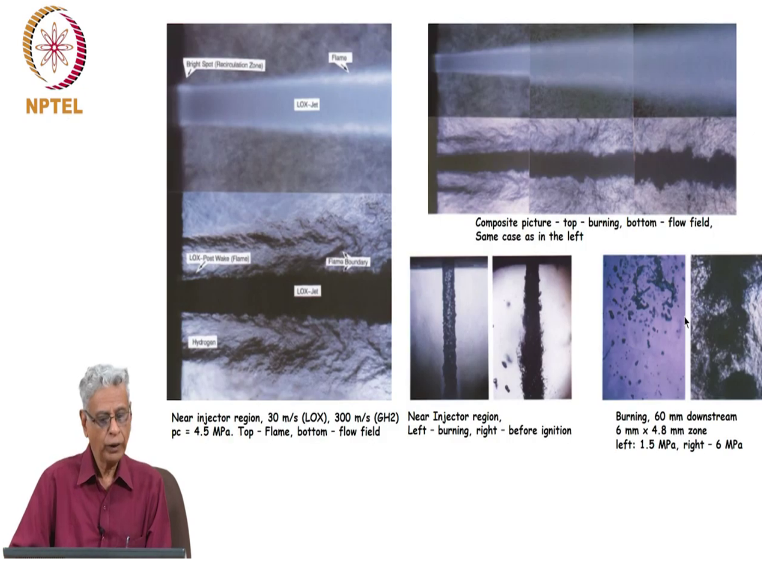

More pictures here, you will see the flame from that from the actual combustion system; LOX jet and bright spot which is a recirculation zone close to the injector phase are different phase and well what else can we get out of that. The same picture, top is burning, bottom is the actual flow field in the system; when it is not burning, you can look at how things are ok, here the jet flow, but actually combustion system is not what you see.

As I mentioned in summary this is about 70, 82 diameter from the injection point; you will discover that the whole thing is broken down. It is a good thing to know, because you also can look upon this in the simulations and make sure that simulation is actually using the combustion chamber, the full combustion chamber, it make design appropriately, ok.

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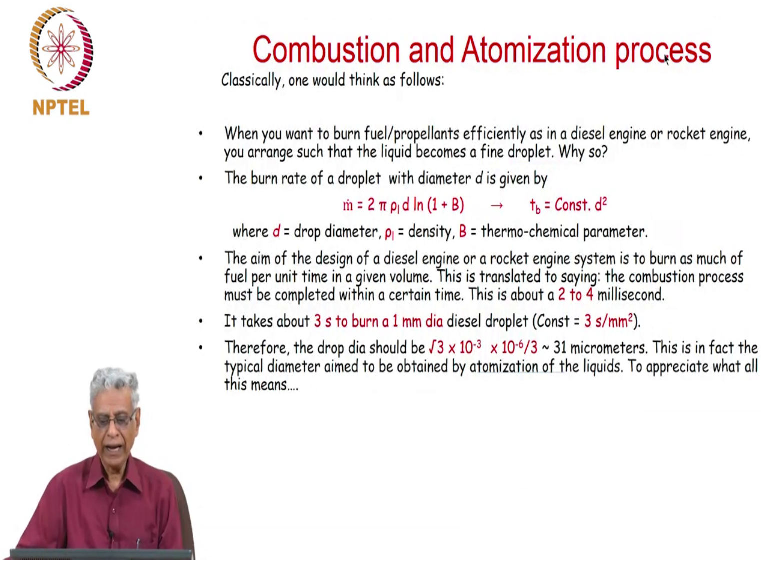

I this may be something which appears like already done piece of work; but just roughly brush through. When you want to burn fuel or propellants efficiently as in diesel engine or rocket engine, you are inserted the liquid becomes fine droplets.

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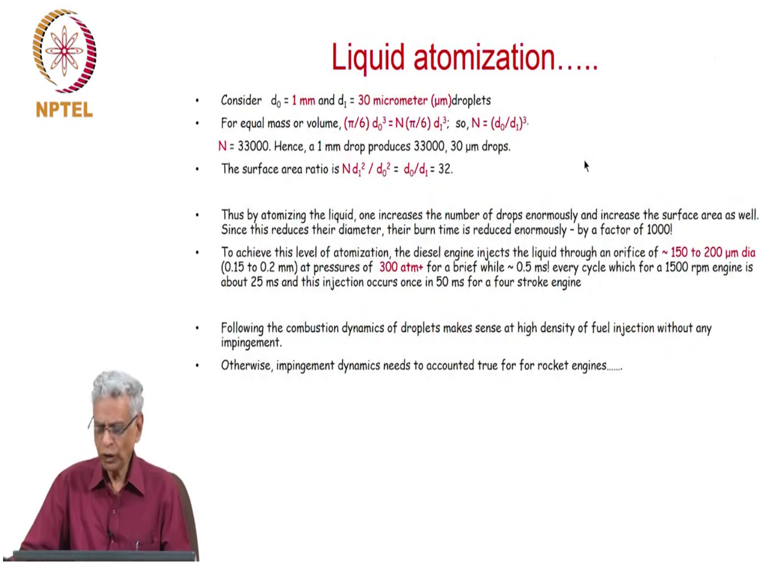

I think you know why you want fine droplets. So, I do not want to spend time on that; perhaps move ahead, just want to show you some numbers, so that you know what this means. I know that you are aware of it, but you should know. If you look at 1 millimeter droplet and a 30 micron droplet, for equal mass or volume you will discover that pi d cube by 6 must be same as the number of droplets of the small diameter d 1 cube. And therefore, the number of droplets of the smaller droplet will be d naught by d 1 cube. So, for 1 mm to 30 mm, you have 30000 droplet 33000 droplets sorry, 30 micron in comparison to 1 mm.

So, the surface area is not as much change is about 30 times and this which is the count in when you look at the evaporation, the surface area dependent stuff. So, nevertheless the benefit from going from 1 mm to 30 m microns is that, there will much larger surface area for evaporation; and therefore, atomization is an important element to convert liquid to gases in as short a time or space as possible, ok.

Since evaporation depends on surface area, you will discover the benefits are very substantial. So, the level to achieve this level of atomization, the diesel engine injects the liquid through an orifice which we talked about some time ago. And for the short duration and same thing is true with rocket engines as well; though one does not use such small diameters, except in the case of monopropellants and things like that, even there the diameter will work 0.5 millimeter. In the case on gas turbine engines that, diameter is typically about half mm to 0.7 mm.

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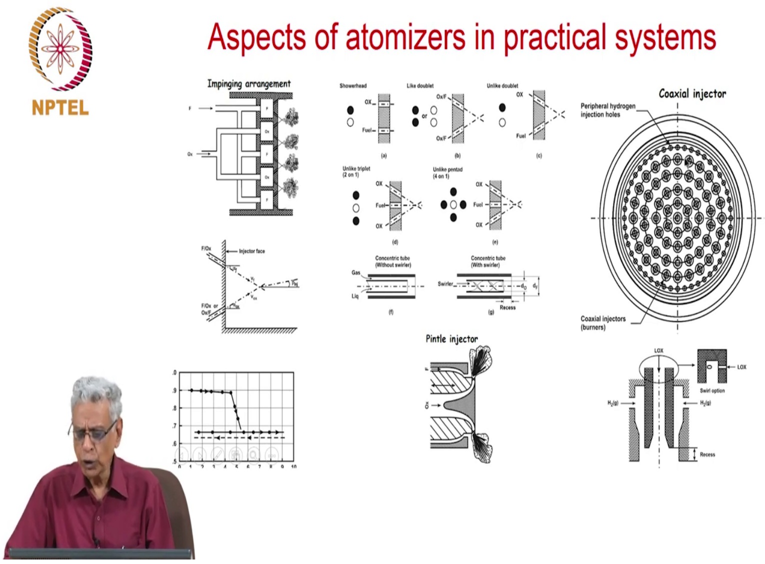

If you look at atomizers in practical systems, you must remember that the liquids and the fuel oxidizer and fuel liquids must be introduced separately. And you can this injector to this is the you know, old time it was been tried out; nobody is uses it, is crushed showerhead injectors.

And the mixing is not going to take place directly, it takes some distance; and coaxial injectors may be thought of as equivalent of this, but designed differently. Like doublet, unlike doublet; that means, fuel and oxidizer impinge here, oxidizer or fuel impinge separating. Point which I discussed a few moments ago; you can use triplets, pentad; it is up to you, you can design whatever you think you want to this.

In fact, so many items of such designs are putting the F 1 injector design. And you have you can also, there are also questions about it; which direction do you want to gets to go, you want to get axial or you want to go to a certain angle. You can depending on the momentum you push here and here; you will find a resultant direction will be of one kind.

And you have concentric cubes without swirler or with swirler and there are many options here too. And this is the standard coaxial injector based on the Russian design; it has LOX coming here and you can also introduce that swirl here and hydrogen coming here axially. You can introduce hydrogen also as swirl; therefore, the ever so many combinations exist in the design of the system.

I mentioned to you about the coefficient of discharge and the hysteresis effect which is just to shown here, I think we talked about it earlier. There are another design called pintle injector, which will develop and support a very stable operation; and it is not really used, these days in any of these systems, but you can read that in the literature.

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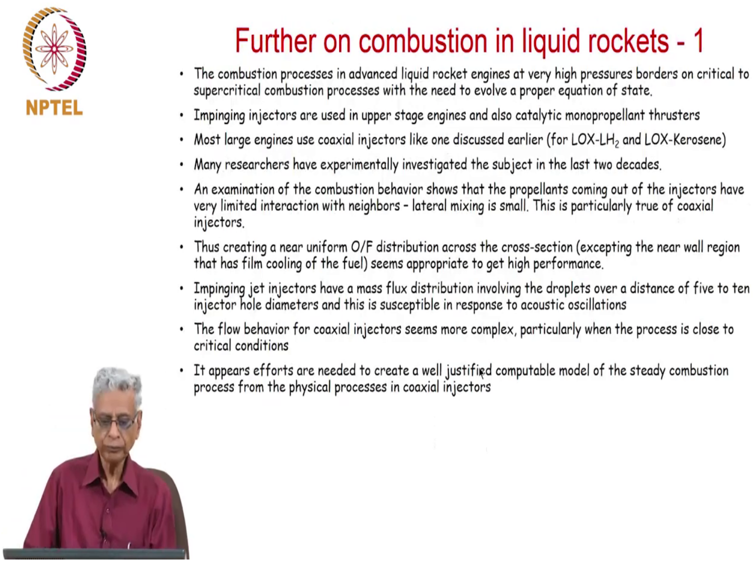

I want to move on quickly to some other aspects as well. The combustion processes in advanced liquid rocket engines at very high pressures borders on critical to supercritical combustion processes, it need to be about proper equation of state which I mentioned to you.

So, if you are doing some analysis on this, you must know how things behave is it; it is important, because the steady operation also should be you should be able to predict it and compare it with the experiments and if it was the right model, you can be able to make predictions for instability.

Impinging injectors are used in upper stage engines and catalytic monopropellant thrusters. Most large engines use coaxial injectors like one discussed earlier, we saw various details. So, many researchers have experimentally investigated the subject in the last two decades.

So, the examination of the combustion behavior shows that the propellants coming out of the injectors have very limited in interaction with neighbors, this is particularly true of coaxial injectors. Let me explain this a little bit that is, when you have a system like this ok; you can design each injector or each group of injectors in a slightly different way, you have a choice.

It has been done in the case of the Russian engine LOX kerosene system. When such things happen you are tempted to ask; why have they done that, is there something tricky. You may say I do not care, I will do something else; you are always worried, it is a large engine, to construct the engine is very difficult, you do not minimize the engineering aspect of that, it a very difficult thing to construct such an engine.

And you may build one engine, it takes 6 months; you do a test, it fails, you are in trouble, you do not know which way to go. So, you are always have to think through carefully say; am I doing the right thing in changing or am I doing the right thing in accepting. And there may be questions on both sides; so sometimes you have to hold your heart and say look, I think this is right and then go ahead. And when you get into problem, you face them and you have to resolve the issues at that time, ok.

The point I want to make is, if you look at each one of them, there is a certain O by F for each of these injectors and you can make them differently; but it turns out when you do an analysis of the system. If you take such groups, they the groups flow inside the combustion chamber, if I want to show you.

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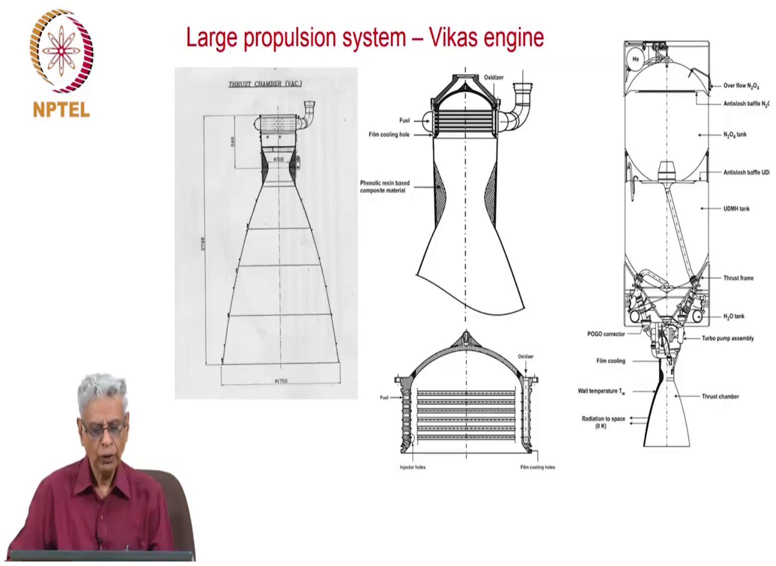

The flow to the combustion chamber is specific streams, it is true even here, they take a specific track and come here; which means, if you take a group of injectors you can track them, they actually move with the same O by F.

So, if you have different O by F across the cross section, those different streams move at different O by F; there is not too much of lateral interaction. The reason is also simple; when you have high injection velocities, the axial momentum is so large that hardly anything is possible for lateral action in terms of mixing, ok.

So, that is the point I made here. And I am also saying creating a near uniform oxidizer or fuel distribution across the cross section accepting the near the wall region where you have film cooling seems appropriate to get high performance. It seems appropriate to get high performance without instability also, the point we will talk about later.

Impinging jet injectors have a mass flux distribution involving droplets over a distance of 10 to 15 injector hole diameters, these are susceptible to respond to acoustic oscillations. Again a I will address it later, but just to let you know, if two injectors meet here, it creates a spray; depending on the orientation, you may get something like this or something like this, you can design it in various ways.

And therefore, you have droplets coming and occupying various zones in front. To determine how much of oxidizer to fuel are coming, you have methods of doing that; you can collect the liquids and say this is the mass flow flux distributing at various stages after the injection has been has happened. And that is important as well when you are looking at a susceptibility to instability and we will see that as I mentioned a little later.

The flow behavior for coaxial injector seems more complex, particularly when the process is close to critical conditions; otherwise it is mostly axial. It appears that efforts are needed to create a well justified computable model of steady state combustion process from the physical processes in coaxial injectors. Whereas, impinging jet injectors have been addressed for a period of time, so coaxial injectors have not been addressed as much. They have been addressed the through competition tools by some groups, but not addressed as much.

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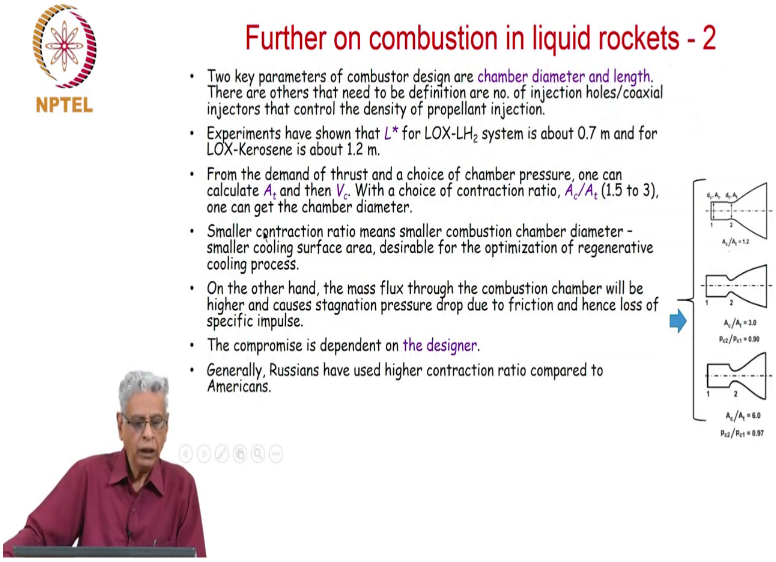

The key, two key parameters of combustor design are chamber diameter and length and there are others that need to be defined need to be defined are; number of injection holes and coaxial injectors that control the density of propellant injection. Experiments have shown that L star for LOX H 2 system is about 0.7 meter and for LOX kerosene is about 1.2 meter. And that you can understand that, kerosene has to evaporate in; the only way if that happening is more difficult compared to hydrogen and therefore, it takes a larger L star.

From the demand of thrust and the choice of chamber pressure, one can calculate A t and V c as I mentioned earlier with the choice of the contraction ratio 1.5 to 3, you can get a chamber diameter, ok. Here is some interesting thing that you must note; Can variety of designs you can take A c by A t as 1.2, you can take as 3, you can take it as 6, many possibilities exist.

Smaller contraction ratio means, smaller combustion chamber diameter, smaller cooling surface area, desirable for the optimization of the regenerative cooling process. Because if you have to have a large combustion chamber, you have to cool all of it; the surface area is large, so the heat flux is much larger, so you need to account for it. But when you have a smaller combustion chamber; that area we through which the liquid flows the smaller, so you are slightly better off trying to cool that zone.

On the other hand, the mass flux through the combustion chamber will be higher; this causes stagnation pressure drop due to friction and loss of specific impulse. You see here that, if you take P c 2 the to P c 1; that is stagnation pressure at the opt end divided by the stagnation pressure at the head end which 0.97 here, 0.9 here, it is even lower here more 0.85 or so. So, at least you are going to lose the stagnation pressure means according to the performance; because what matters is the fact that, what delivered to the nozzle or stagnation pressure at which it is delivered to the nozzle that gives you the thrust, P c 80 by C star that P c refers to the stagnation pressure at the inlet to the throat, ok. I have few more aspect to be looked at.

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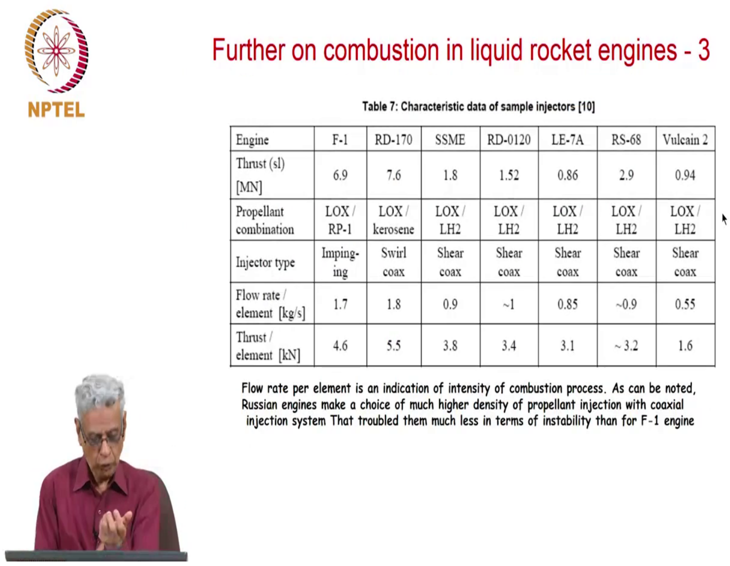

Engine	F-1	RD-170	SSME	RD-0120	LE-7A	RS-68	Vulcain 2
Thrust (sl) [MN]	6.9	7.6	1.8	1.52	0.86	2.9	0.94
Propellant combination	LOX / RP-1	LOX / kerosene	LOX / LH2	LOX / LH2	LOX / LH2	LOX / LH2	LOX / LH2
Injector type	Imping-ing	Swirl coax	Shear coax	Shear coax	Shear coax	Shear coax	Shear coax
Flow rate / element [kg/s]	1.7	1.8	0.9	~1	0.85	~0.9	0.55
Thrust / element [kN]	4.6	5.5	3.8	3.4	3.1	~ 3.2	1.6

Further on combustion in liquid rocket engines, if you look at variety of engines; in the respect of what I talked about in the previous slide, you have F 1 engine, RD 170, SSME engine, these are Russian engines, this is a reference engine, American engine, Russian engine, French engine. Various levels of thrust, various propellant combinations, various injector types; but you will see that most of these are coaxial swirl, some have swirl and some do not have swirl.

And the key point I want you to address is, flow rate per element and thrust per element; that is what does this mean? You have certain thrust, the certain injector hole combinations. How much is the thrust per element, that is a measure of the intensity of combustion if which you are using the combustion chamber. And the point to note is that, Russian engines make a choice of much higher density propellant injection with coaxial injection. That troubled them, in fact charge of the trouble much less in terms of instability compared to F 1 engine.

The amount of F 1 effort that has gone into F 1 engine in terms of instability removal is mind boggling; but this is happening in one end of the world, the other end of the world they are happily building large engines without any instability. So, the matter which is perplexing and one of the aspects is related to the fact that, they use only coaxial design. You may ask why is it they use coaxial design, why they did not contemplate the injectors impinging inject injectors?

Many of these related to history and where exactly they got the input from an world war 2 occur; they got some hardware from Germany, some people from Germany, some native thinking, some combination led to coaxial injection systems. In the American systems they develop based on impinging engines.

Once you get into a certain design, proceed far proceed some distance along the length; you have invested money, you have invested people, you have done experiments. Now maybe halfway down you realize that, you could have changed to something else; because you learn it from some other sources that Russians are using essentially coaxial injectors. You cannot change at that time, you are committed to certain action; that is the reason which I mentioned to you in large scale development, you need reviews, you need lot of thinking and sometimes to think for yourself and pray lord that, that choice is right.

I am not saying this is the in a loose sense, this true for every designer in every part of the country; you are taking great risks when you take a large system design. You get input from many sources, some conflicting, some supporting; where they supporting, you take the decision no problem. When there is conflict, you have to make a choice, where is it, which is it you trust more; sometimes a calculation is more trustworthy than an experiment to result, and the calculation otherwise worthless compared to an experiment, you make a combination in your mind, think and make a choice and that works, it works, that is all, ok.

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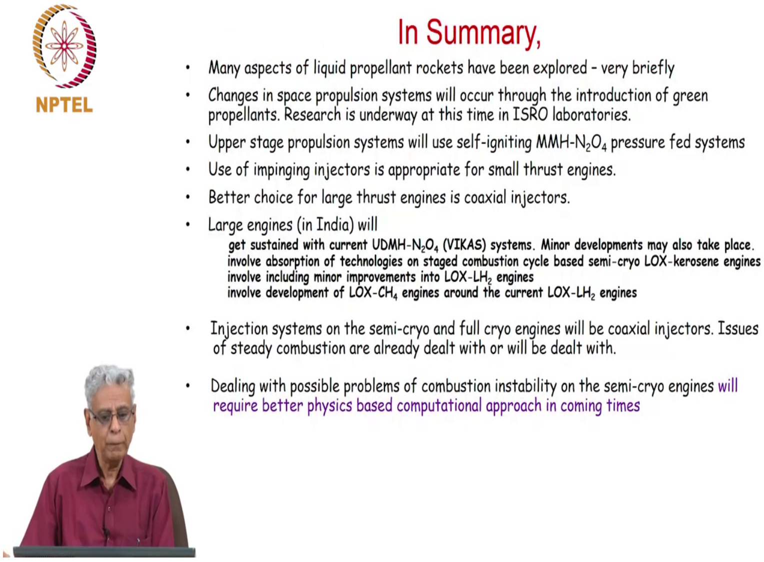

In summary I want to say, we have looked at many aspects of liquid propellant systems at very briefly; normally liquid propellant rockets occupy a three created course in a new university. So, you need to look at each one in some detail; but just as a taste of what it is, we are just looked at briefly. Changes in propulsion, space propulsion system will definitely occur through introduction of green propellants; and not because of great desired, of pressure. Research is underway this time in ISRO laboratories. Upper stage propulsion system will use self-igniting monomethyl hydrogen, nitrogen tetroxide pressure fed system and that is something which you cannot change too much.

Use of impinging injectors is appropriate for small thrust engines. So, why I should not look like blaming impinging jet injectors, they are still of value in small thrust chambers. Better choice for large thrust engines is certainly coaxial injectors. I must also tell you something I would not have known some years ago; there is something which in the Russian technology development came to my attention, then only many of these things seemed so interesting, I must say that. And it also because lot of we are actually faced with a lot of American literature; Russian literature is not as much available, nor are we affected by it. So, this is the problem of culture.

A large engines in India will get sustained with current UDMH N 2 O 4 systems, is it not; many minor development may take place with their own minor. They involve absorption of technologies and staged combustion cycle based semi-cryo LOX-kerosene engine that is something to happen. And they also involve including minor improvements in LOX LH 2 engine which have been successful. Involve development of LOX machine engines around the current LOX LH 2 engine, I think it will become successful.

Injection systems on semi-cryo and full-cryo engines will be with coaxial injectors. Issues of steady combustion are already dealt with or will be dealt with. Dealing with possible problems of combustion instability on the semi-cryo engines will require better physics based computational approach in coming times. I think these are the issues I wanted to bring to your attention.

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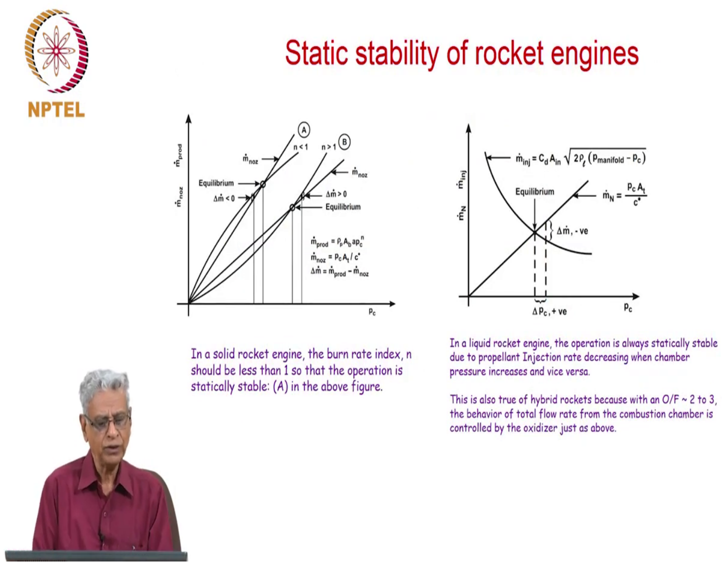

Finally, I want to ask, I want to just show you this feature in relationship to what Doctor Varun mentioned yesterday about equilibrium. He spoke a whole lot about the instability which will occur when the pressure index is more than 1, and stable when it is less than 1 for case of solid rocket engine. It is true; in solid rocket engine burn rate index should be less than 1, so that the operation is statically stable. And nobody were talks of static stability for liquid rocket engine, you know you cannot find it in a book I can assure you; but the answer is simply here.

If you look at the flow through the nozzle as in this case and you will find it is a straight line with an angle slope of A t by c star; this is drawn it will be up to Pc, so the slope of this line is A t by c star. But if you look at injection the C d A injector, where it have 2 rho d into P manifold is ahead of the injector and P c; because of this it comes like this.

So, as P c increases, the flow rate comes down; that is the reason why if the some pressure particles increases the pressure, flow rate comes down; if pressure pulse decreases the chamber pressure, flow rate increases. So, it is statically stable. And I must also tell you it is true with hybrid rockets that, the oxidizer to the fuel ratio is large; so mostly oxidizer which comes in 25 percent fuel, 75 percent oxidizer, so it comes through injector.

So, this broad behavior which you see here is also valid for hybrids; which means, liquid rockets are always statically stable. Just two great solids, because when they get to trouble, they do dynamically the unstable and took you into difficulty; this is the we should be addressed and we will perhaps look at it tomorrow. Till that time, good bye.

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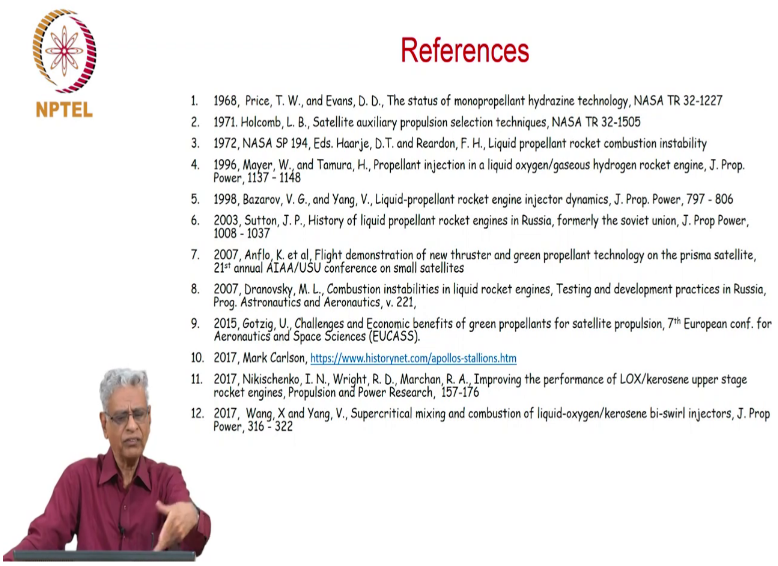

I have set of references which you know want to look at it later. Now, all what I have written here is based on most of it is covered in these references.