Fundamentals of Aerospace Propulsion
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Lecture - 40

Let us start this lecture 40, with a thought process from great scientist Albert Einstein.

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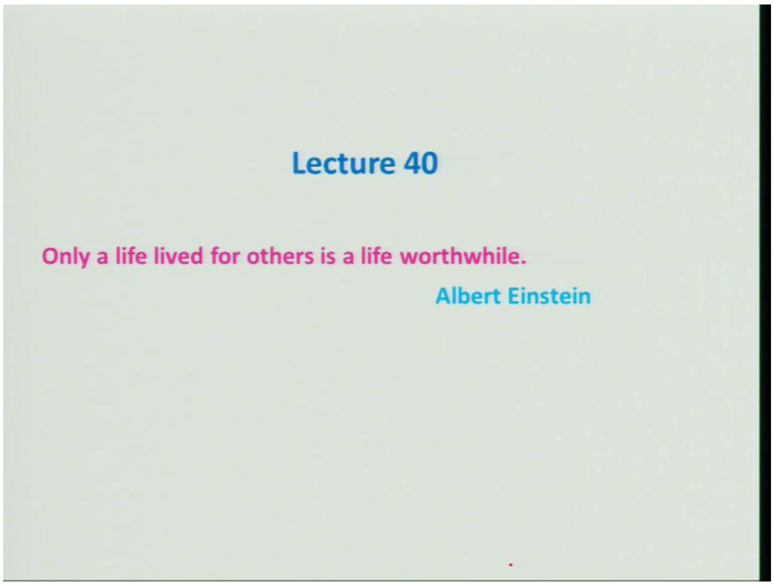

Who says only a life lived for others, is a life worthwhile, I think we should wonder about this thing and look at our life. Let us recall what we had learned in the last lecture, we are basically started with of course, little bit about solid propellant, and looked at the stability of the operation. And then, we moved in to what you call like various grain, structures and other things.

And then, we looked at the liquid propulsion systems and various components, and one of the major important component is, what you call the injection system. If we look at this injection system and whose objective is basically to atomize the liquid fuel, and oxidizer.

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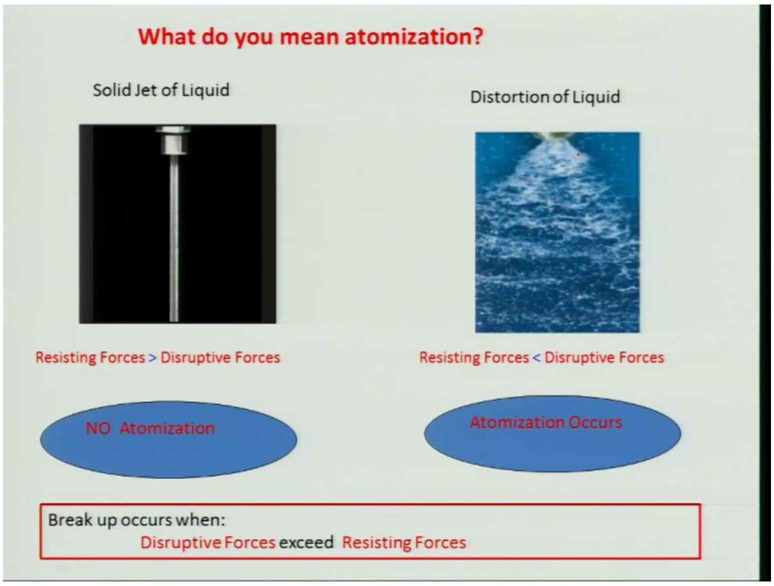

But, question is the just what do you mean by atomization, and what are really processes which involves, I will just give a brief description about that. For example, you might be knowing or you might have observe that, if there is a liquid which is passing through a small RFS, it will be coming like a jet here. So, what is happening here, it is like a jet which is not being fragmented that means, all this molecules will be together and moving.

That means, although there is a flow, because you have applying little pressure or you will allow the pass due to the gravity, like if I take a whole and put it. Now, we need to disrupt it, basically atomization is a processes of bricking the bulk liquid in to the spray, or in to the number of droplets. That means, we need to apply certain kind of disruptive forces, and that disruptive forces must be greater than what, resisting forces yes or no.

What are the resisting forces which will be acting here in the liquid, what are those like viscosity is one of them and other is you surface tension force. So, whatever you are applying is basically, the disruptive forces what in this case it will be gravity, if you are not applying the pressure. And if you will apply pressure, it will be pressure which will be momentum forces will be acting under the thing.

And therefore, there is no atomization, if you look at and that is very important that means, you would need to have a higher resistive force than that of the disruptive forces, so that you can manage your identity. But, if I look at our modern life, what is happening we are getting disrupted, we will become a kind of things. So, let us look at what is happening to the disrupted liquid else, I will go and increasing the pressure of this at the upstream of the RF is, which is not shown here.

Then, what will happen it will be subjected to instability of course, that will call relevant stability and several other instability ((Refer Time: 04:10)). And the liquid which will be spreading out and it will be interacting with the air and the liquid, if look at that the this is a film kind of thing being produces thin down, it is a bulk is coming jet you cannot really break it. So, you will have to thinning down, there is several ways of thinning down the things that means, you will be basically disrupting.

So, what is happening here is that resisting forces is less than the disruptive forces, this is a very simple fundamental thing. And then, as a result this will be ligaments will be formed from the liquid surfaces; and this ligaments will be broken at further, and it will be whenever ligaments and other things formerly called primary atomization. Then it will be fragmented and interacting with the air, momentums and other things together, you will get a secondary atomization and droplets will be there.

So, basic idea is that, the atomization occurs only when the resistive forces is less than the disruptive forces, but if you look at our life, our life is that, we do not really keep our humanity we get affected by this disruptive forces, due to the lack of proper education and control over our forces. So, this a very interesting thing, whenever I look at the spray, I look at the life of course, here objective is to look at how to produce the spray, how to break the bulk liquid in to the spray, and small at the droplets better it is for the combustion purposes.

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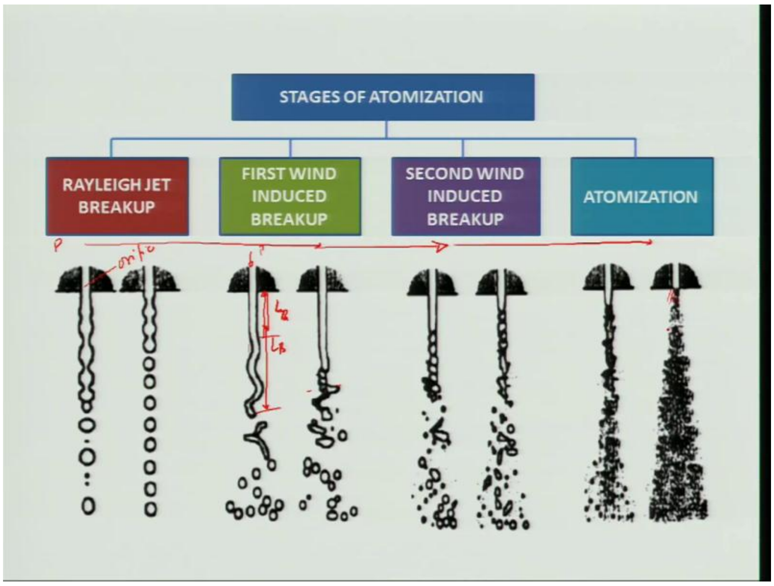

So, and also it is a distribution is very important, I will be not getting in to detail about that, but I would like to give tell you what are the stages of atomization, if I take a RFS, if you look at this is basically RFS write a small hole, and prove each the liquid is coming. And if it is coming without really any pressure, so you will find there is a undulation of these liquid that means, it is subjected to kind of a Rayleigh jet break up kind of thing, because of instability.

And then, there will be satellite droplet and droplet will be coming, as you goes on making this little pressure, so you will find this is going up and of course, there it is not very high. And when you apply the pressure more, this pressure increases, if you look at pressure is increasing in this direction injection pressure. So, what is happening, if the injection pressure is happening the liquid become a more state, because the momentum of the liquid is more.

So, then it become subjected to unstable and this distance I can call it as a break up distance, there length of break up, this known as break up distance, no actually basically if you look at, you can say this is the basically break up distance. Because, this until it is broken out this distance and this is the code distance which will remain, so if you look at this is LB break up distance. And as it is pressure increases further, so what happens this droplets like breaks little higher that means, break up length is decreasing with the increasing in the ((Refer Time: 07:37)).

And in this case the wind, because the momentum is coming some of the air also will be trying to wind and it will be some chipped out, like this kind of things it will be occurring. So, that is known as first wind induced break up and then, when the pressure increases further, pressure is increasing along with direction as we are going from left to right towards that pressure injection pressure is increasing.

So then, this instability is go above and then, oscillation it will more rigorously oscillated, so that it will be fully will be the stiffed, ripped out. And then this also goes up and then, this it is increases further, if you look at then the started breaking of ear kind of things and when it increases further, then this is atomizing, just very near to the RFS it salary. Of course, if you look at the angle of this spray also is increasing, that is also one good thing about that, so which will be helping in mixing kind of thing.

So, in case of this raising what I am asking and about discussing here, the second wind induced break up, like it means more wind will be coming entering may, it will be breaking out and the break up distance it goes becoming a reduce as it will go up. So, here of course, the droplet size will be very small when atomization per, so we will be operating in this raising of atomization, because these are the not being used very much.

So, I would not be getting in to the processes which is quite complex in nature, but what I would conclude that you need to have a very high pressure and then, smaller RFS to have a some meaningful atomization, which will be use for the combustion.

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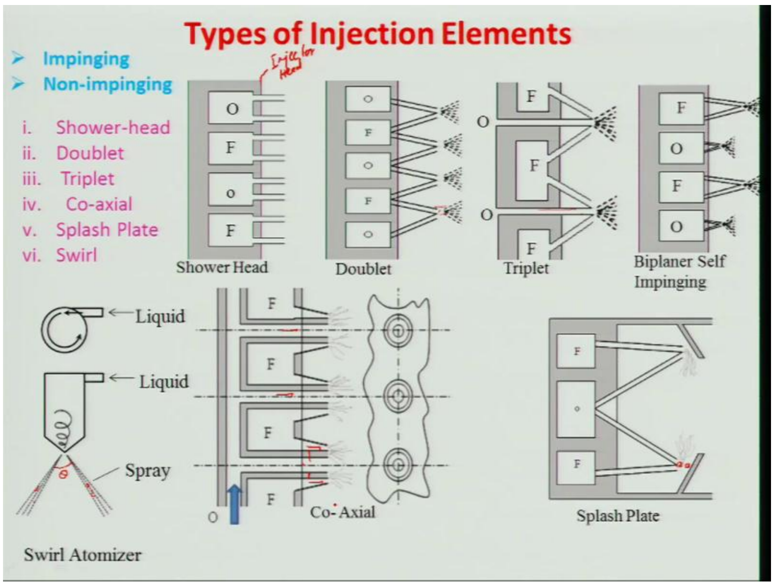

Now, I will be now talking about what are the kind of atomizer, one will be using in a kind of rocket engines, so there are it can be broadly divided in two categories. One is impinging atomizer, other is non impinging mostly the impinging atomizer being used, in case of which propellant liquid propellant definitely, but non impinging also will be using for non liquid propellant.

Whenever atomization is concerned, it is about liquid we want be atomizing gas nor atomizing the solid, so naturally it will be liquid, but what kind of propellant, it is there are two propellant we discuss about, one is hypergolic, other is non hypergolic. So, in case of in impinging one, what will be using will be using the hypergolic, not non hypergolic, because we need to mix this by propellants. Of course, the propellant can be by propellant, mono propellant, but particularly when we are talking about the by propellant we should have the impinging.

But, not all the time as you go along I will discuss about, so some of the injectors which I will be discussing is shower head, doublet, triplet, co-axial, splash plate and swirl. But, there might be several other varieties which a being developed, because that depends up on the requirement and also the creativity of the person who is developing, so that is very important.

So, if you look at this is the first one, what we are looking at here is the shower head, shower head means it will be having a straight RFS, which is like our shower what we take, if the bath in every day, it will be going straight. And of course, this is for fuel and this is for oxidizer, as a result what will happen it will be converting in to spray depending on the pressure. But, it will take more time for mixing, as the resolve the length of the combustors in this case will be higher.

But, the one advantage is that the length of the combustor may be higher, but the heterogeneity of this fuel and air will be more in the near the injector head like, if you look at this is your injector head. So, the flame or the combustion will be taking place little away from the your injector head, so this is your injectors head. So, the temperature of the heat cannot really come, not much will be coming towards this injector head, and the fuel properties would not be getting affected.

Because, like fuel property and there might be also a carbon formations and other things would not be there, which is very important for the clogging of the atomizer, for the performance of the atomizer. So, but however, you will have to pay penalty the length of the combustor will be high, then it will become heavy and then, all those thing. But, if you look at this shower head is been use in earlier rocket, that is the V 2 rocket engine, you must aware about with the first rocket engine been against used by German, against the Britisher's.

So, there is a inner to overcome this problem of like better mixing we want, and also the shower head can be use for the non hypergolic propellant, where you need not to mix fuel and oxidizer to have a liquid phase reactions. But, where as in the for hypergolic we need that fuel and oxidizer to be mix liquid phase, so that some heat it can be developed, and it can ignite itself. So, therefore, doublet is been use and it is a one good part is that, it is been mixed at certain to particular point, whenever it will be pinging on each other there will be a in this zone, there will be a fan which is been form.

And then, fan will be form perpendicular to the what you call the plane, which have drawn here and this fan will be interacting and with the air and then, it will be also chipped out those ligaments and then, form. But, problem is that this kind of course, there is a droplet the size of the ligaments, which will be formed will be different on the thickness of this span which is formed. And it will be subjected to in stability as well, the problem with this suppose like we know that, we need to have a higher amount of oxidizer as compare to the fuel.

So, therefore, for the same size RFS, then the momentum will be higher for the oxidizer as compare to the fuel, and sometimes you will be using of course, one can design in such a that momentum will be similar. But, if it is one of the momentum of the oxidizer all the fuel is higher than the meeting impinging point will be different, and if that is different the naturally your performance will be very poor.

So, in order to overcome that problem, what is been use is the triplet, where you will have the oxidizer it will be coming in the centre and there is a fuel and then of course, the fuel will be coming over here. And then this is can be again use for the hypergolic propellant, but it does not matter if one of the these thing is been higher, and oxidizer been higher it will go little away, but you can manage to have that.

But, if there is a lot of difference then it will be leading to the problem, but there is a liquid plus combustion will be taking place, liquid plus reaction will be taking place and also it will become compact nearby. But, if you face this problem there is another one which we can think of using is known as a flat plate, so use a doublet this a basically doublet kind of things. But however, there is a flat plate in case of this impinging point not here, it will go to here, it will impinge in to the plate itself.

And then, so that you can converted in to ligaments and will do that, but there is a problem, because if it is a hypergolic and this will be heated and then, you are having to pay some penalty for that. So, there are several varieties, if you look at this is known as the un like impingement that fuel and oxidizer, like and in sometimes we use for the like impingement, like oxidizer is impinging in to oxidizer, and fuel is impinging in to fuel.

In this case by plan a self impinging, you can call it a self impinging atomizer kind of thing, these generally is being use for the non hypergolic propellant, where it is not required to ignite, you need to have ignite separately, there is no need I mean there would not be any liquid plus reaction which will be occurring. So, therefore, it will be but however, here your mixing times would be most, so that oxidizer will be mixed the fuel and gas phase that will may be liquid and droplets.

And then you know vaporization all those things, so length of the combustor in this case will be higher. So, that is the like, but it is use for the non hypergolic propellants, there is a another one which is use very much particularly for the cryogenic engine, that is known as coaxial kind of atomizer. If you look at the oxidizer is going through here and here, and in this case and it is having the fuel, the fuel is passing through this and it is the coaxial in nature.

So, that what will happened like, if you look at the in this case that cryogenic engines or the any other liquid fuel, the fuel is been use as a coolant, to cool the converge and diverge nozzle. And also the body and heat carries and mostly it will be particularly for liquid hydrogen, it will be a gaseous space. So, the amount of velocity with which will be coming it will very high, it will be horror of may be 300 meter per second, whereas the liquid will be passing through the kind of, what you call very low velocity order of may be 30-40 meter per second.

So, therefore, these will be basically gas momentum which is a lighter one, which will be because you need to have higher momentum to interact with this and then, do that in over to augment the performance of atomizer people research. That means, what they will be doing, they will be not in the same plane of the atomizer both the what you call oxidizer and the fuel.

They will start here, like they will be some zone where some mixing will be taking place between the liquid oxidizer and the gaseous fuel, so that it will be two phase floor and then, you will ignite. So, that is basically is known as internal mix atomizer people are using now a days, this is a modern design and inhere to overcome this problem of mixing and then good atomization kind of thing, and compactness of the what you call the combustors.

People are thinking of using a swirl that means, they will pass this as basically liquid which will be passing through a swirller, the tangential entry. And then, it will be having some angle it will be fix and the liquid film will be thin down, when it is centrifugal force been acted up on that. And then, after from this here, liquid will be coming out and then ligaments will be formed and will come, so that what happens it is going towards back.

And then, mixing I will be better of course, the it will be having a hallo cone kind of thing sometimes will be solid cone as well, but what is important there should be hallo, but the distribution of the atomizes or the droplets also little bit bad in that, so you need to look at it. In generally the swirl being use even in the coaxial kind of things, you can make it swirl as a fuel, particularly in the oxidizer it is been used, and sometimes it is been combined with the fuel also.

So, there a various varieties and various tool, these are the if you look at is the element or ideas are available, one can use it for different applications shell as a things. So, generally this coaxial kind of thing is being use for the non hyperbolic propellants, and impingement generally being use for the hypergolic propellants.

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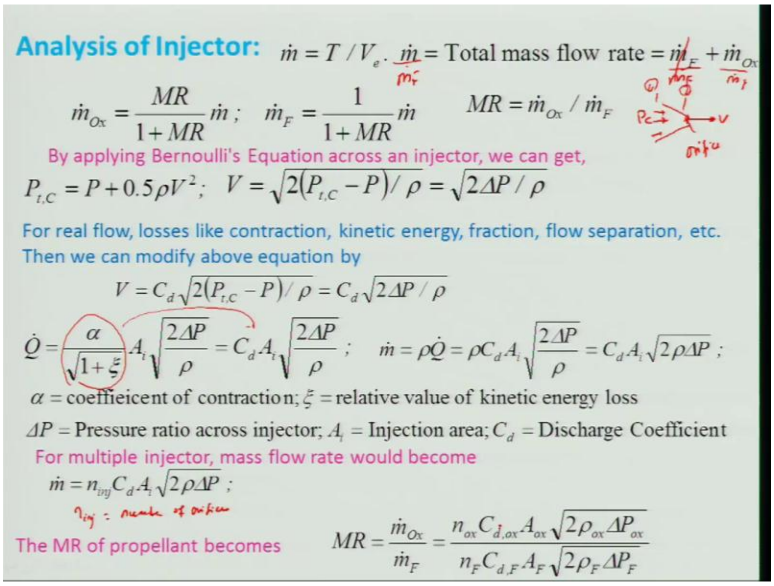

So, let us look at some analysis of the atomizer, I will just look at quickly we know this thrust expression, the mass flow rate of propellant can be express, in terms of thrust and exist velocity, or equivalent velocity you can use. So, what is the total mass flow rate of the this thing that is nothing but, mass flow rate of fuel and mass flow rate of oxidizer. Suppose, what I will do, I will divide this by the mass flow rate of fuel and then, it will be cancel it out, if I say this is oxidizer flow rate by the mass flow rate of fuel is known as mass ratio, M R that is a mass ratio.

Then I can get an expression m dot F is nothing but, 1 over 1 plus M R that is the mass ratio in to total mass flow rate and similarly, I can get an expression for the mass flow rate of oxidizer, in terms of mass ratio and total mass flow rate. Keep in mind that, you should keep this in mind that is the ratio mass ratio is basically mass flow rate of oxidizer divide by mass flow rate of fuel, in some places people do other way you will have to careful.

So, by what will do, if I take an atomizer kind of things there is a small hole here, and at the P C is being applied here, and this is having certain velocity V, it is a RFS, RFS through which the liquid is being pressurize, I can apply a Bernoulli's equation. Of course, the losses will take care by differently and that is the P t, C is nothing but, a local that is P is the static velocity plus half rho V square, V is the velocity at the nozzle or the RFS.

So, if I look at I mean, then velocity will be basically root over the change in pressure divided by the density of the liquid, so that is for the high really in which is there is no losses, no separation other things. So, but where as in real procedure there will be contraction like this, it has to be contracted and there is a flow separation may occur, there is a friction. And it can be we can modify this equation by using a quantity, we call it C d, C d is basically disture coefficient, and that is the actual flow rate divided by the total flow rate or the ideal flow rate.

So, if I look at the actual flow rate q dot will be basically alpha divided by root over 1 plus zeta in to A I and root over 2 delta p by rho, if you look at alpha is a coefficient of contraction that means, how much it is been contraction, what is the area ratio between the this inlet. If I take this inlet and if I take this outlet, and relative value of kinetic energy loss that energy loss will be there, and delta P is the pressure ratio across the injector and A I is the injector area, cross sectional area at the exit of this RFS.

And C d is the distures coefficient, so what I will put all this together, I can put in to other C d, like for when I am conducting, I need not to worry about that I will just put in to C d. And if I express this in terms of mass flow rate that is nothing but, rho in to volumetric flow rate, this is Q dot in to rho in to C d A, I can get C d by just take inside I will get C d A I root over to rho delta P rho is the liquid density. Delta P is the pressure across the RFS of the injector whatever you call.

Basically, across the injector that is the right one, so for multiple injector there might be several injectors, in a rocket engine we use several injectors, so I have already shown you how it will be. So, mass flow rate would be basically m dot n i is the n j is basically number of RFS, how many are there may be 50 may be, 20 may be 100 like any number depending up on the design. And the MR ratio of the propellant became MR is equal to m dot oxidizer divide by m dot F which is nothing but, number of oxidizer the holes or the RFS in to C d of oxidizer keep in mind that C d for oxidizer may be different than the fuel.

It may happened may be same as well, but generally it will be different, and A o x is the oxidizer of individual RFS root over 2 rho oxidizer and a density of oxidizer delta P x, that is the pressure difference across the oxidizer injector, and similarly for the fuel. And you can design this values and finding out whatever you need, and depending up on what

C d and other thing, those data can be taken from experimental data or some you may have to design and conduct experiment yourself to find for certain things.

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Naturally, because a liquid naturally it is a liquid fuel, we are not dealing with a gas it is a liquid, so it will be a in compressive it will be, so let us look at a we will be looking at this impinging atomizers.

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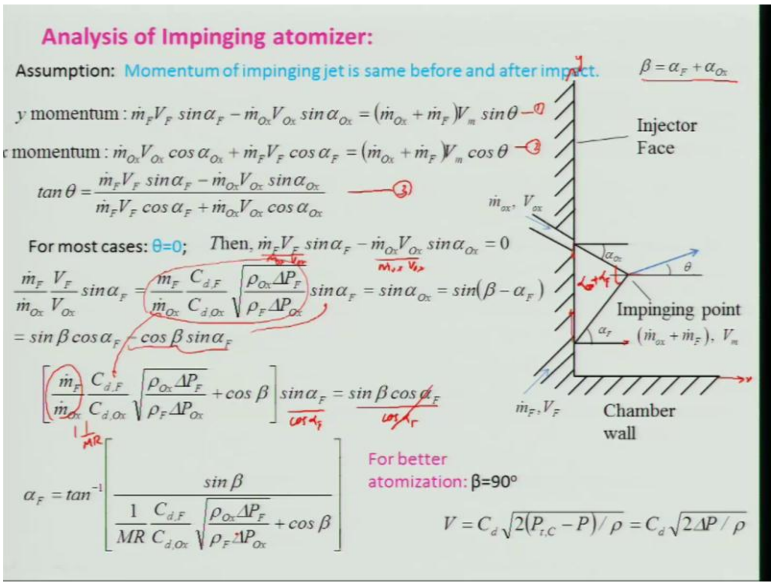

So, let us look at that this fuel will be atomizer is at an angle alpha F and oxidizer is been atomize in the alpha x, let us say that this is in x direction, this is in y direction and keep in mind that these angle is nothing but, alpha x plus alpha f. And that what we call it basically a beta and what we are assuming in this momentum of impinging that is same before and after the impact, and real situation it may, not you will have some loss. But, we are assuming that be same for the design purpose for the simplicity, and what will do we look at y momentum.

What is this y momentum, if I say this mass flow rate of fuel and oxidizer, there is a two component one is this direction and this is in y direction, y direction will be m dot F V F sin alpha F minus the oxidizer it will be in this direction. So, that will be minus m dot o x V o x sin alpha x is equal to m dot o x plus m dot F V m sin theta, similarly for the x component I can right down the cost component, which have written here.

And what I will do, I will just divide this by what you call equation 1 with the equation 2, what I will get, I will get tan theta is equal to the m dot F V F sin alpha f minus m dot o x V o x sin alpha o x divided by the cos components, which we have written, then these are the things. Now, if I take most cases the theta will be 0, if the momentum is fine it need not to go with a alpha provided, if the momentum of the both the fuel and oxidizer same it will be moving in this direction ideally.

But however, if may go move at a certain direction rite yes or no, so if one of the momentum is higher, it will be having this direction. If the fuel momentum is higher it will go in this direction, if the oxidizer momentum is higher it will go in this direction, any direction. So, but we will be assuming it to be 0, so then what is saying that this become, this expression equation 3, will became m dot F V F sin alpha F minus m dot o x V o x sin alpha is equal to 0.

What we will do now will basically look at what I will do, I will just divide this equation by m dot o x V o x m dot o x V o x and then, I will get this V F by V o x sin alpha x and in V F I can put in terms of C d and pressure ratio. That is V for the velocity will be in terms of C d and root over delta P by rho, so that we are doing, so that delta P F by rho F is coming, and 2 is cancel it out for the oxidizer that one, so you will get sin alpha. And what is this sin alpha and the sin alpha will be coming and is equal to sin alpha o x sin alpha o x is nothing but, sin beta minus alpha x, because beta is equal to alpha x plus alpha o x.

So, then you can expand this sin terms and then, you will get this expression and what we will do, we will take all this sin alpha term this term to this side and we will do that, so what I will do, then I will take sin alpha F is the common, I will get these term, these term as here plus cos beta is equal to sin beta and cos alpha x. Now, what I will do, I will divide by this cos alpha x and cos alpha F, so this cancel it out this became tan alpha F. So, what I will get, I will get this alpha f is equal to tan inverse of this quantities, like which is of course, I can write in terms of this is nothing but, here basically 1 by MR.

So, I will write that down and I will get, because if I know this beta and I know all those things, I can get what will be alpha F and alpha o x we can get very easily. So, you can use this as a design tool keep in mind that for a better atomization, people always suggest to go for beta is equal to 9, but however, in real situation you may not get, but this is a thing which you can.

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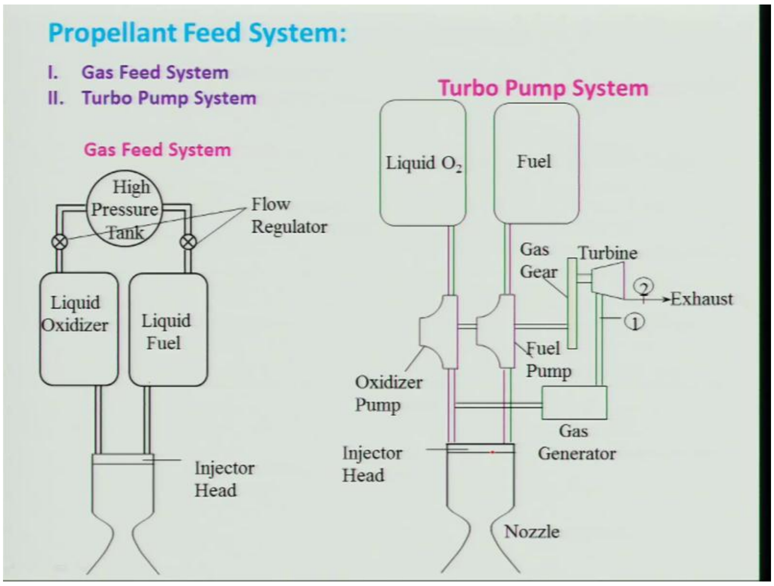

So, you can use this for finding out alpha and then, other play around this thing about the mass flow rate, the delta a P and then, look at what will be MR ratio you can use the other design tool for it. So, let us look at propellant feed system, we talk about injectors and atomizer how to go about it, but we have not looked at how to feed this, because we need to have a pressure, otherwise we cannot feed.

So, to have it can be divided in to two categories of course, there is several other varieties, but I would not be discussing gas feed system, and turbo pump feed system. Gas feed system is generally being use where the duration of the operation is small number 1, and the requirement of thrust is not very high that means, the chamber pressure should not be very very high. Otherwise, my overall weight will be very very high, so the typical gas pressure system can be think about a high pressure tank, which contains the a gas.

Any gas, then basically nitrogen, on organ some other gas which is neutral and it will be pressurizing the liquid oxidizer, and liquid fuel and you do not need a feed system, this is quite lighter enough. And then, it will inject in the fuel to atomizer and it will pass through the engine thrust chamber, combustion chamber and then, you will get this thing this is a very simplest system. But however, limitation is that the duration is very small, and the pressure chamber pressure should be small you keep in mind that there is lot of pressure losses across the injector head.

So, therefore, if you want to have a very high pressure in the chamber then, it will be at least something two times or three times that chamber pressure you need to have in that feed line. And then, you will have to go another very higher level of 4 or 5 kind of things high pressure time, so therefore it is being limited, but inner to and then time duration should be small. Otherwise, your tank pressure tank will be very high, otherwise you cannot operate, but inner to overcome that problem.

So, what is been done is that we use a pump, the pump for the oxidizer and pump for the fuel and to run this pump, which we need to have a turbine of course, through the gear box we can use that, I mean you can reduce the RPM of the, so that you can get the better efficiency of that. And to run the turbine we need to have a gas generator another combustors that is a very important thing however, will run it. So, this is being use for a long range and a for a very high thrust label kind of thing, what I will be showing now you discussing about three types of turbo pump system.

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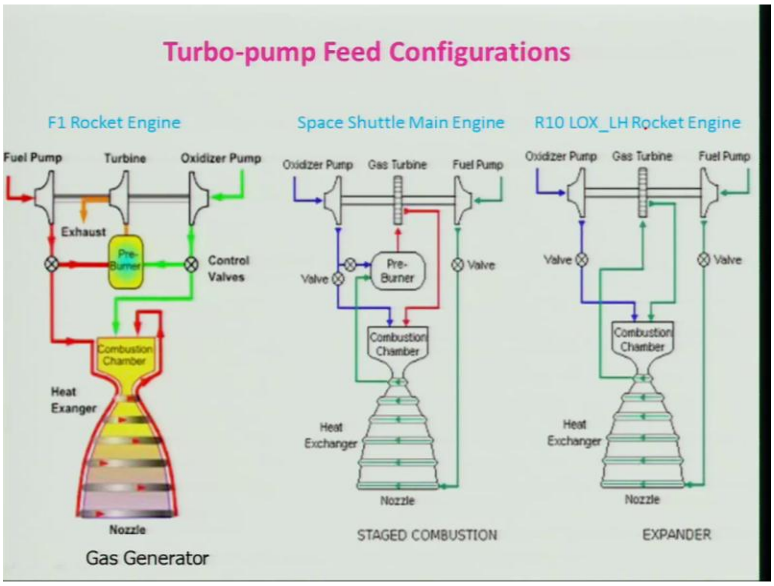

There are the three types, but there can be several other types as well, one is gas generator, if you look at it is having fuel pump and oxidizer pump, which is run by the turbine. And in this case the fuel being separated one line goes to the pre burner, and other line goes to the what you call rocket engine which will be cooling and then, it is injected in to combustion chamber. And whereas, the oxidizer again divided in two stream by the control valve, one is the burners, three burner for the turbine which will be repair high pressure, high temperature gas which will be expanded in the turbine.

And these turbine will be expanded till the ambient pressure, generally it will be low in the particular when you are operate operating at the higher realty tool, then the pressure ratio is quite high, then the number of stages requirement will be more. And if you go for more number of stages, then the way it will be more of course, you will get a higher, therefore this pressure operation operating pressure for this pre chamber is being very very low being used.

And as a result, then the chamber pressure, if it is not operated at a high and the work is not more, but then you cannot have a high pressure in pump, the chamber pressure which is being limited to low pressure. generally people talk about something high mega Pascal kind of things. And it is this kind of system is being use in the what you call, F 1 rocket engines, the most which is use for the high or the high thrust rocket engine is known as stage combustor.

If you compare the stage combustors, it is the gas generator, it is the same only difference is that only difference is that, that high pressure, gas temperature and gas which will be burnt will produce free burner is being expanded till the pressure. whatever it is required. That means, after it is getting expanded turbine it will come in to the combustion chamber and heat operated and here it was a loss, because the fuel some of the fuel or high temperature will be there or some of the these thing.

Here you need not to operate at a these thing and you can operate this combustor at also a fuel lean some of the fuel can be utilize here, as a resolved you can operate at a very high pressure this chamber pressure, combustion chamber pressure or the thrust chamber pressure which is order of 50 mega Pascal instead of 5 mega Pascal's kind of thing. So, that is being use in space certain main engines, it is being use of course, little modifications is there, but there it is a fuel and oxidizer pumps are separated is say to the same gas turbine, but there is a being separated.

So, the another one which is being use the complexities of free burner is not there, rest is similar to that of the stage combustor, but problem here is that like you cannot real gate a very, because when the fuel will pass through, it is not having very high enough pressure to operate in that to the that. So, therefore, very less amount of pressure you utilize in the gas turbine, because you will have to operate and therefore, this is being use for the small rocket engine.

Where the pressure chamber pressure there restricted to around 2.5, 2.7 mega Pascal kind of thing, so that is being use of R 10 something liquid oxidizer liquid, hydrogen rocket engine and several other places. So, this is not that you should think these are the only 3, but there can be several varieties depending up on your requirement, depending up on your mind, depending on your creativity to meet the demand that is the duty of the engineer work.

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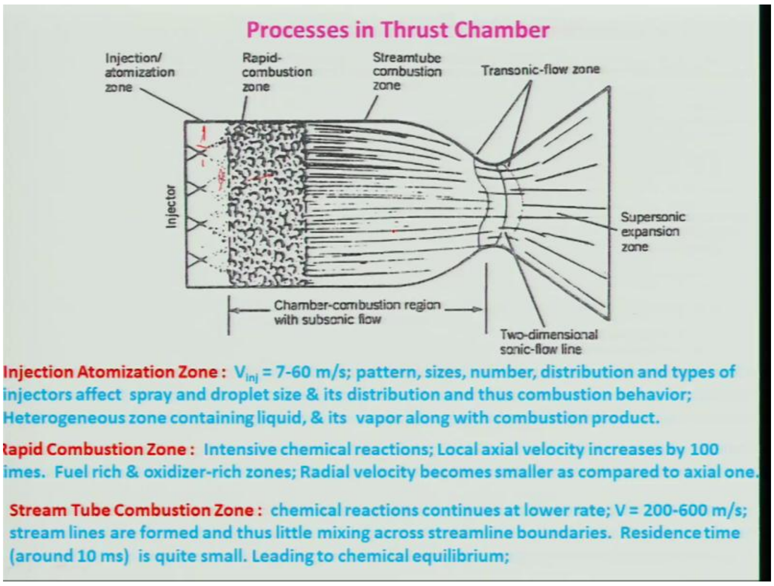

So, let us look at what is happening in the processes in the thrust chamber, if we look at we have seen the rocket engines and then, it can be like injectors head are here, and it is having you know like a two phase flow kind of thing heterogeneous, mixtures will be there. And there will be also the velocity with which it will be coming is something coming 7 to 6 meters per second, and if you look at the combustion here will be depended on the spray quality.

Spray quality will be depended on injector pattern, sizes number like number of injectors or RFS, distribution and type of injectors what we, because we have seen several inject types and then, the combustion be every will be detected. So, therefore, this is a very important part for that we have this, but the thing is that it will be having heterogeneous in nature, there is a liquid phase, vapour phase, vaporization will be occurring.

And also some of the combustion which will be coming in to these places also, because particularly in this zone, so therefore some kind of thing and may be some reaction might be taking place, but it would not be releasing any amount of heat. That is known as injection atomization zone, there is a rapid combustion zone where intense chemical reaction takes place. And the local velocity will be increase by 10 times for example, if it is sixty meter per second, it will be going to the very very high velocity 7 meter per second, it will be going to 700 meter per second.

But however, it is a order it may be go to 50 times as well, but general it will be very high, so there might be fuel rezone and oxidizer rezone will be there, and the radial velocity. Because, here it is impinging the radial velocity will be there along with the axial velocities and then, might be tangentially the swirl, here the radial velocity is more and very very less and axial velocity will be very high. And then, you will get a what you call very high velocity region, and particularly in this zone reaction taking place.

But, in this zone reaction will be reduce, that is known as stream tube combustions and a zone where stream combustion will be taking place, it will be reaching going towards the what you call equilibrium positions. And but however, the radial component is very small, negligibly small, therefore it is a stream tube there would not be any mixing between these tubes or the stream lines, tubes. And the velocity which will be order of something 200 to 600 even more meter per second, and some combustion will breaking place and this zone where sub sonic resume will be there.

Sub sonic, because velocity is very high, because the temperature is high, therefore it will be sub sonic, and this zone it will be expanded and sometimes, some of the combustion goes ill the throughout area, but that will be very very negligible you should reach. So, if you look at it is a quite complex process that amount of time, for residence time for this is order of some mille seconds, 10 millisecond, 7 millisecond, 15 millisecond like kind of thing.

So, therefore, it is a very intense combustion takes place as I told you the amount of heat release in the rocket engines is much higher as compare to the gas turbine, particularly per unit area; I told you around 60, 70 kind of things, because you will per meter cube.

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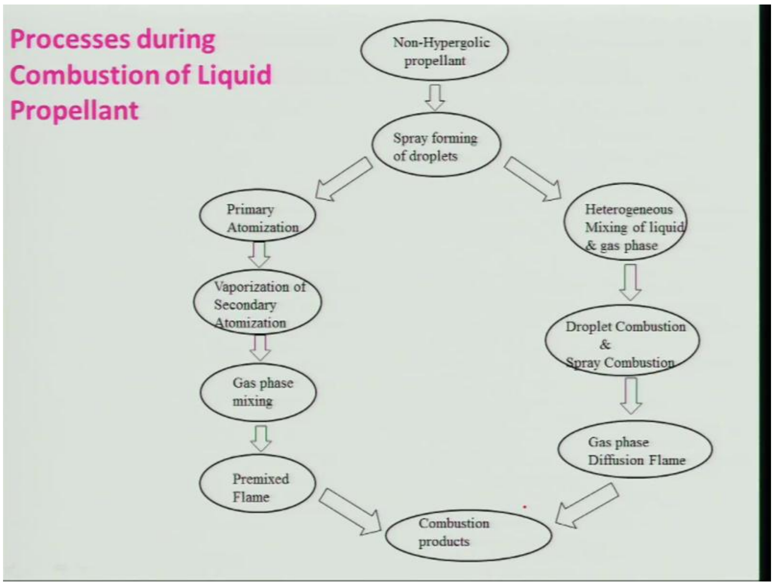

So, let us look at what is really happening in combustion zone, so I will talk about two kind of thing one is hypergolic propellant, that is a spray forming of the droplets, non hypergolic propellants. And it can be having primary atomization and then, when primary atomization occurring, then vaporization of secondary atomization can take place. And there might be a gas phase mixing, so vapour has come fuel and oxidizer can mix, and it can leave to a pre mix flame, some places is not that all the places, some places there might be a pre mix places.

There is another root heterogeneous mixing of the liquid and gas phase can take place, and there might be a droplet combustions, I will show you in the next slide there might be spray combustion and sometimes the group combustion. Like several droplet will be together will be burning and to droplet will be interacting each other, anything can happen, then there will be gas phase diffusion flame will also will occur, so there is a combustion. So, if you look at it a very quite complex, whatever we have learnt in a diffusion gas, pre mix flame and then, partial pre mix flame all will be occurring in various places.

So, it is very difficult to say what is happening inside, and which is not been understood really till death.

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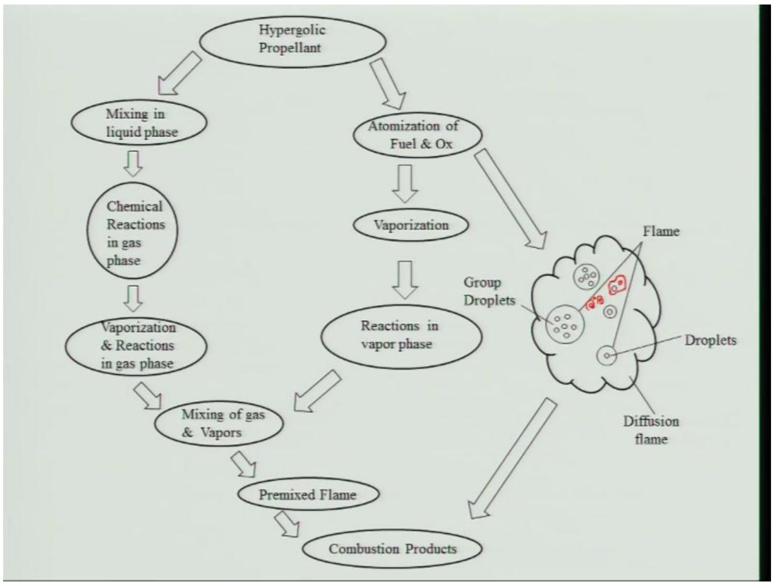

So, let us look at hypergolic propellant, the mixing in liquid phase will take place and chemical reaction in the gas phase go on is likely to occur, because is a hyper hypergolic in nature. So, vaporization reaction in the gas pressure also will be occurring simultaneously, so this all processes whatever I am describing will be occurring simultaneously, not that one will occur like that way arrow is given.

So, then mixing of this gas and vapour and there might be atomization of fuel and oxidizer, there is a vaporization and vaporization occur it can mixed, and there might be a vapour phase reaction on the gas phase reaction. Vapour basically gas phase reactions and then, this some of this vapour will be also mixing with the liquid the product and then it will be reading to the pre mix flame. There is an another root, which is only the atomizer, there might be these are the group combustion what I am taking about and this is the plane.

And there might be a small droplet, there might be another droplet here it is a kind of things which will be occurring, there might be one droplet here, and another droplet here, like it will be occurring. So, any complexities it can happened. any permutation computation can be happened it is a random in nature. So, therefore, the combustion product will be getting which is quiet complex, it is not easy to model it is not really even look at in experimentally, but system is working, but we have not understood what really is going inside.

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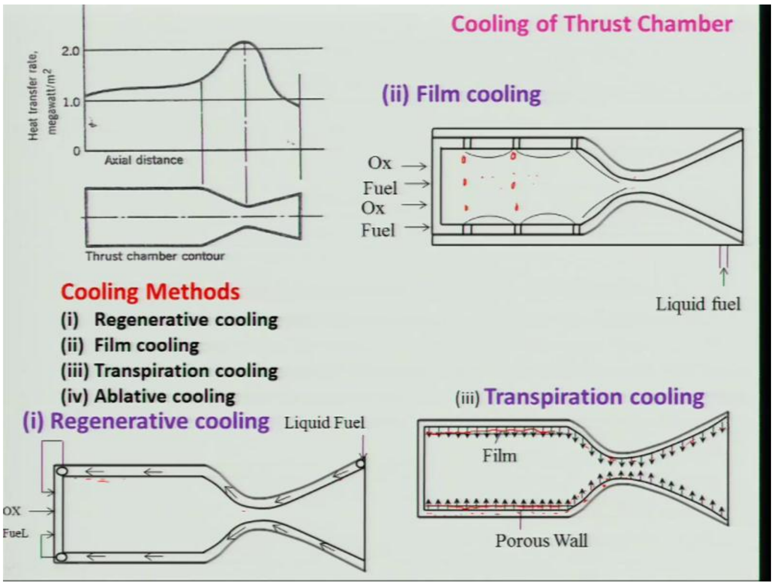

So, with this what I will be talking about is one is the cooling of the thrust chamber which is very important, because if we look at lot heat is being generated here. And as I have told you that the amount of heat being generated is quite high, it is a order of something 30 Megahertz rule for meter cube and the heat losses will be there to this zone. And keep in mind that, a material it is not there to which stand high temperature, because very high temperature and high pressure, pressure is a order of 100 bar kind of thing, 50 bar, 60 bar, 100 bar like that.

So, therefore, the material has to be cool to have a take care of this under high pressure temperature, otherwise it will fails. So, therefore, it losses or the cooling of chamber is very important, if look at the amount of heat transfer which is occurring in these zone is very very small, in the length of the combustor along the length, it goes on increases. And it become fix at the throughout area, throughout area is most vulnerable part failure, because there are almost two times or more than that what is there in this zone. So, there are several methods which I had been talked about, one is regenerative cooling and film cooling, transpiration cooling, ablative cooling.

So, let us look at regenerative cooling what happened, generally the liquid fuel is being use which will take the heat and then, vaporize so that this portion of the cooling, like oval will be at a lower temperature. Of course, there is a another way of doing is that you can reduce the heat losses to the wall by having a reach fuel here in this zone, so that heat would not be going it is like a insulating acting that is of course, one can design.

And it is being use in your cryogenic engine very much and then, liquid rocket engines also, but there is a problem with that, because losses will be very high under thing. There is a another cooling which is being use is known as film cooling, in the film cooling what will happened there will be small hole, so is a hole will be here in the in the similar way, across the hole circumference. And it will creative film like a insulating layer, between this combustion zone which is at higher and between the metal.

And this film it is very important and it is having a length which is has to be very very small distance has to be maintain, otherwise it will be destabilize and then, it will be also oscillating, because of flow will be very turbulent and other thing. So, mixing will be taking place and it will be, if you look at the number of film is very much and 10 percent of the liquid we can give, otherwise it will reflect, it will be participating and it is a loss. Because, it is not participating in combustion it will be acting like a insulating layer, so the ISP will be going down.

And another important thing that is the nozzle it is a very high velocity throughout, you cannot really cool it which is a very important one, inner to overcome this problem of course, one idea is that known as sweat cooling. That is you use a porous materials and then pass through this liquid such that, it will be having a force and it will be very very low velocity a film will be created, film is not like that way I have shown. But, are the a film very small layer, and here in this case instead of 10 percent generally 1 or 2 percent of fuel or the liquid you will be giving.

So, that it will be good enough to have, but fortunately because of material it is not being use very much it can do a any portion even including nozzle. So, that is a challenge what is been, but experimentally people are working on this, there is a another one which is a ablative cooling.

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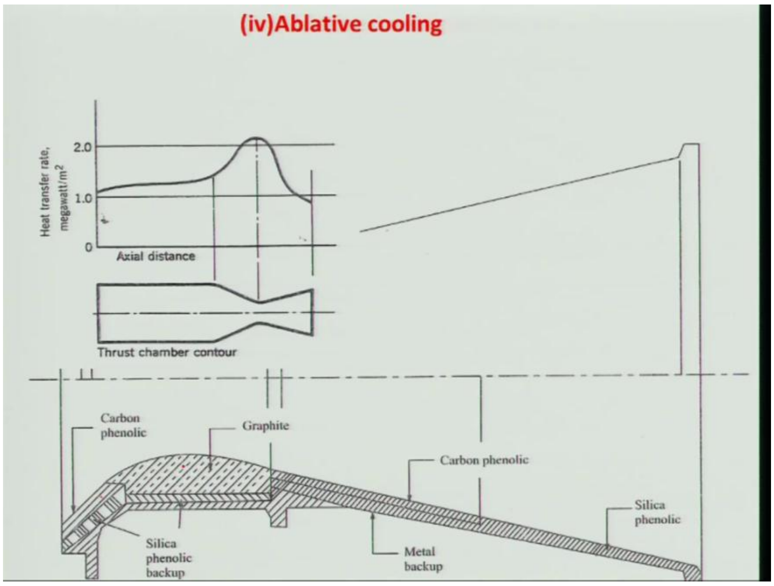

And this is a ablative cooling, what is being use is basically at a high temperature, it will be converted in to a char and a liquid or vapour, depending up on what you are using. And it will be receded, but those material which will be remaining is act like a what you call insulation, so that it would not allow the heat to pass through the main metal. And in this is being use particularly in the nozzle region other places, and there are several ablative material, but the carbon phenolic and silica phenolic which being use, because it is having a higher ablative atomizer.

Particularly the silica phenol is having little better, particularly because it is insulating properties are higher as compare to carbon. And then, temperature whenever it will reach 1400 or 1500 Kelvin depending up on your material, then you will start ablating, ablating means you will be receding vaporizing, so that it will be cool the thing.

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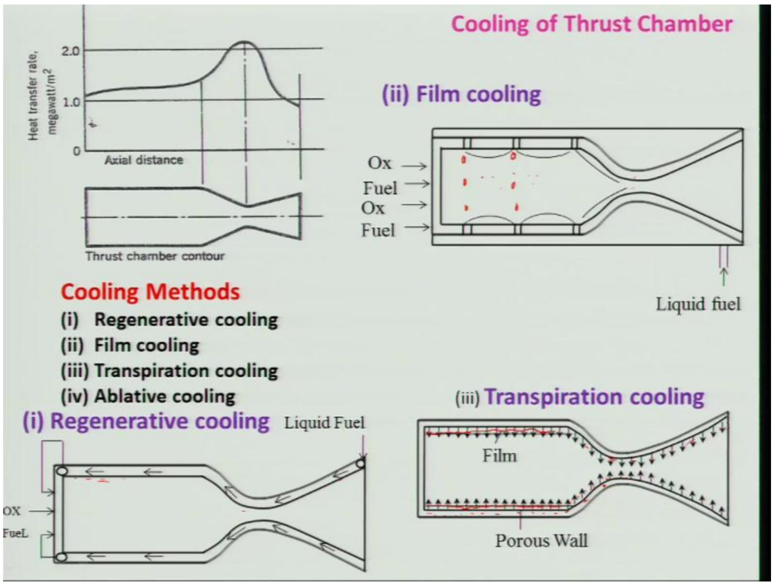

And of course, the throughout region is very very high, and if it will reduce because of this ablative, then there will be a problem for that, we use the graphite, high temperature graphite. So, that it will be take the high temperature and also some of the heat act like a insulating layer.

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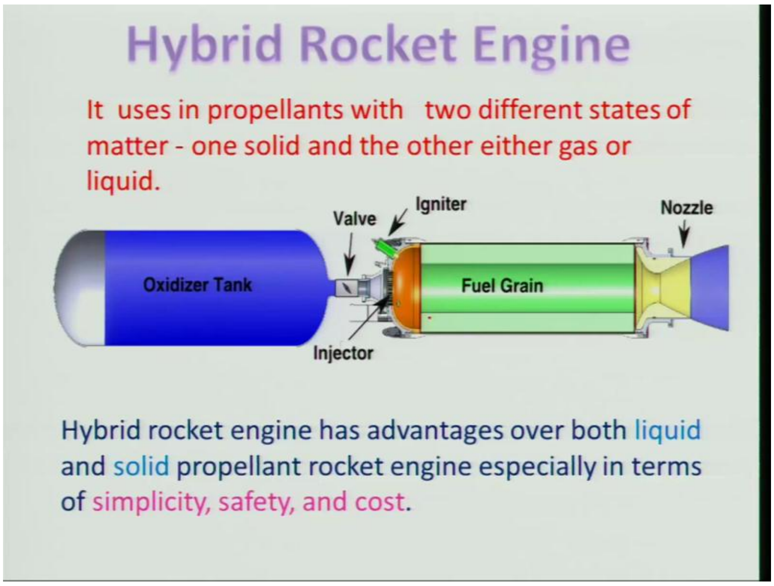

So, what you call we will be now looking at the hybrid rocket engines, and which is being used basically to have a better control, and it is quite simple and safety kind of thing. Where will be using the fuel, if we look at this are the fuel grain which is being use solid, this is generally solid and the liquid oxidizer is being use of course, you can think of any other combination, but generally the solid as a fuel.

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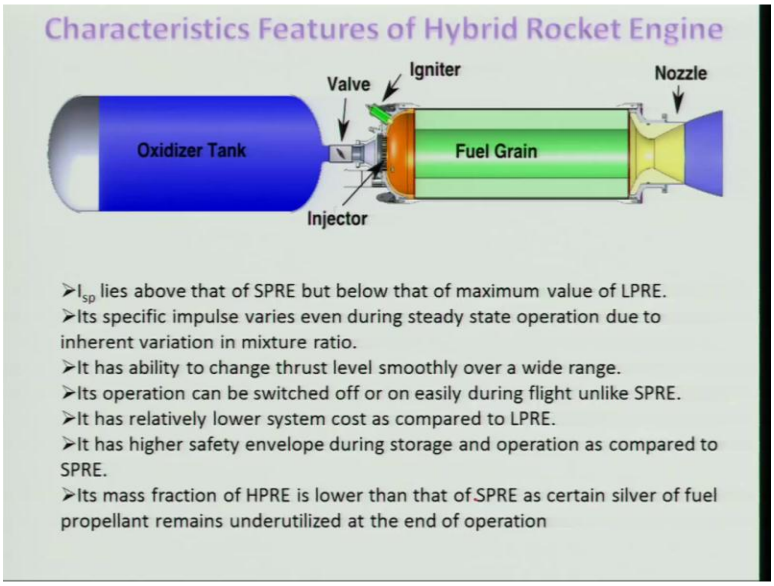

There as several fuel can be use, but it is having several advantages for example, it is highest will be lying between the solid propellant rocket engine, and LPRE there is liquid propellant rocket engine maximum values. And it is specific impulse varies even during steady state operation of course, due to inherent variation in mixture ratio MR what we are talked about. It has ability to change the thrust labels, smoothly over the wide range, suppose you are moving, you want to take a trajectories path.

You can do very easily, where the liquid rocket engine one can do, but solid is difficult, so that is a one advantages, it has a relative lower cost has compare to LPR, because the system is simple is only for the one liquid oxidizer, but if the fuel line or other things. And it has a higher safety envelope during storage operation as compare to the solid propellant rocket engine, because the only fuel even fuel is nothing is happened unless it comes in contact to oxidizer, so it is also not mix with the oxidizer.

So, it is the very safe and its mass fractional like is quite lower as compare to the solid propellant rocket engines and of course, the certain silver liner. Liner means some propellant will be remains at the end of burner, so that is having higher, so that is the one disadvantage with this but however, one can design the engines properly.

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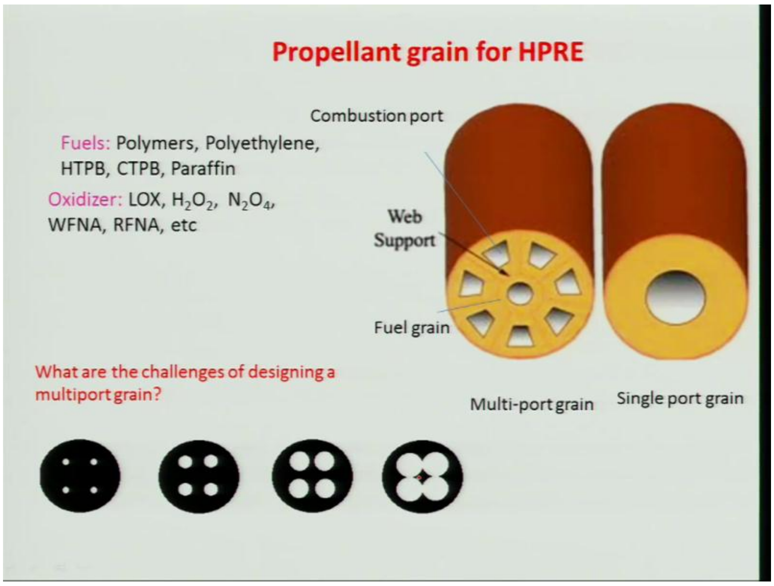

For example, fuels you can use polymers, polyethylene HTPB, CTPB, paraffin several other fuels whatever you use. And oxidizer like a liquid oxygen what you call, hydrogen peroxide, nitrogen tetra oxide, white fuming nitric acid, rate fuming nitric acid that are the several other liquid. Keep in mind that lot of interest in western countries to have their own, even in the universities of having hybrid rocket, example several universities in USA having their own systems, students had been there.

And in our place only the IIT, Madras they are working on this, if you look at the important one is this is the single port, the grain kind of things, that the limitations of the this single port is that like, it will be having restricted surfaces area, length will be more. Keep in mind that burning rate, in case of a hybrid propellant will be order of 1 3rd of the solid propellant rocket, because its only fuel, so therefore burning rate is reduced. So, if you want to have a higher thrust, you will have to go for multi port kind of grain, and where the multiport grain design is very important, it is not that easy.

Because, if we are having this holes and this having waves support, it should be supported, otherwise it will fall outer and then, it is a very important if we look at if I am having this kind of port. And if I go on adding this, go and receding then there is a place where this portion propellant will fall, because there is no nothing supporting. So, then therefore it will be creating a lot of problem, because the stress will go our it may explode and other things, so design is very important.

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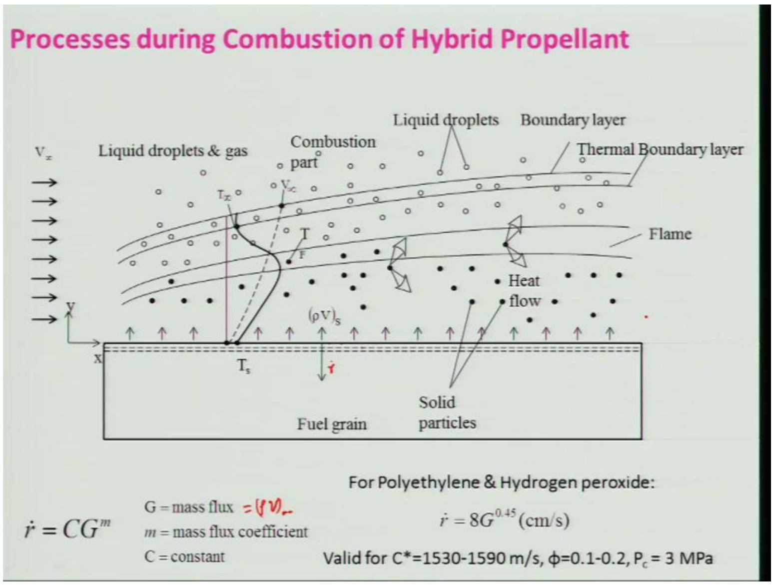

And let us look at what are the processes involve during the combustion of hybrid propellant, is quite difficult complex, but I will just give a brief overall view. If you look at this propellant is here solid propellant, these are the liquid droplets and gases are coming. And it will be some heat will be transfer, I am igniting of course, you can do s a separately, but let us say there is a flame, if it is a flame there will be some solid, some heat will be transfer due to radiation, convections, because the fluid is moving.

And this will receded and then, this mass will be receding like, it will be coming down, it will be regression at a certain regression rate, and some of the particles also can get in to these are solid particle which will be also passing some heat. And then, heat temperature also will be going up and it will be peak at flame temperature here and then, it will be having there is a thermal bounded layer There might be boundary layer hydrodynamic or the hetero dynamic boundary layers and then liquid droplets, which will be coming which will be vaporizing entering in to that is a quite a complex process.

So, therefore, it is difficult to talk about it but however, one can really model it as a r dot C G m, where G is the mass flux is basically rho in to V average velocity, this is the average velocity of mass flow rate which is coming through that. And this is the constant and for polyethylene and hydrogen peroxide, if we can get r dot is equal to 8 G power to 0.4 m centimetre per second if is semi empirical result. So, one has to be worry about the units when you are handling, and it can operate over the 1530 to 1590 meter star C star.

There is a character velocity equivalence ratio 0.1 to 0.2 and pressure of 3 mega Pascal's, so when we using you cannot really use that thing, for all like your solid propellant, here because fluid is playing a very important role of this thing. In this case and some of the fuel will remain un bunt even at the exit, therefore multiport is very important to mix this fuel and you can have a higher performance efficiency.

So, there is a lot more work has to be done solid propellant rocket engines, so with this I will stop over, I have taken given a very bars I view of the rocket combustions, rocket engines and with this I will stop over.