Indian Institute of Technology Madras
Presents

NPTEL
NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

Aerospace Propulsion

Liquid Rocket-Pressure Fed System

Lecture 38

Prof. Ramakrishna P A
Department of Aerospace Engineering
Indian Institute of Technology Madras

The last class we had looked at how vaporization times are determined by the droplet diameters right and we had said injector with the devices that are used to autumn eyes the propellants now let us look at what are the various kinds of injectors that are used and how do they operate and what are the difficulties in operation.

(Refer Slide Time: 00:35)

Now injectors are devices that put the propellant into a fine jet of liquid okay, now what happens to this jet of liquid I am sure most of you would have played with a garden hose right when you reduce the area it comes out like a thin sheet and then breaks up into droplets why should it break up into droplets yes what is causing that instability now if you look at what are the forces that are at play in this process one is inertia force then there is a surface tension of the liquid right the other thing is the viscous forces because there is an ambient atmosphere that is still right and therefore you have viscous forces that are trying to slow.

It down and that breaks it up into very fine droplets okay so that is what also actually happens in a liquid rocket motor so you use you bring out the propellant and a fine jet then it will break up and become very fine drop let us the size of the droplets has a relationship to the size of the injector we will see what that is in a short while now the basic job of being actor is to break up the propellants into fine space or fine drop let us right so it has to be designed such that firstly we need stable combustion okay.

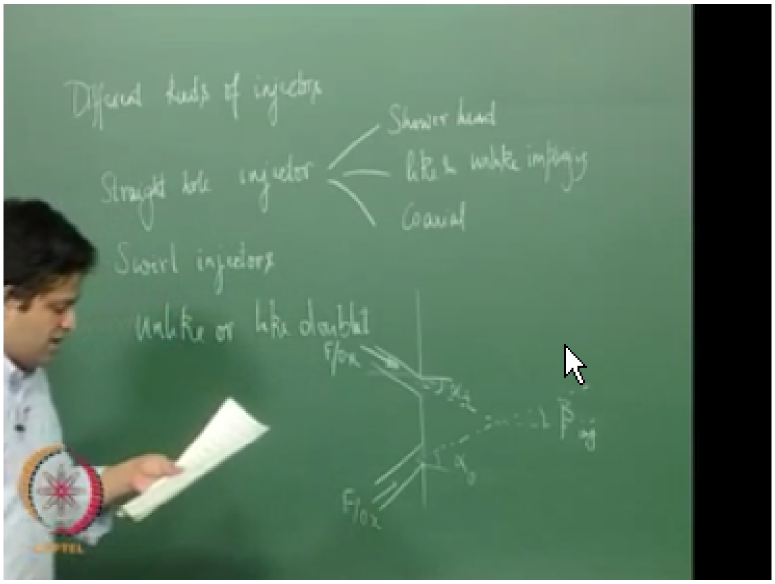
If the combustion is unstable then we have n2 of first we need stable combustion then we need high combustion efficiency that is we are looking at excess of 92%if the combustion efficiency is small although we are using propellants we are not getting a maximum benefit out of it only a fraction of it is being utilized okay, so we would want the combustion efficiency to be as high as possible now we also want this to make sure.

That the combustion chamber length a small please remember this is a pressure vessel that we are talking about combustion chamber is a pressure vessel and if you have a larger length then it means weight so we want it to be as short as possible we want to have very high combustion efficiency is also so there are two things that are running in opposite directions right.

I mean one is forcing it to be longer you want higher conversion efficiencies you want it longer but then if you have it very long then your weights will go up so designing it is a challenge and lastly this also has to ensure that combustion temperatures what do we mean by this there is a spray that is there we do not want any kind of hot spots okay we do not want some places to be very hot than the other places to be not so hot because that would in turn mean that the cooling problem becomes more acute in some region and the motor might give way in some portion.

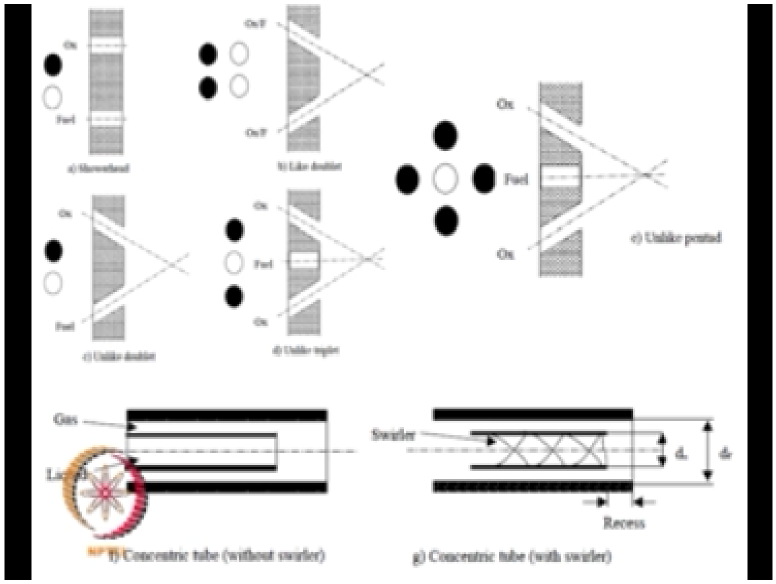
Okay so we do not want that and therefore we want the combustion temp temperature to be within limits this is in some sense if some of you have studied aircraft engines there is something called as pattern factor which is talked about in gas turbine combustors also at the end of it you want a nearly uniform distribution because then you are feeding it into the turbine you do not want hot spots there so all these things needs to be ensured by a proper injector design now let us look at the there are different kinds of injectors that are used in the industry for this purpose.

(Refer Slide Time: 06:23)



One is a straight hole injector then there are swollen get this now in the straight hole injectors there are three types one is shower head and unlike like and unlike impinging and lastly coaxial.

(Refer Slide Time: 07:50)



Let us look at how these areas you can see here the first one is the shower head injector this is nothing but very similar to the shower that we use every day right and these are straight holes and there is fuel and oxidizer that is coming now notice that they are going parallel to each other right so therefore in essence you are not utilizing the possibility of using the momentum.

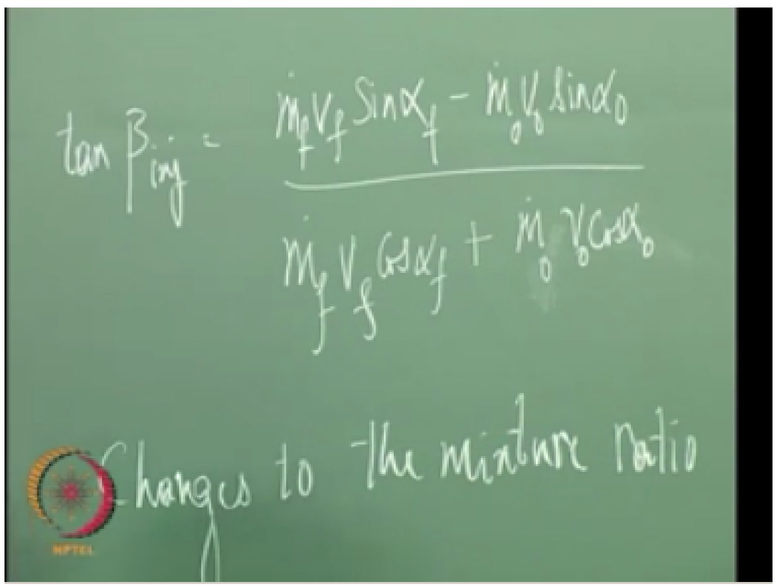
Of these Jets to break them upright one is as I said if you push a jetinto qui sont air there is viscous forces inertia forces and surface tension these interact and make it into fine droplets but in addition to that you could make the Jets interact with each other and therefore break up into a fine spray in a much shorter distance right so in this showerhead it has not done whereas in a light doublet this is utilized that is you have either an oxidizer or fuel jet coming here and either oxidizer or fuel jet coming here.

The name like is there because you are using either fuel on fuel or oxidizer on oxidizer okay so these Jets interact and they break up into very fine droplets in a much shorter distance whereas if you look at this is an unlike jet unlike impingement that is you have oxidizer coming and impinging on here okay, this kind of arrangement people would not use in when they are using hypergolic fuels right hypergolic fuels if you remember they do not need any injection and once they see each other they start reacting.

So in this case you would have heat release very close to the injector head which sometimes might not be recommended and therefore whenever people use hypergolic fuels they use this kind of combination that is like combination that is fuel on fuel or oxidizer on oxidizer now if you look at like or unlike doublet the Jets come here right we will be able to show something if you take a look at like or unlike doublet it is something like this you have either fuel or oxidizer coming here and either fuel or oxidizer coming in here right if you look at these jets interact at some point and the resultant direction.

In which the jet goes off is given like this so this angle if we call it β injector and this let us say this is **α** F α o XBF we can show that if there is any problem with one of the Jets right in this case we are going to have a change in the direction of the resulting jet and sometimes it might go and impinge against the wall the hot gases so we would not want that.

(Refer Slide Time: 12:43)

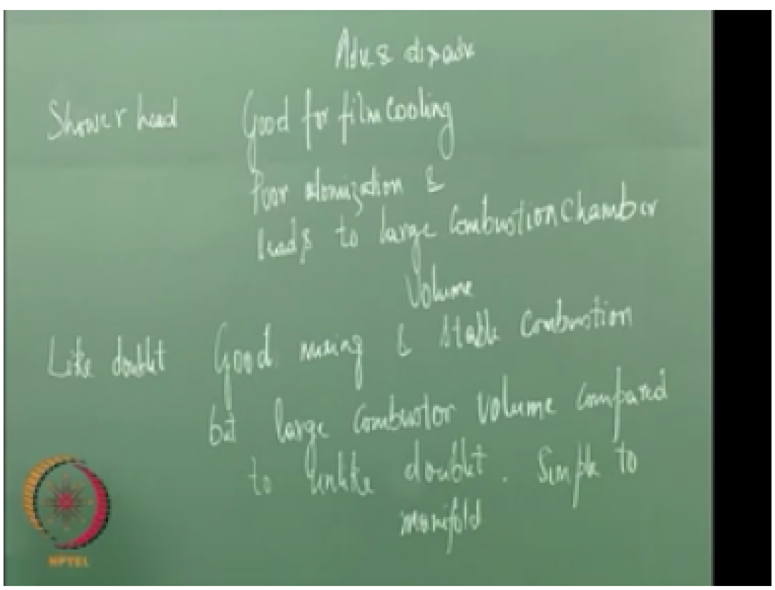


So if we calculate the tan of the angle β injector this can be expressed as this is from purely momentum balance now if due to any reason the mass flow-rate or one of the parameters of one of the Jets varies then the resultant direction will also change which is not a very good thing right it will also result.

In changes to the mixture ratio locally the mixture ratio might also get affected we do not want that and therefore use of an unlike triplet as shown here is more recommended in this case the direction does not change and it is more robust and you also can use something like anun like pentad as shown here that is we are only seeing a section here which will show three there will be one more on the two more on the either side okay in addition to this we have looked at shower head and like and unlike impinging I said there are coaxial injectors which is shown here coaxial injectors are typically used for cases.

Where you have liquid oxygen and liquid hydrogen because if you remember hydrogen would already be a gas so then it is easier to have this kind of injectors wherein it is coaxial you will have the liquid in the core and the gas on the periphery you could also swirl it the inner fluid that is the liquid and you will get a swirl injector so coaxial injectors you will have many of these repeated right each is one unit and you can repeat it to get your overall injector now let us look at the various advantages and disadvantages of these injectors firstly.

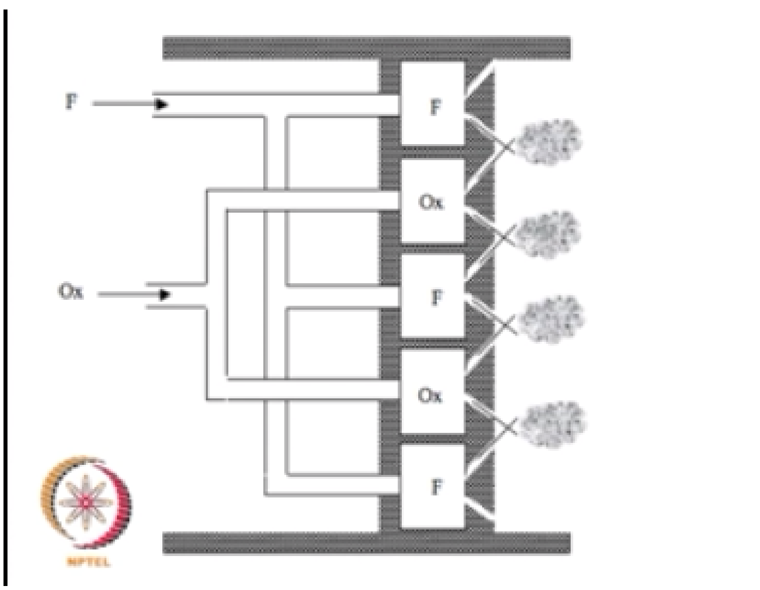
(Refer Slide Time: 16:15)



Let us take the showerhead now showerhead if you look at it is also very good for film cooling remember we probably are going to use film cooling because you need a layer of fuel on the walls injected on the walls it is easier to get that with a showerhead but as I said we are not using the momentum of the Jets to break up into very fine droplets. So the automation is poor and hence it will require a very large volume for combustion chamber design so although this is good for film cooling then the like doublet right in this case the mixing is a lot better because you are using the momentum of the Jets.

To break them up so it also leads testable combustion and the volume of the combustion chamber is also very small but it will have a larger control a larger combustion volume compared to unlike doublet but it is also very simple to design the manifoldwe will see what is the manifold in a short time.

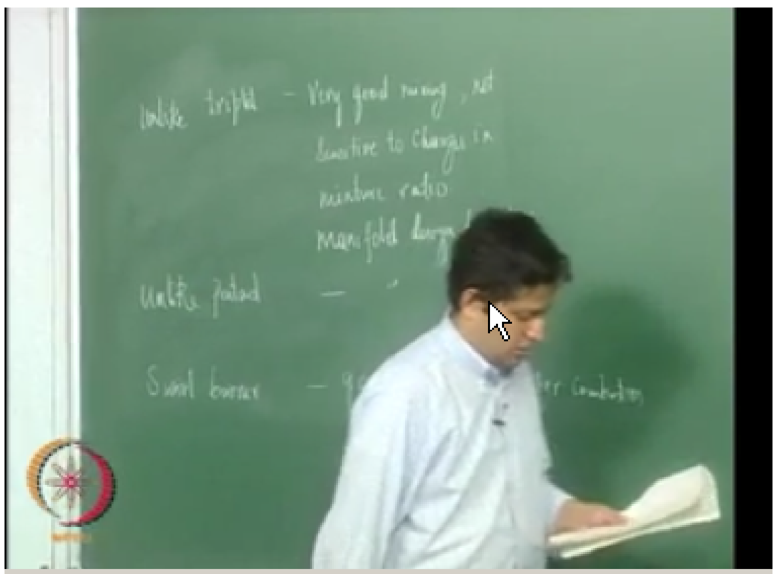
(Refer Slide Time: 20:01)



What you see here is the design of the manifold the portion that is upstream of the injector is called the manifold now if you want to have unlike injection unlike doublet. You see that the fuel and oxidizer must be I mean you should have one fuel manifold and then oxidizer and then fuel and then oxidizer so it is not easy to design the pipeline and other things upstream of this right it becomes very complicated but whereas if you have a like doublet it is a lot more easier because you are going to have only fuel on fuel or oxidizer on oxidizer this has very good mixing so faster combustion and smaller volume of the combustion chamber it is also not very difficult to design this manifold but as we said earlier.

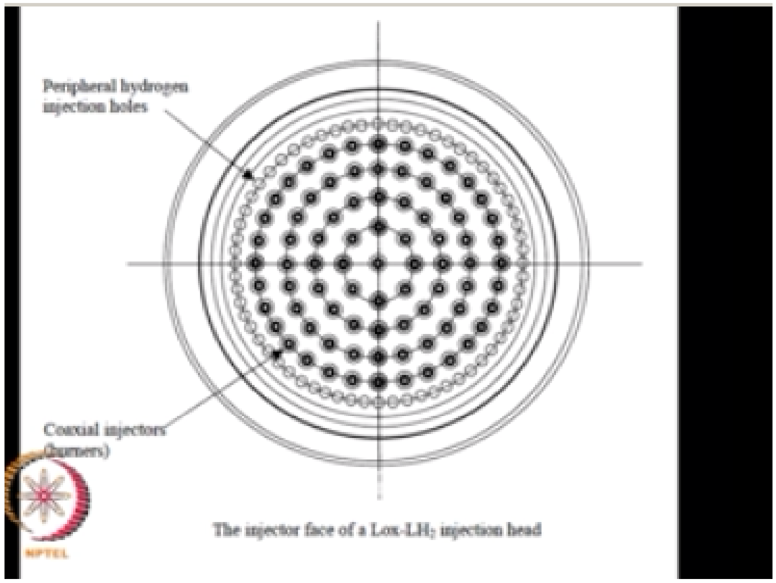
We should not be using this when we are using hydraulic droplets okay both these designs as we discussed earlier are I mean the design is very sensitive and prone to changes in mixture ratio because of what we discussed here the angle at which they come in and interact so they are very sensitive to mixture ratio changes.

(Refer Slide Time: 24:12)



If you take a look at what unlike triplet that we discussed this would have very good mixed ring properties and as well as it is not sensitive to changes in mixture ratio but the design of the manifold could be a lot more troublesome in this because you want fuel oxidizer and then again fear so very similar to unlike pentad is also very similar. To this okay ,then lastly the swirl burner now in the case of a swirl burner it is probably going to be very difficult to use film cooling simply because if you look at this figure.

(Refer Slide Time: 26:34)



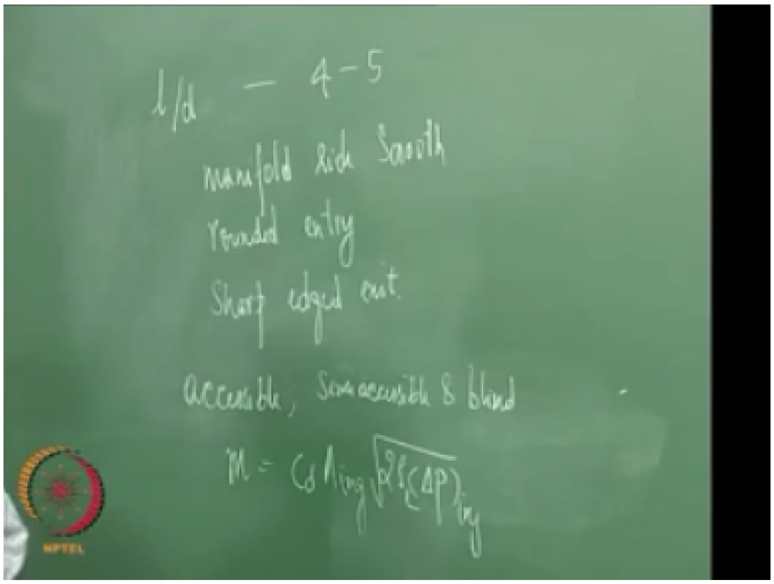
Here as I said earlier there are going to be a number of elements of this so you have to kind of make sure that on the periphery you take care to ensure that you have only fuel being injected something similar to what is shown here all this has coaxial injectors in the center right if you look at it there area large number of coaxial injectors in the center.

But on the periphery you have holes wherein only hydrogen is injected so this will have good mixing and faster combustion but it might have issues with mm cooling okay now all these injectors one of the troublesome issues with liquid rocket engines is if you look at a liquid rocket engine it is very manufacturing intensity it has firstly it as if you are looking at turbo pump fed systems you have to design pumps you have to design turbines and all that there are a lot more moving parts firstly and if you come.

To the thrust chamber or the combustor itself the design is very intensive in terms of manufacturing if you have cooling regenerative cooling then those coolant tubes need to be very carefully done manufacturing is a very critical thing there because you are looking at very fine tube sizes and the torille tolerances that you can give is not very large so it really you need to have very good manufacturing skills in order to make sure that you have a very good liquid rocket system if you look at the injectors also all of them are very small holes.

And you need to take special care to ensure that the design is very good right one of the things that people take care of what should be the L by Dratio length.

(Refer Slide Time: 29:27)



To diameter of each injector it is typically something between four to five and you need to ensure on the manifold side all right manifold side it has a manifold side entry smooth rounded entry and on the combustor side. It has a sharp edged exit now one of the troubles is if you look at how to make this rocket motor right there are some designs which allow you to make the injector first and then weld the entire injector plate to the manifold such designs are called accessible and there are designs.

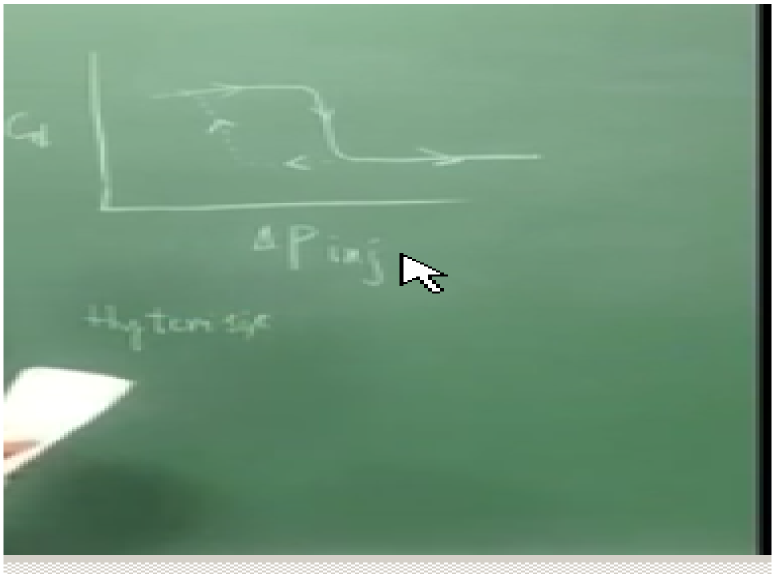
Wherein in this case accessible design you can remove whatever birds that are there due to manufacturing before you finally weld it but if there are birds that are thereon the injector right then the mass flow rate of one particular injector might change. So that creates a problem in the functioning right and that needs to take care of so that is why I said manufacturing is a big problem in terms of liquid rocket motors.

So there are three kinds of injector h1 is accessible that is you can make the injector head and then weld it on to the rest of the motor so both sides you can now see and remove the burrs that are there and while manufacturing this that is possible in this there are semi accessible and then blind also that is you will not be able to access it at all.

So in that case you have to look at some different kinds of ways to remove the burrs okay,like electro polishing and other techniques otherwise you cannot remove these birds through mechanical means right okay now we have kind of understood how injectors work and we also know what is the mass flow rate expression for mass flow rate through an injector we had said that m dot is equal to CD into a injector under root to ρ L **Δ** p right so if you want to change the mass flow rate remember liquid rocket motors we can throttle the thrust that is we can increase or decrease the thrust so if you want to change.

The mass flow rate if you look at this expression CD is fixed density of the liquid is fixed injector area is fixed so the only thing that is available for changing the mass flow rate is the Δ P so therefore you can change the upstream pressure of the combustor that is the manifold pressure and get a higher or lower injector River Δ P across the injector and get the required mass flow rate through the injector while doing that one needs to be a little more careful as I said while doing the change in the mass flow-rate one needs. To be a little more careful simply because there is a region.

(Refer Slide Time: 34:45)



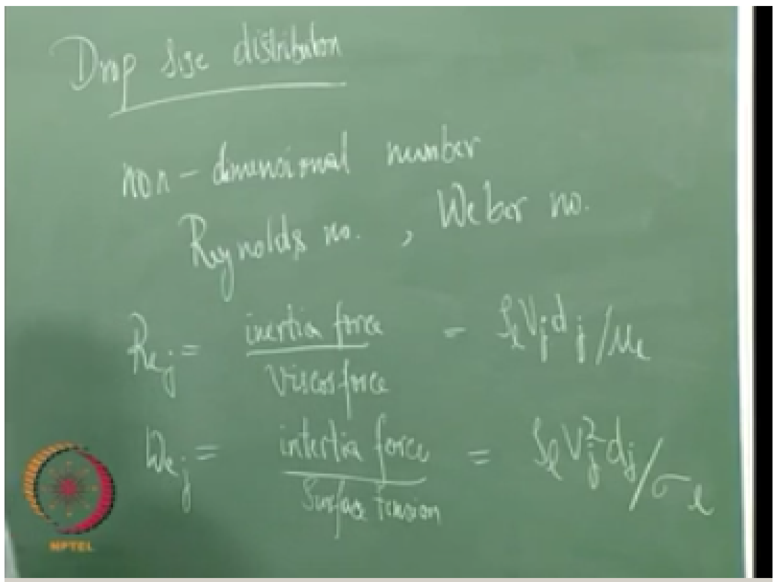
Where in the CD the coefficient of discharge if we plot the Δ P across the injector and CD coefficient of discharge the coefficient of discharge remains constant over some region and then drops and then goes like this like right but there is no guarantee that if you are reducing the **Δ** P injector it might follow the same pattern it could follow a different path something like this while coming back this is known as hysteresis that is while going in one direction it takes a particular path while coming back it does not come back along the same path so if you are operating the motor.

In this you need to be very careful and it would be advisable not to operate the motor in this region and to avoid it completely because while doing the operations in one way it will have some mass flow rate while coming back it could have a different mass flow rate **Δ** P you can change by either changing the pump output pressure this is possible probably only near if turbo pump in the other one you have a pressure regulator so you can regulate the pressure that is acting in the tank in a turbo pump you have to change the pump power out input then you can get a lower or higher **Δ** P across the pump and therefore.

The pressure at the manifold but in the case of a pressure effect system you have to operate the pressure regulator to get the required throttling it partly this happens because if you look at it the fluid is going through a path right there could be flow separation and other things now if you are reducing the injector pressure the processes might not the flow separation process might not follow the same path while you are coming back right and that is why this kind of hysteresis is observed so we have now learned what is the mass flow rate through an injector and if you remember.

We can calculate based on the thrust and ISP what is the mass flow rate of fuel right now what the other information that we need is what is the area of injector that we need to use in order to design a particular liquid rocket motor right if we know this area or the diameter then we can design these injectors now how to go about designing this injected size.

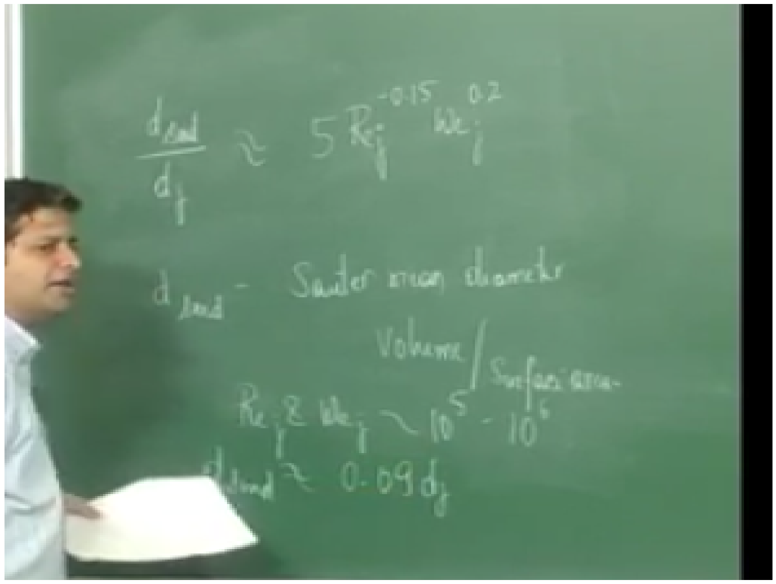
(Refer Slide Time: 38:43)



Now as I said earlier if you look at what are the things that control the droplet size one is the injector diameter and the other is the interplay between inertia forces viscous forces and surface tension okay? So if you put this down in terms of non dimensional numbers then the non dimensional numbers that are of relevance here would be we said with one is Reynolds number and the other one is label number Reynolds number.

You know is inertia force by viscous force similarly the Weber number then they defined as ratio of inertia frice to surface tension. So we can express Reynolds number of the I put this of XJ to indicate yet this we can write it as P LV L P LV J right then ∑ here indicates surface tension forces so using this. We can come up with an expression for something known as Sauter mean diameter to the jet diameter.

(Refer Slide Time: 42:01)



What is Sauter mean diameter the idea heard of it before Sauter mean diameter Sauter mean diameter is nothing but the ratio of volume to surface area okay, if you take that ratio you will get the dimension as one meter so that is something that is used ratio volume to this is more relevant in some sense because we said heat transfer depends on surface area right larger the surface area then better will be the heat transfer.

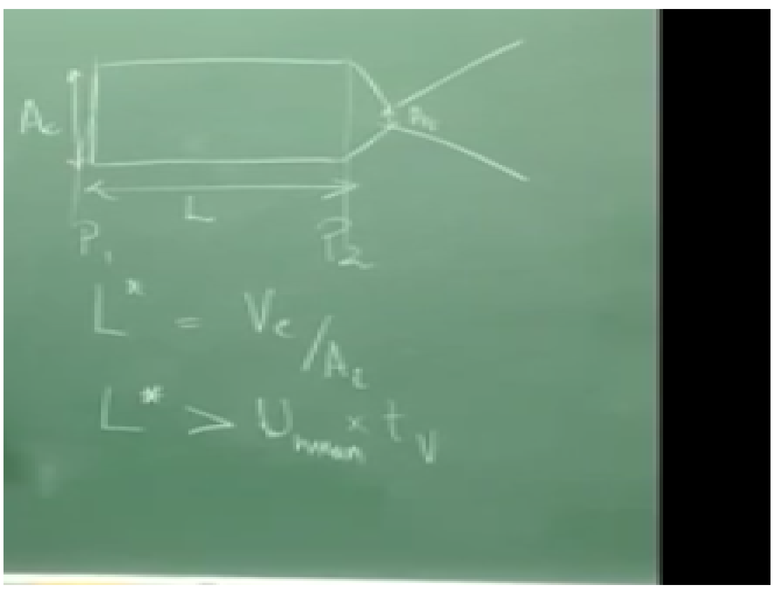
So surface area to volume is what is known as autumn in diameter and this dsm-v by dj is given as okay this is the expression for Reynolds number and Weber number connecting the diameter of the jet to the sort of mean diameter so if we want a particular sort to mean diameter right if you want the combustion to be complete within some length we would want a particular sort of mean diameter. Let me if you remember in the previous class we discussed about how vaporization times are affected by the diameters of the droplets so we will know what kind of diameters to use and therefore using this we can calculate.

What kind of jet diameters we would need right fine typically the range of Reynolds number and Weber number would be of the order off or rocket engines 10 power 5 to 10 power 6 so we would get DSM D to be approximately equal to something like DJ so if you have a one millimeter jet diameter or an injector diameter of one millimeter then your Sauter mean diameter will be something like 90 microns right, so you can now based on this you can design the number of injectors to be used I mean the injector diameter and then to get the required mass flow rate of fuel and oxidizer you can decide on the number of injectors.

And then on the injector plate you cannot have all of them with a very small gap between the two so you need to have a sufficient clearance between one and the other so using that you can now inject this design the entire injector plate right yeah they do not diverge at an angle the resultant jet will go at an angle the which diameter DJ you are talking about DJ is nothing but we are simply assuming DJ is nothing but equal to the injector diameter okays, we have now learned how to design the injector now the only part.

That is remaining is how to size the entire engine right I said we can now using this design the injector diameter and the number of injectors and how to arrange them and all that so we now can design the overall thrust chamber.

(Refer Slide Time: 47:18)



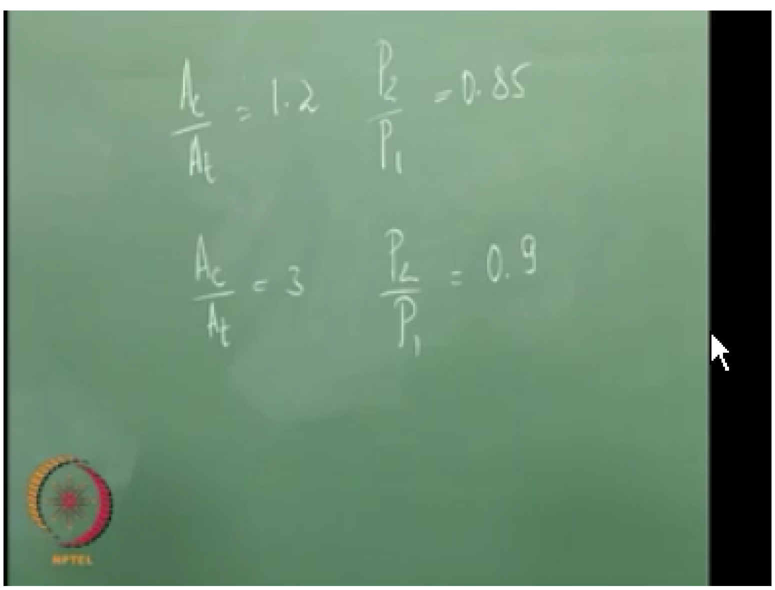
If you remember AP right AT we had got from what considerations thrust and mass flow-rate considerations right. This is fixed then what we are left with is how to design this length of the motor and what should be the cross-sectional area of the motor or the engine. In this case so this is AC and this is length if you remember we had defined something called L star with respect to solid rockets right.

We had said L star is nothing but VC by AT so this L is very similar to this now one way to look at this LS the gases will have some mean velocity let us call that as you mean so L star should be greater than you mean into time of vaporization and if we have to have we discussed this in the previous class that the vaporization time, is probably the slowest process is the vaporization process and this is the time that will be the largest other times are smaller than this so if you design a motor such that L star is greater.

Than this then you are going to have chamber wherein the combustion is going to be nearly complete okay so we have now looked at what is the length now this is a chamber in which you are adding Heat. So therefore the pressure from heading to nozzle end is going to drop right but for all our calculations of trust and other things what we are interested in is this pressure right this is the pressure that if you look at the thrust equation PC 80 CFP C 80 right this is the one that governs this so we need to ensure.

That the pressure drop from the head end to the nozzle end is as small as possible right so then this sizing need to be also done primarily this AC is determined on how many injectors and how do we house them that is the one that drives how we choose AC okay.

(Refer Slide Time: 50:41)



So if we have different AC /AT if we have AC/ AT= 1.2then P 2/ P 1 this ratio would be 0.85 and if we have AC / AT= 3will be larger because you now have an larger area to have a mass flow through so with this we complete our discussions on liquid rocket motors right we have learned how to go about designing pressure fed systems pump fit systems and then also how to look at what is the droplet size and also look at what is the length of the combustion chamber we need to have this finishes our discussions on liquid rocket motors in the next classes we will look at hybrid rocket motors thank you.

Online Video Editing /Post Production

K.R Mahendra babu.
Soju Francis
S.Pradeepa
S. Subash

Camera

Selvam
Robert Joseph
Karthikeyan
Ram Kumar
Ramganesh
Sathiaraj

Studio Assistance

Krishnakumar
Linuselvan
Saranraj

Animations

Anushree Santhosh
Pradeep Valan .S.L

NPTEL Web & Faculty Assistance Team

Allen Jacob Dinesh
Bharathi Balaji
Deepa Venkatraman
Dianis Bertin
Gayathri
Gurumoorthi
Jason Prasad
Jayanthi
Kamala Ramakrishnan
Lakshmi Priya
Malarvizhi
Manikandasivam
Mohana Sundari
Muthu Kumaran

Naveen Kumar
Palani
Salomi
Senthil
Sridharan
Suriyakumari

Administrative Assistant
Janakiraman. K.S

Video Producers
K.R. Ravindranath
Kannan Krishnamurty

IIT Madras Production

Funded By
Department of Higher Education
Ministry of Human Resource Development
Government of India

www.nptel.ac.in