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NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

Aerospace Propulsion

Liquid Rocket-Pumps

Lecture 37

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Good morning in the last class we had seen how what is the head required and what is the kind of flow rate that goes through the pumps in a pump fake system in this class let us look at what are the efficiencies that are possible with these pumps and how does it affect the overall performance of the rocket engine and some other related issues.

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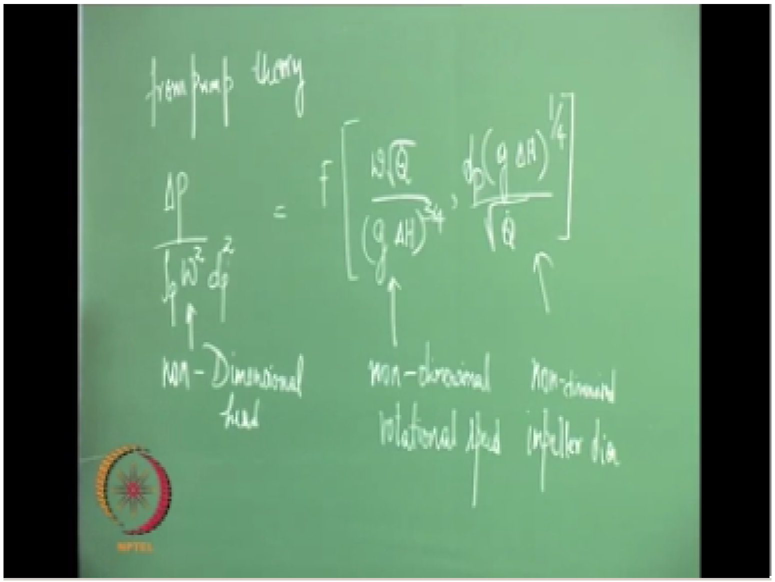

Now from pump theory it is a theory wherein you non dimensionalize the head right and it is a function of rotational speed and impeller diameter so it is written like this Δ P by this is the non-dimensional head this is equal to a function of okay so this is non-dimensional rotational speed and this is non-dimensional impeller diameter.

Now if you see here this comes from Buckingham π theorem which you must have studied some time in your undergraduate the ρ P here corresponds to the density of the fluid ω corresponds to the rotational speed in RPM and DP corresponds to the diameter of the impeller okay and Q dot is the flow rate and Δ H is the actual head rise okay g is acceleration due to gravity.

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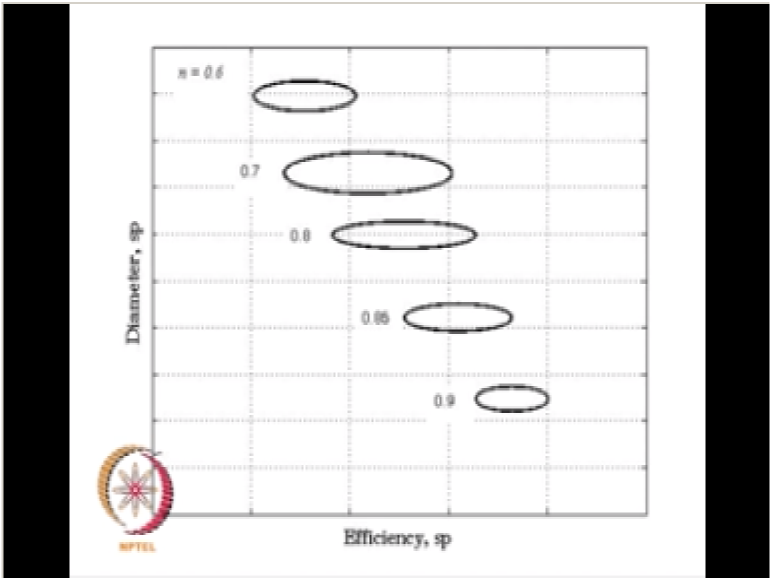

If you have this then you come plot it as shown here in this figure on the x axis you have the non-dimensional rotational speed given as n SP and on the y axis you have the non-dimensional impeller diameter given as DSP if you notice here the numbers that are given here are efficiencies Oh point 6.7 and it goes all the way up to point line right now if you want to have as seen here.

If you want to have high efficiencies you need to be in this region right which means that your impeller diameter needs to be very small and also your rotational speeds needs to be very large okay so this is nsp and this is DSP so for high-efficiency nsp needs to be large and DSP needs to be as low as possible.

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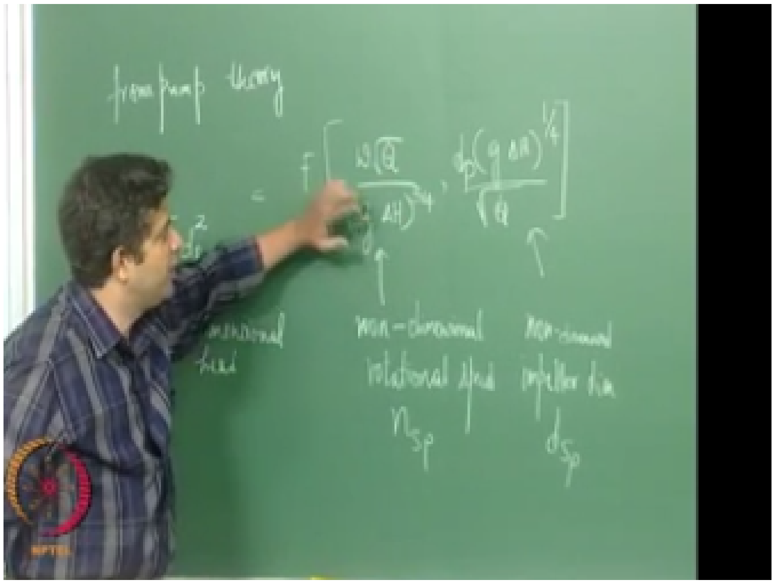

So then you will get to very high efficiency why is high efficiency required if you remember the efficiency of the pump are matters a great deal simply because that determines how much of propellant you are going to consume to pressurize the fluid okay so if it is as small as possible then the rest of it can be used for useful propulsion activity right this does not directly come into propulsion activity.

Because the flow through the nozzle is what causes the propulsion effect so in that sense you would want to minimize this to a small number as possible but actually speaking how many how much is it possible to reduce it to is given in this table here.

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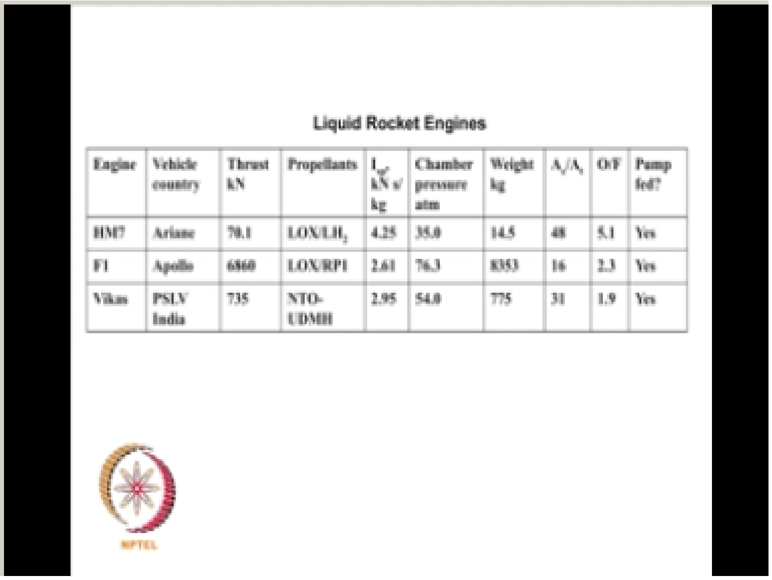

Liquid Rocket Engines

Engine	Vehicle country	Thrust kN	Propellants	I_{sp}, kN s/kg	Chamber pressure atm	Weight kg	A_e/A_t	O/F	Pump fed?
HM7	Ariane	70.1	LOX/LH$_2$	4.25	35.0	14.5	48	5.1	Yes
F1	Apollo	6860	LOX/RP1	2.61	76.3	8353	16	2.3	Yes
Vikas	PSLV India	735	NTO-UDMH	2.95	54.0	775	31	1.9	Yes

If you look at the power of the pump and the efficiencies the actual achieved efficiency is somewhere on 44% and it goes up to something like 60% for the pumps whereas for the turbine it goes all the way up to 80% okay so which means that even though you spend a lot of propellants for turning the turbine all of it is not obtained as useful work to run the okay only a fraction of it is.

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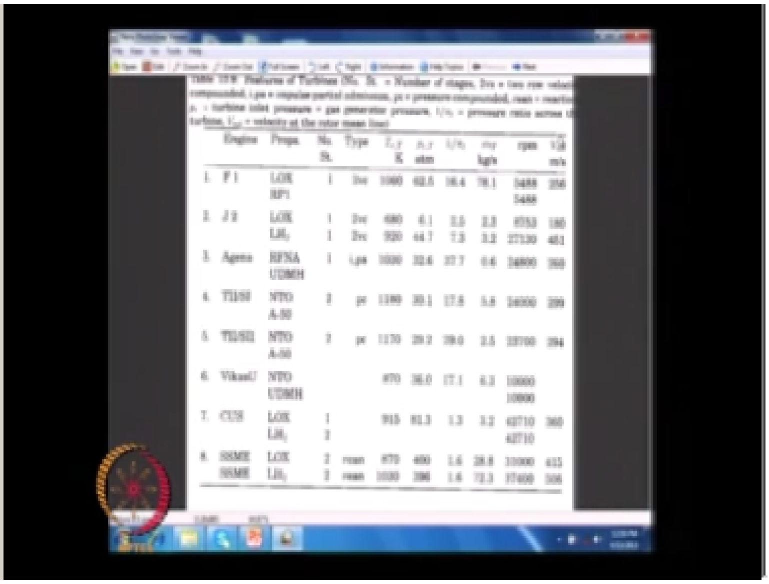

	Engine	Props.	No. St.	Type	$T_{0,T}$ K	$p_{0,T}$ atm	$1/\pi_T$	$\dot m_T$ kg/s	rpm	V_{bl} m/s
1.	F1	LOX RP1	1	2vc	1060	62.5	16.4	78.1	5488 5488	256
2.	J2	LOX	1	2vc	680	6.1	2.5	2.3	8753	180
		LH_2	1	2vc	920	44.7	7.3	3.2	27130	451
3.	Agena	RFNA UDMH	1	i.pa	1030	32.6	37.7	0.6	24800	360
4.	TI/SI	NTO A-50	2	pc	1180	30.1	17.8	5.8	24000	299
5.	TII/SII	NTO A-50	2	pc	1170	29.2	39.0	2.5	23700	294
6.	VikasU	NTO UDMH			870	36.0	17.1	6.3	10000 10000	
7.	CUS	LOX LH_2	1 2		915	81.3	1.3	3.2	42710 42710	360
8.	SSME	LOX	2	reac	870	400	1.6	28.8	31000	415
	SSME	LH_2	2	reac	1030	386	1.6	72.3	37400	506

If you look at this table here it gives you what are the RPMs that these pumps are run at remember we said that the diameters need to be small and rotational speed needs to be as large as possible if DSP and needs to be small and nsp needs to be large nsp invariably means if you look at this, this is nsp for a fix it flow rate and pressure head okay for a fixed flow rate and pressure at the only way you can get a high nsps by increasing the rotational speed.

And if you look at the numbers here they are rotated at very high speeds for the locks hydrogen systems something in the range of forty thousand rpm very very high rpms what does the this is this cause any problem is what we need to look at there is something called cavitations in pumps which comes out as a result of this high rpm what usually happens is if you remember lofts liquid oxygen.

And liquid hydrogen are low boiling point fluids right you must have done this experiment somewhere where in you have a tank and you to tend to suck through the tank it is something like this that let us say you have a tank here and you have a pipeline that is going here if you look at the actual difference in head it is this much right but there is a limit because at this point you do not want the pressures to drop below what vapor pressures right.

So similarly in pumps what happens is when you rotate it at very high rpm right the static pressure can go below the vapor pressure at that temperature okay once that happens then bubbles get form right it boils in some sense and bubbles get form these bubbles they move over to a high pressure area and then implode right when they implode they cause severe vibration loads okay.

And that is not the only thing the mass flow rate through the pump kind of oscillates okay now or only the vibration aspect is not such a serious problem in a launch vehicle simply because we are looking at a one-time-use right we are not looking at using it very often end unless you are looking at Space Shuttle main engine and things like that you are not looking at using it very often so you could probably deal with the vibration part.

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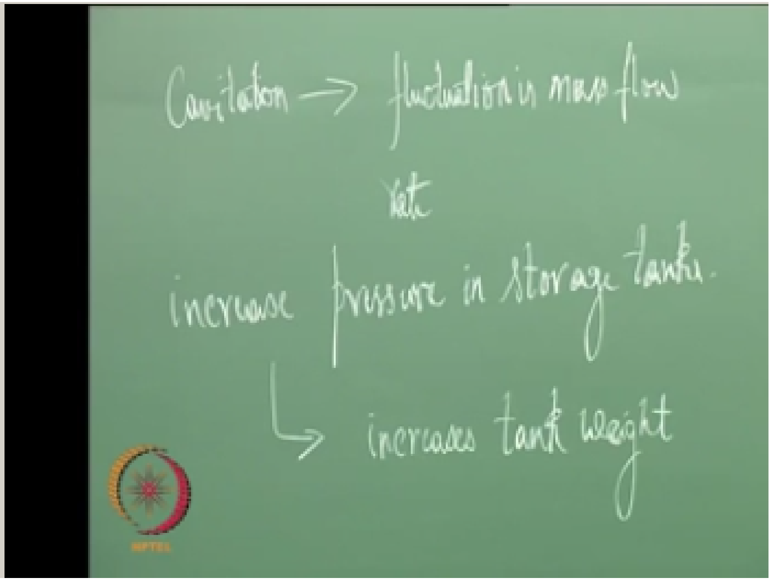

Cavitation → fluctuation in mass flow rate

increase pressure in storage tanks.

↳ increases tank weight

But the other part that is a very great significance is the fluctuations in mass flow rate that it leads to how does this affect the functioning of the rocket motor firstly the mass flow rate that is coming in is fluctuating right which could trigger an instability in the liquid rocket motor and it could have very, very serious consequences on the mission itself because, because of instability usually liquid rocket motors are very, very prone to combustion instability.

And usually they have very, very high frequency instability which simply means that as we had discussed earlier with regards to solid propellant you are having a fatigue loading of the motor right and if the frequency is a very large firstly they are being subject to very high heat transfer rates and also very high stresses and remember the factor of safety that we can use is very small and.

Therefore it could lead to a catastrophic failure of the whole setup so you would not want that to happen so therefore it is pretty much essential to ensure that cavitations and pumps does not happen okay so it is imperative that we reduce the or we eliminate the cavitations in pumps one easy way to do this is in some sense if you look at it if you kind of increase the pressure here right if you increase the pressure here.

Then or you will not get this problem right or in other words what we are looking at is increasing the pressure in the cylinder itself or the storage tank one way to overcome this is but what does that mean if you remember this is a turbo pump fed system we said be pressure in the tank is something of the order of three to six bar which will ensure that the wall thickness of the tanks is very small right.

But if you increase the pressure then your wall thickness goes up and your weight goes up which is not a desirable solution here right so there are other ways to tackle this problem other than increasing the pressure in the tank so this increases there is something that we can define as known as net positive suction head that is P stagnation minus P vapor pressure if we increase this part which is what is in tank which is what we discussed right.

Now okay the other way to look at it is something that has been quite rightly use this is to use something known as an inducer okay inducer or separate pumps in series so the way pumps operate is like this in the there is a rotor and stator right in the rotor you rotate it at very high rpms and therefore you give it the kinetic energy or in other words.

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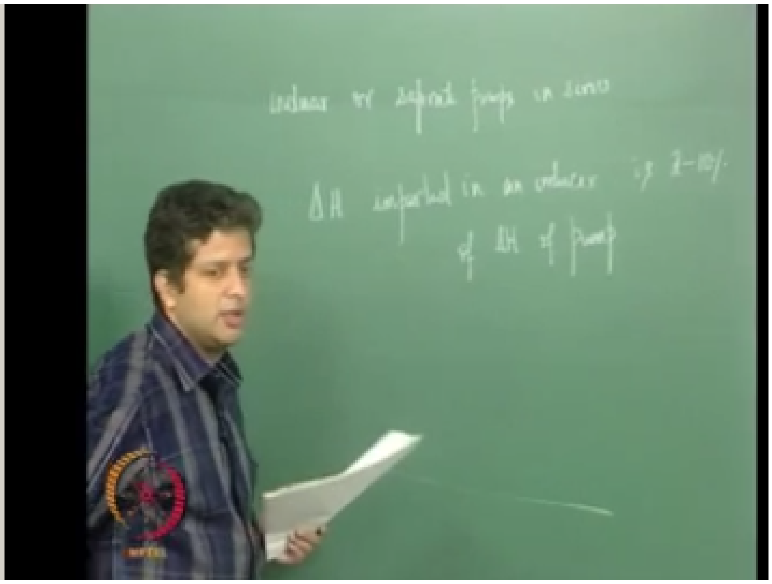

The velocities are very high which is kind of recovered in the diffuser stage right or the status cage as pressure fine so if you are giving a very, very high rotational speed in the first stage itself then it gives rise to this kind of problem but later on if you in the other stages after the first stage if you give it this problem is not very severe but this is very severe in the first stage okay one way to overcome this is to have things in series.

That is you do not look to give the entire pressurize in only one single stage but give it in a number of stages okay which is what is having separate pumps in series means okay the other way is to use an inducer now individual is also a pump but the only difference here is inducer the Delta H that is imported you tend to import a very low head in the first stage or the inducer stage in a sense you are rotating at the same rp mall of it is mounted on the same shaft.

But the head drives that is given is very, very small in the inducer so that the pressure at the exit of the inducer is higher then what causes this problem of cavitations and then you can give it the head rise in the other stages right so in this way you are going to overcome this problem this is in a sense the same thing is having pumps in series but in this case an inducer is some kind of special pump we are in a very small head rise is given.
Although it is rotating at the same rpm okay the velocity triangles are adjusted such that the Hydra is given is very, very small so in this way you can overcome this problem of cavitations and pumps now there are various ways in which one could arrange the pumps and the turbines which is shown here in this figure here okay.

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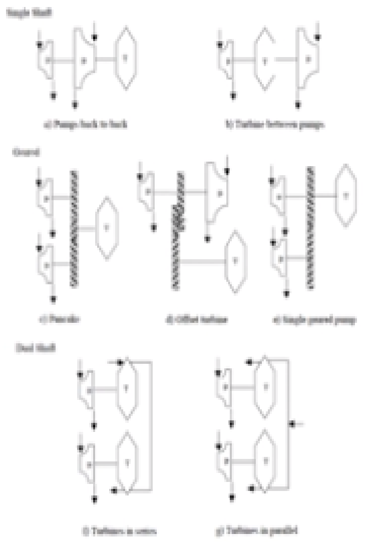

Various pump drive arrangement

If you look at this figure the first arrangement as shown here is one in which the pumps are arranged back-to-back that is one is the oxide fuel pump the other is the oxidizer pump and they are mounted on a common shaft that connects to the turbine now if you look at this kind of arrangement what it does is it reduces the axial thrust right because the axial load on this pump is in one direction the other pump is in the other direction.

This kind of cancels each other out and you have to deal with a smaller problem of axial loads the axial thrust that comes on the shaft okay the bearing that needs to take this can be designed such that it deals with a smaller axial thrust this is in some sense probably similar to what some of you have studied in IC engines the problem of balancing.

Right if a piston is moving inside a cylinder then if it is not properly balanced right if you have an arrangement wherein it is two cylinders are opposed then the imbalance in the loads get cancelled out right or if you have an arrangement radial arrangement of cylinders then there is no problem of balancing but if you have only one cylinder there is a problem with balancing right so that is very similar to the problem that you have here.

So this takes care of in some sense the axial thrust there are other arrangements that is used that is this is known as some pancake arrangement no win this arrangement there is a turbine between the pumps the turbine and the pumps are run at different rpm and they are connected through gate rain okay in the first one there is no gay train connecting the pumps.

And the turbines so whatever rpm the turbine is running it the same rpm is where the or is the RPM that the pumps are run it here you have an extra control on the RPM of the pumps okay then you have various arrangements wherein you have a separate turbine for each pump in this case so if you look at this CB and f here you can use this when there is a difference in the density of the two propellants like.

If you have lox and lh2 locks has a density of the order of 1100 right and the density of hydrogen is very low something around 70 so they need to be run at different rpms right if you have to run it at different rpms either thereto be connected through a gear train right or they have to have separate turbines which are running at different rpms right in this way you can ensure that these arrangements that is b c and f take care of things which have dissimilar densities okay.

Now the arrangement shown here d which is the turbine and the pumps or in this case the turbine was on one side and the pumps we are on one side in this case the turbine is in between the two pumps this works fine for propellants with similar densities ok because the Hydra is required is nearly the same so therefore if the densities are the same you can work it out that they need to be rotated at the same rpm.

So this works for propellants with similar densities whereas a b c and f work well for propellants with dissimilar densities then this arrangement C&G you have in this case in see the pumps are arranged in series whereas in the other one you could have sorry turbines are arranged in series that is the gases pass through the first turbine and then the same gases pass through the second turbine.

So depending on what is the head rise that is required in the two pumps you can work it out in this fashion but whereas in this case the turbines are in parallel okay that is the flow coming in from the gas generator is fed to both the turbines okay this kind of arrangement has been used in Space Shuttle main engine and this kind of arrangement was used in f1 engine.

Okay the f1 engine on Saturn for that took man to moon had this kind of arranging arrangement for LOX kerosene where in densities are similar that is if you look at locks it is around liquid oxygen is around 1100 the other one is around800 okay so this finishes our discussions on the pressure fact systems that is not the pressure of the turbine turbo pump fake systems we earlier discussed how to design a pressure effect system.

So we have discussed the various kind of feed systems that are possible now we have discussed what happens in the nozzle earlier we have discussed the feed systems let us now discuss what happens in the thrust chamber okay thrust chamber of a liquid engine the first thing that one encounters in the thrust chamber is what is known as a injector.

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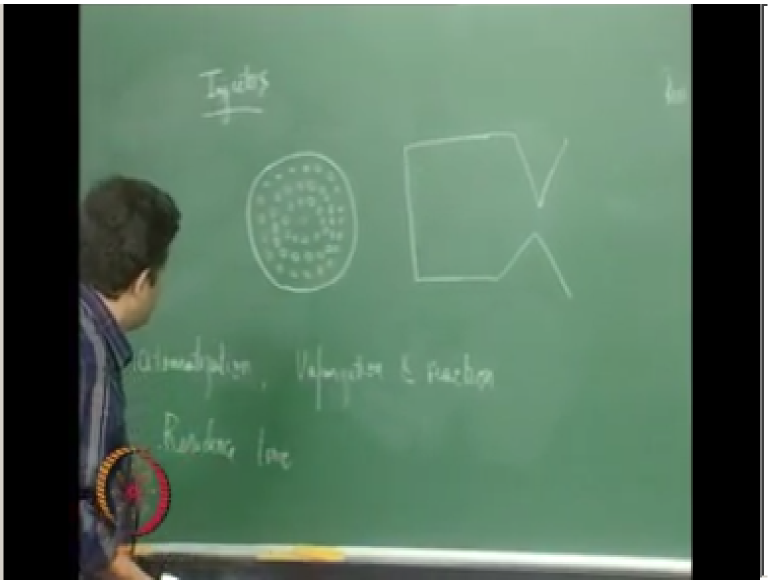

Now why do we need a injector why not inject you know we are injecting in some case two fluids if it is a by propellant system and in a monopropellant system we are injecting one fluid why cannot we simply inject them as one single pipe, pipe flow right why do we need these kind of small injectors are these kind of fur if you look at the liquid rocket motor there will be this kind of large number of small holes.

This will be the kind of arrangement in a liquid water rocket motor and let us say this is the thrust chamber and here you have the nozzle now if you look at it from that direction this is the kind of arrangement that you will have the liquids are pumped at high pressure through this large number of holes now the question is why do we need this kind of injectors.

The answer lies in the fact that if you are looking to have a reaction right you want these fluids to first leave a price right and then react reactions take place in the gas phase so there are a few things that are happening in the thrust chamber first is what is known as automation okay so you have atomization then you have these are the processes that need to take place within a liquid rocket motor.

And all these need to be completed before it enters the nozzle all the reactions need to be completed if this happens or there is something known as combustion efficiency that we look at where in how much of this is completed before it enters the nozzle it is good to have a larger fraction of these reactions something in the range of 92 to 95%

Because then what you will get is from the is ps that we had calculated we will be able to get a fraction of the those ISPs depending on the value of combustion efficiency the heat release that we get depends on what is the combustion efficiency if reactions take place after this then we will not be able to utilize it that effectively.

So you need to have all the reactions or a large fraction of it getting completed before it enters the nozzle now if you look at it there are three processes that take place this is like a relay race right first this happens then this happens then this happens right so in a relay race who gets to decide how fast the relay race is completed right does the fastest one get to decide how quickly the race gets over or does the slowest one the slow e stone is the limiting factor right.

So the slowest one gets to decide what kind of times it takes to complete the reactions so typically what happens is these liquid droplets are coming in okay one can define something known as a residence time okay residence time is nothing but what is the time that is available for reactions to be completed okay or what is the state I am of this of fluids in the combustion chamber okay so we have something known as residence time.

So all these processes need to be completed within this residence time or a large fraction of this needs to be completed within this residence time so that the F combustion efficiency is high now typically the state I am or the residence time is of the order of three to five milliseconds okay remember in a liquid rocket motor unlike in a solid rocket motor solid rocket motor you are storing.

The propellants also in the same team right in liquids you are able to store them separately and you introduce the min a chamber where they combust and react so the combustion chamber is very, very small okay so the residence time therefore is very small in a liquid rocket motor now let us look at what are the typical times for these three events to happen.

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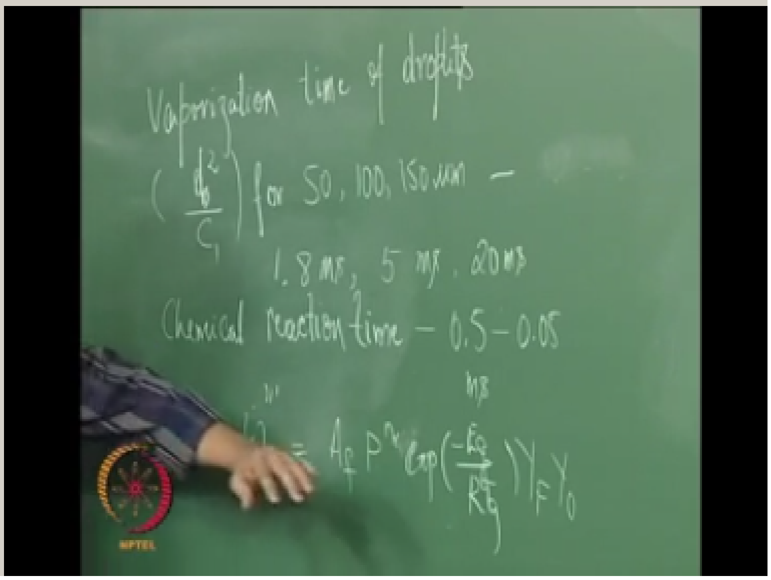

The vaporization time of droplets is a strong function of the size of the droplet okay so it goes as something like D0 ^{2} / D 1and 4 50 micron 100 micron and 150micron droplet size the time for vaporization is something like 1.8millisecondokay so if you notice here if the droplet diameter is small then the vaporization time is mark if the droplet diameter is large then the vaporization time is very large.

And therefore if you have a state I am residence time of this then most of the reactions would not get completed the reaction times are much smaller it is of the order of 5 20 point zero five milliseconds so it is very much smaller compared to this so this is the slowest process in all this okay so therefore this is the one that decide how fast the reactions get completed right so depending on the length of the chamber you can estimate a residence time.

And all your reactions need to be completed within that the reason why the reaction times are very small is if you recall what we had said about reaction rates right if you look at the relationship for reaction rate w dot triple dash that we had derived earlier it was something like right into YF you.

So if you notice that it is a strong function of pressure and temperature right the temperatures inside rocket motor or very, very high something of the order of 3000 so this term will be large and also if you remember liquid rocket motor depending on the kind of pressurization systems that we have if one is leaked looking at a pressure of X system the pressures are very low something of the order of 30 to40 bar right.

But if you are looking at the turbo pump head systems the pressures are extremely high something of the order of 200 / 100 to 200 x and the factor to which it is raised depends you goes something like it is of the order of 2 it is square of the pressure so the pressures are very high then the reaction rates are very large and therefore the reaction time is very small so in a sense this reaction time is small primarily due to the coupled effect of pressure being large.

And temperatures being large now it becomes clear why we need to do this atomization right atomization is the process in which you create this small droplets if you create these small droplets then the vaporization time as we see here goes something like d^2 we will be discussing waters that factor or a little more in detail of this vaporization time.

So the smaller the droplet the faster it way evaporates this is something similar to you know a match stick is made very small right simply because if you look at the surface area to volume which is very, very important it in heat transfer the larger the surface area to volume that you have the better it is for heat transfer so in essence if you are creating very small droplets the surface area to volume increases okay.

And that means there is a lot more heat transfer that is taking place instead of having one large droplet if you break it up into very, very fine large number of droplets then the surface area to volume is very large and heat transfer is better and therefore its vaporization times will be much smaller asses in here.

So you need to kind of make sure that it is atomized that is it is broken into very fine droplets and then these fine droplets will then evaporate fast and the reactions take place in the gas phase and these get completed very, very quickly.

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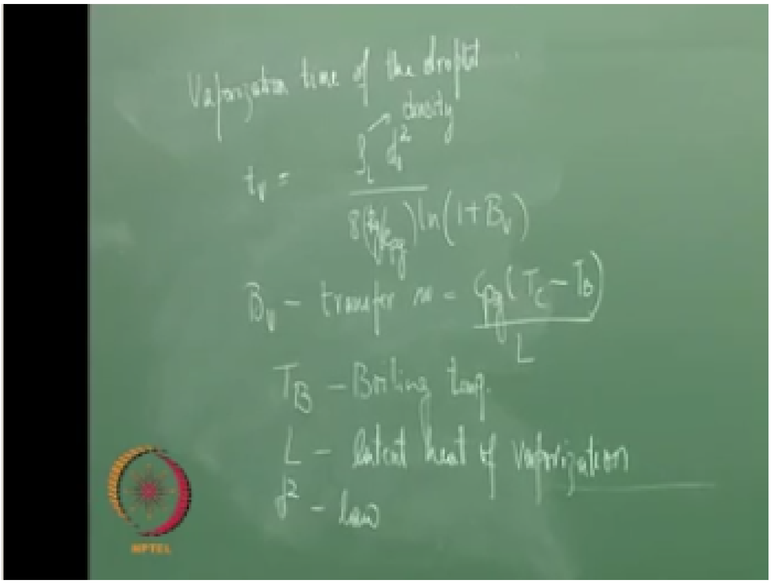

Vaporization time of the droplet

density

$$t_v = \frac{\rho_l d^2}{8(k_g/c_{pg})\ln(1+B_v)}$$

B_v - transfer no = $\frac{c_{pg}(T_c - T_b)}{L}$

T_B - Boiling temp.

L - latent heat of vaporization

d^2 - law

Now the vaporization time TV is given as we are bv if you recollect s the transfer number that we had discussed earlier that is it is the ratio of here TB indicates the boiling point okay TB is the boiling temperature.

And L is the latent heat in a sense we are making an assumption that all the liquid is at its boiling point right and then it is only required to be given its latent heat of vaporization if you have the liquid if the boiling point of the liquid is very high this is a fairly good assumption of the boiling point of the liquid is very low something like lox and hydrogen but if the boiling point of the liquid is very high.

Then you need to add the other term that is the heat that is required to take it from whatever temperature the liquid is apt to the boiling point okay so this is kg is nothing but the thermal conductivity this is the specific heat then this is the density of the liquid what you can see here is that the vaporization time is a very strong function of the diameter of the droplet okay so there is known as something this is called as the d square law.

So you could rewrite this as something like so this is nothing but a constant that takes into account all the other things other than the diameter okay so as we can see here the vaporization time is a strong function of the diameter and therefore it makes sense to have very small diameters okay now we will discuss in the next class how we can get the small diameters by the process of optimization what is the process of atomization.

And how does it ensure that you get very small diameters of droplets and what are the various arrangements that are possible okay if you remember most of the propellant combinations you have two liquids it is only in the case of liquid hydrogen and liquid oxygen wherein if you use hydrogen for the regenerative cooling part it is mostly a gas while coming into the combustion chamber right so we will discuss what kind of arrangements of injectors we need to have for various kinds of propellants in the next class thank you.

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