Rocket Propulsion

Prof. K. Ramamurthi

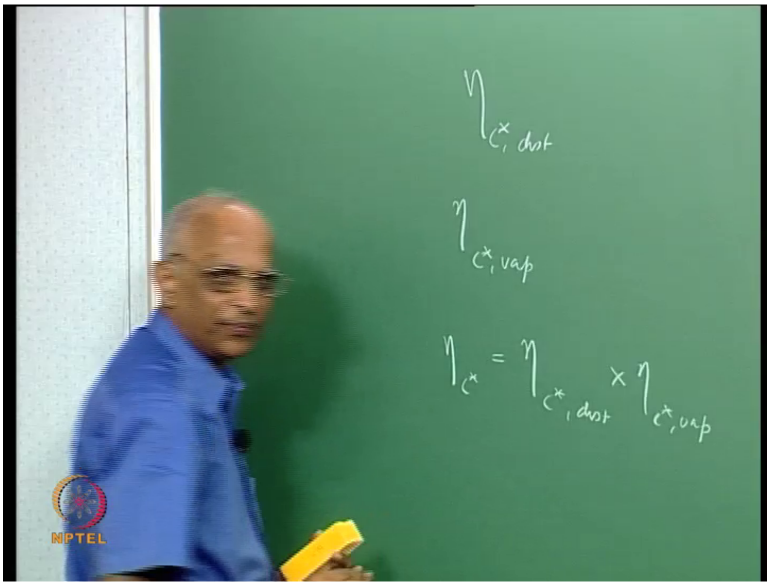
Department of Mechanical Engineering

Indian Institute of Technology, Madras

Lecture No. # 31

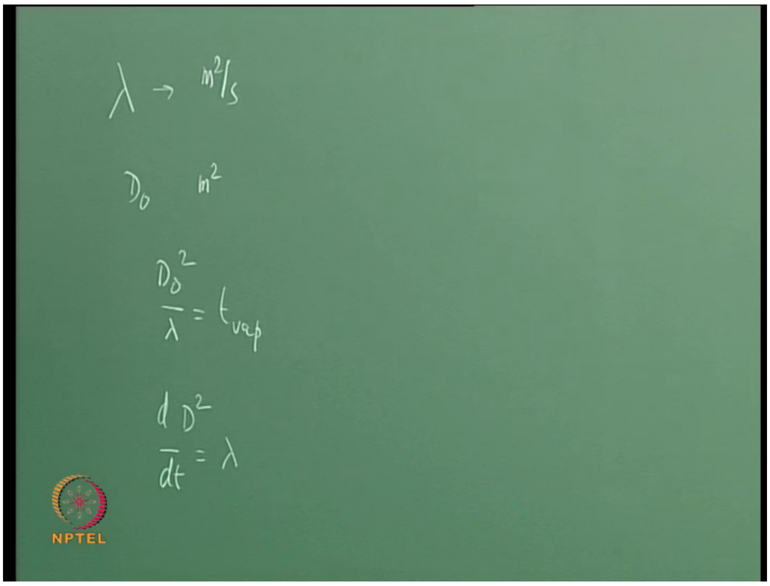
Pumps and Turbines: Propellant Feed System at Zero "g" Conditions

(Refer Slide Time: 00:18)



We continue with what we were doing in the last class namely efficiency of C* due to distribution, the time taken for a droplet to evaporate, the value of the evaporation constant lambda and C* due to incomplete evaporation. And we said that C* efficiency due to these two effects is equal to the C* efficiency due to the distribution and multiplied by C* efficiency due to incomplete vaporization. We thus get the efficiencies. We would like to spend a couple of minutes on the vaporization.

(Refer Slide Time: 01:02)



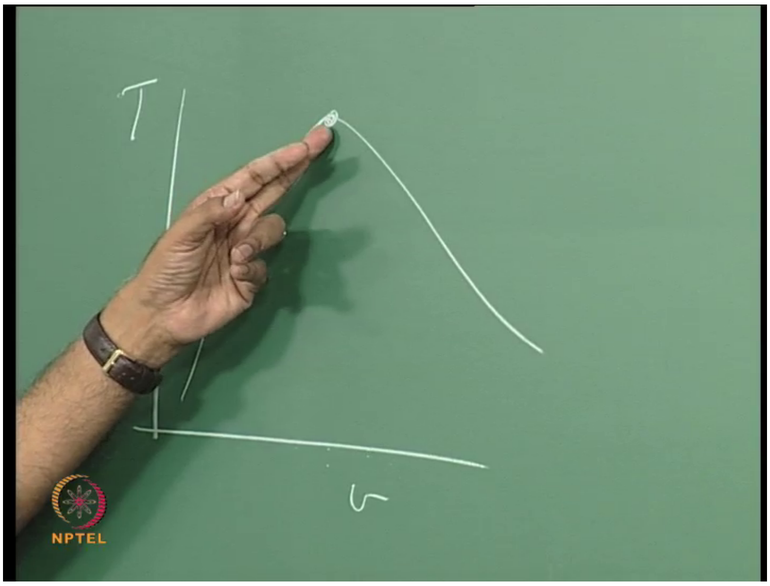
We found that dD^2/dt is a constant equal to λ and depends only on the properties of the fuel and oxidizer. The value of λ for a given fuel say diesel or kerosene is around 0.2 mm^2/s.

If I have a hydrazine droplet in a hot medium it is something like almost 4 mm^2/s. We can get the value of λ from experiment or from the expression that we derived. We can therefore find time taken for a droplet to evaporate and is equal D_0^2/λ. We thus know the time in seconds for evaporation; D_0^2 naught square this has units of $meter^2$ by lambda with units $meter^2$ / second.

The question of λ being a constant is not immediately convincing. Why is it a constant? We find anyway $dD^2/dt = \lambda$ which we call as evaporation rate constant, does not does not depend even on the diameter as per the expression. It is just a function of the diffusion coefficient, density of the droplet and density of the medium and therefore, lambda tends to be a constant for a given fuel in a given oxidizing medium at a given pressure.

If you go to a lab on combustion, you often find experiments on droplet burning. The time taken for vaporization of a droplet is often measured. But, then there is a complexity. This complexity comes whenever we have a droplet burning, it is in a given medium. That droplet tends to sort of adsorb the particular gaseous medium on the surface and therefore, λ is not really a constant at different pressures. At low pressures well it is a constant. At high pressures when we did some experiments we found a different behavior. In fact, one of your seniors did this work. He did a series of computations on equilibrium between liquid and gas phase at high pressures, calculated the value of λ and λ at high pressure tends to decrease. In fact, his work was published in physics of fluids and that is what we do research work on in combustion evaporation rate. We found that λ decreases at high pressures, But, again it picks up at very high pressures again. At very high pressures, a liquid droplet may behave as a gas; if we were to plot something like temperature versus specific volume diagram a T and v diagram, we have the liquid line, we have this line which is a saturated vapor line line.

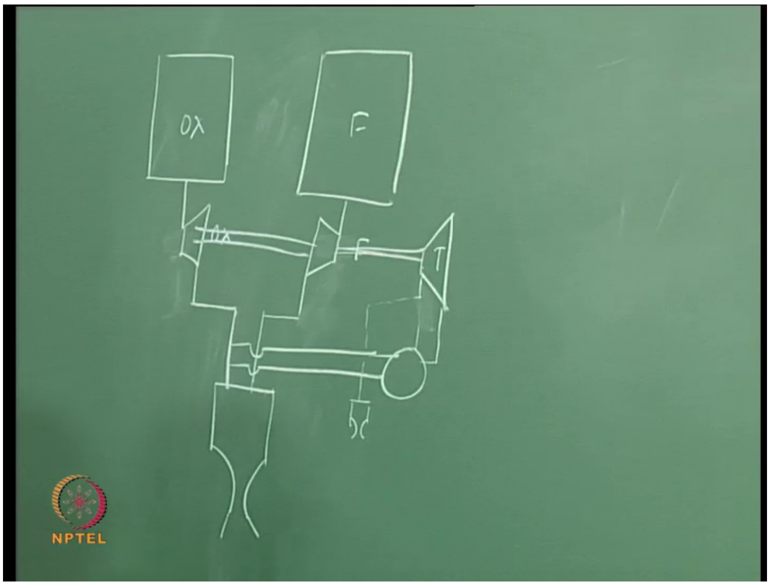
(Refer Slide Time: 03:18)



This is the critical point. When we approach the critical point and this critical point is not very high for kerosene in the presence of its own paper; it could be as low as 50 bar and we operate the chamber pressure at much high values. At that pressure what happens is may be oxygen gets adsorbed on the surfaces, the critical pressure increases in this binary medium and even at very high pressures exceeding the critical pressure of kerosene in presence of its own vapor, the droplet would still be in the subcritical case. And therefore, this question of λ is important in which lot of papers are written and therefore, I think you all of us should have a feel for it.

Let us let us take a quick summary of the liquid propellant rockets.

(Refer Slide Time: 04:19)

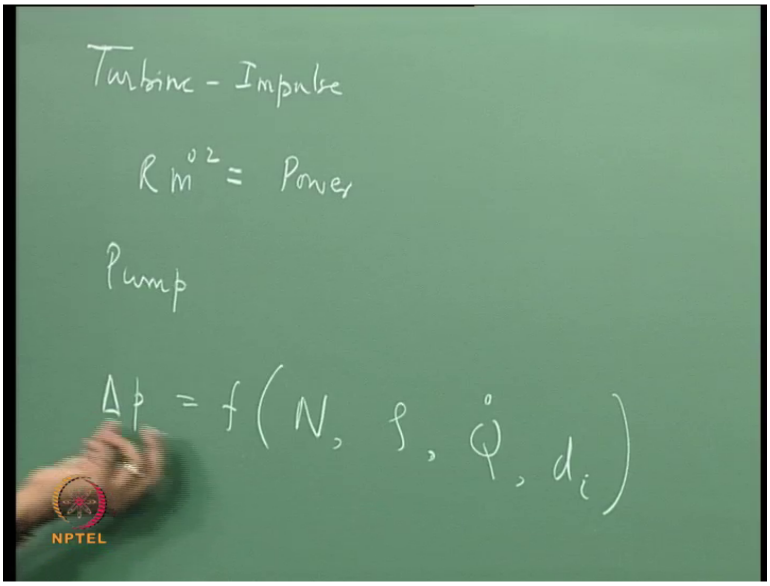


We started with tanks and said that liquid propellants are pushed into the chamber. I could have either a regulated gas pressure mode, I could have a pump fed mode, I could have something like a blow down mode. Ultimately what is it that we did was that we brought the fuel and oxidizer into the chamber. We looked at the efficiencies, we looked at the chamber. We already looked at the nozzles.

But what we have really not looked is at these pumps and turbines in a gas generator cycle. We increase the pressure of the liquid propellant using the pumps. We have a pump for fuel the second one for oxidizer and we bled some of the fuel and oxidizer for the gas generator. This amount of oxygen or oxidizer and some amount of fuel is burnt in a gas generator and then used to drive the two pumps. That means, we supply hot gases to a turbine, we expanded the gases in the turbine and do work. We generated power in a turbine and drove the pumps. When we took the exhaust gases and put it back into the chamber, we called it as stage combustion and when we allowed the turbine exhaust to go out to an auxiliary nozzle we said it is a gas generator cycle.

Therefore, may be we should spend some time on these pumps and turbines. Normally, the turbines that we use are of the impulse type. This means it is velocity driven. We just convert the enthalpy gases into high velocity gases.

(Refer Slide Time: 06:13)

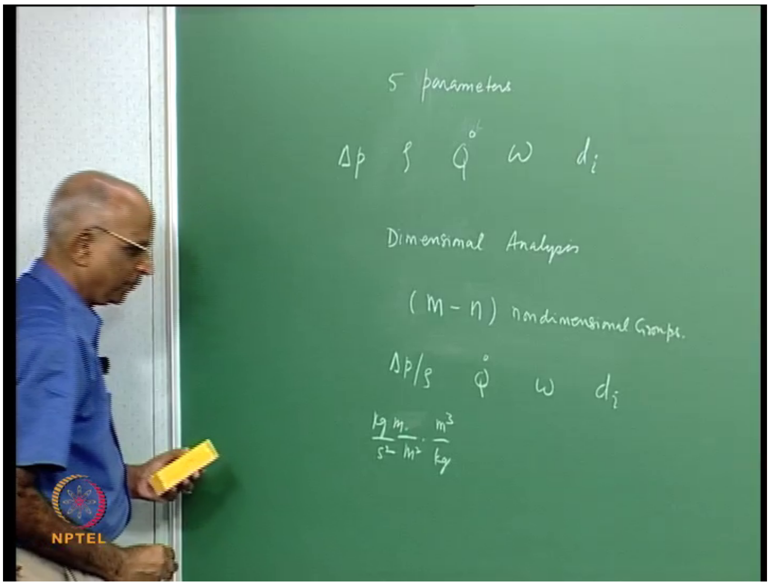


We have the enthalpy of the hot gases at the exit of the gas generator that is at inlet to the turbine. We have at the outlet of the turbine the enthalpy and the enthalpy at entry to the turbine is partly converted into velocity. The velocity impinges on the blades, rotates the blades and that is what drives the pumps. That means, we say turbine is generally of impulse type and how do we say this? We say well, it goes as the resistance R into something like a mass flow rate m^{o2} that gives the power to run a particular turbine. This I just put as resistance. I will be revisit this expression a little later.

We also have the two pumps; they are of a single stage if they are for a small engine; it could be a centrifugal one wherein I have small flow. But, if I need high pressure and high flow rates it could be a series of axial flow pumps or it could be combination of centrifugal and axial flow pumps. In other words, it could be a combination of radial and axial flow and therefore several possibilities exists for a pump. If we have to go into details of pumps for fuels and oxidizers, it becomes an exercise in turbo machines and we will not go through it in detail. But, I also want to do some justice to pumps and turbines. We should be clear what a pump is required to do. A pump must generate pressure and what are the parameters in a pump? May be the speed of the pump? So, many N rpm and generally pumps rotate at very high speed so of the order of 20,000 to 60,000 rpm.

In fact, we have a new liquid propellant rocket engine known as Vinci for which the speed is almost one lakh rpm. Why do we need high rpm? The dimensions must be small therefore the speed must be large such that I am able to get a high pressure. Therefore, one of the factors is N rpm. The pressure delivered by the pump depends speed of the pump, on the density of the liquid used, depends on the volume flow rate that is the mass flow rate through the particular pump. It must also depend on the dimension may be a nominal dimension like let us say diameter of the impeller or some mean diameter of the system. Therefore, we say that the head developed by a pump must be a function of a set of parameters. In other words to be able to quantify the pressure rise in a pump, we need these parameters. We find the parameters which affect the performance of pumps are Δp, the speed, the density, the flow rate and the impeller diameter. In other words we are talking of five parameters, which are required to characterize a particular pump.

(Refer Slide Time: 09:06)



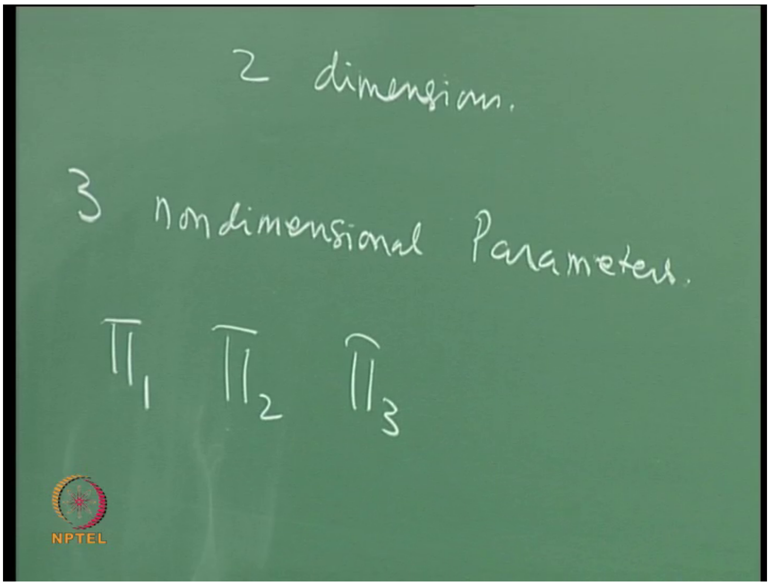
The five parameters: Δp; pressure increase across the pump, density of the propellant, the flow rate of the propellant, and speed. Instead of writing N rpm, we rather put it in terms of radians per second (ω) omega, which is 2πN. The last parameter which we said is the impeller diameter or a mean dimension di.

Now, we want to find out the influence of all these parameters on Δp and vice versa. How do I do a complicated problem in engineering, which involves a number of parameters? Dimensional analysis: excellent! We have to do something like a non dimensionalisation or dimensional analysis. Therefore, let us do it. At least we have the satisfaction of having studied pumps through a dimensional analysis procedure.

We look at the Buckingham pi theorem for the dimensionless analysis. We have five parameters for the problem. And Buckingham pi theorem states if we have a problem involving m parameters and having n primary dimensions in it, we can from m minus n non dimensional groups. This is Buckingham pi theorem.

Therefore what are the primary dimensions we are talking of? When we look at Δp and ρ, Δp/ρ is the head. Then we look at flow rate Q°, ω, di. Let us put the dimensions of the quantities: Δp/ρ = Newton/meter^2/(kilogram/meter^3) cube. But Newton is equal to kilogram meter/second^2. Therefore, this gives me unit as meter^2/second^2; that means it is equal to m^2/s^2. Let us let us put down the primary dimensions now.

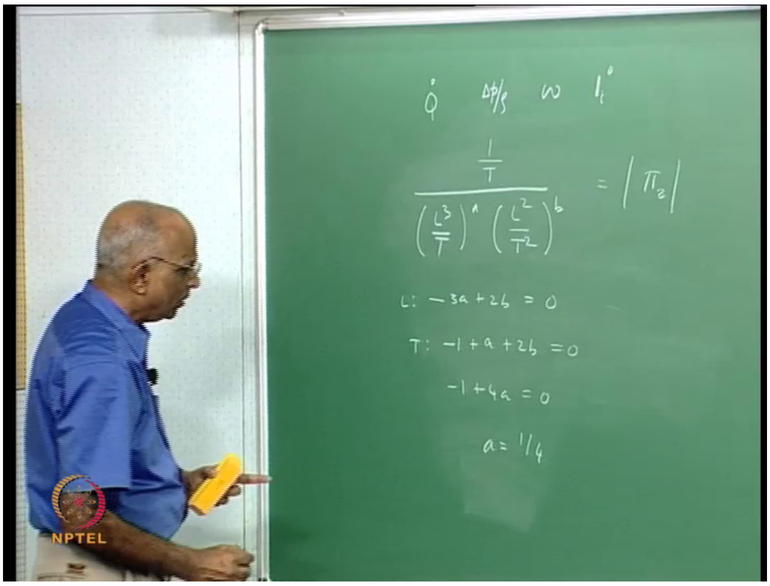
(Refer Slide Time: 11:35)



The primary dimensions for this problem are ΔP/ρ with unit of L^2/T^2. Q dot has dimensions of m^3/s that is equal to L^3/T, ω has dimensions of 1/T and we have di which has dimension of length L . Therefore, how many fundamental dimensions do you have? L and T alone. That means, two fundamental dimensions and the number of parameters that we have are five.

Therefore, we should be able to get three non dimensional parameters. Therefore, I say for the case of pumps and turbines put together i.e., a turbo pump, we want to develop non dimensional parameters π_1, π_2 and π_3. Well, let us derive these non-dimensional parameters π_1, π_2 and π_3 and then try to describe turbo pump operation and how to go about choosing a turbo pump.

(Refer Slide Time: 13:25)



The five parameters are Δp, ρ, $Q°$, ω and di. You know that the head of the pump is delta p by rho and therefore we consider as a parameter.

We know $\Delta p/\rho V^2$; ρV^2 has units of pressure and therefore, we can directly write $\Delta p/\rho V^2$ as one non dimensional parameter. Rather with $V = \omega \times di/2$, by observation we write a non dimensional parameter as $\Delta p/(\rho\omega^2 di^2)$. Just by observation. Why is that? We know ρV^2 has units of pressure, density has units of kilogram/meter^3 and meter^2/second^2 has units of Newton/meter^2 by density. Therefore, by observation, we get this as a non dimensional parameter. This could be π_1. We saw earlier that $\Delta p/\rho$ can be expressed as L^2/T^2, which has the same units as $\omega^2 di^2$.

Let us do one non dimensional parameter by detailed analysis. Consider the non dimensionalisation for $Q°$. We find that $\Delta p/\rho$ should cause variation in $Q°$. Well, we have ω which influences $Q°$. We have to some extent already taken di in the non dimensional term π_1 viz., $\Delta p/(\rho\omega^2 di^2)$. Let me not consider di again.

We interested in let us say $\omega = Q°\,^a \times (\Delta p/\rho)^b$ over and this could also be a non dimensional parameter.

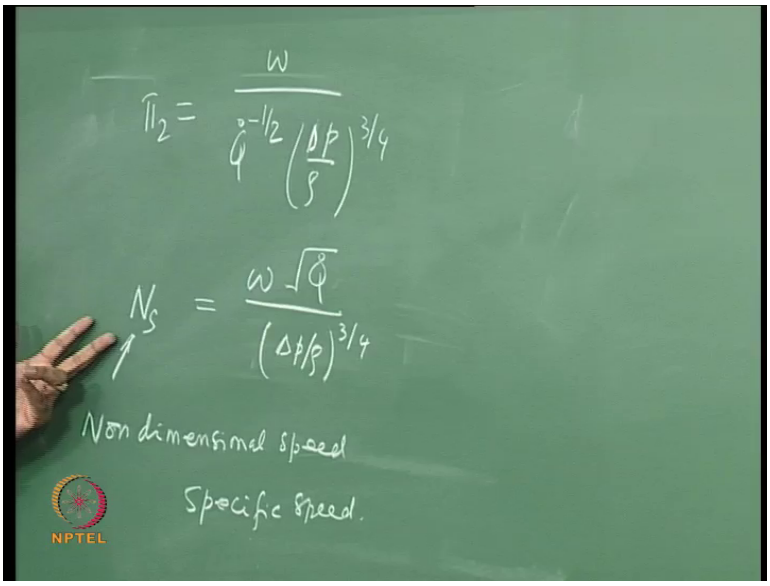
We would like to non dimension the speed of the system ω as a function of flow rate $Q°$ and the pressure head $\Delta p/\rho$. Can we derive a non dimensional term for the speed? We find ω has units $1/T$; $Q°$ has units of L^3/T; $\Delta p/\rho$ has units of L^2/T^2. The combination should give us a non dimensional parameter $\pi_2 = \omega/[Q°^{\,a} \times (\Delta p/\rho)^b]$. What should be mthe choice of a and b in this expression for it to be non dimensional? Let us solve it so that we get L^0 and T^0. We have $\pi_2 = (1/T)(L^2/T)^{-a}(L^2/T^2)^{-b}$

If I solve for L to be independent i.e., L^0, we $2b + 3a = 0$. Similarly, to be independent of T, we get $-1 + a + 2b = 0$.

And what is it we get? We get $2b = -3a$. If 2b is equal to 3a, we get $-1 + a - 3a = 0$ or $a = -\frac{1}{2}$. The value of $b = 3/4$

Let us do it again. $-1 + a + 2b = 0$ and $2b = -3a$. Therefore, $a = 1 - 2b$ i.e., $1 + 3a$ or $-2a = 1$ giving $a = -\frac{1}{2}$. If $a = -1/2$, $b = 3/4$.

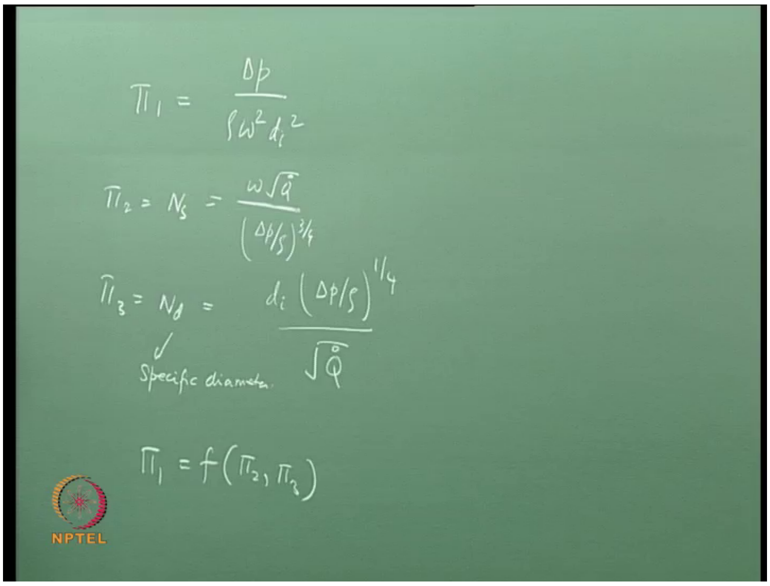
(Refer Slide Time: 20:50)



Therefore what will be my expression for π_2? $\pi_2 = \omega/[Q°^{\,-1/2} \times (\Delta p/\rho)^{3/4}]$. This equals $\omega\sqrt{Q°}/(\Delta p/\rho)^{3/4}$ or rather this tells me that the value is equal to omega root Q° divided by delta p by rho to the power three by four. This π_2 is what we call as a non dimensional speed or a specific speed.

Therefore, I have got the second non dimensional parameter. Therefore, let us put down the parameters together.

(Refer Slide Time: 22:03)

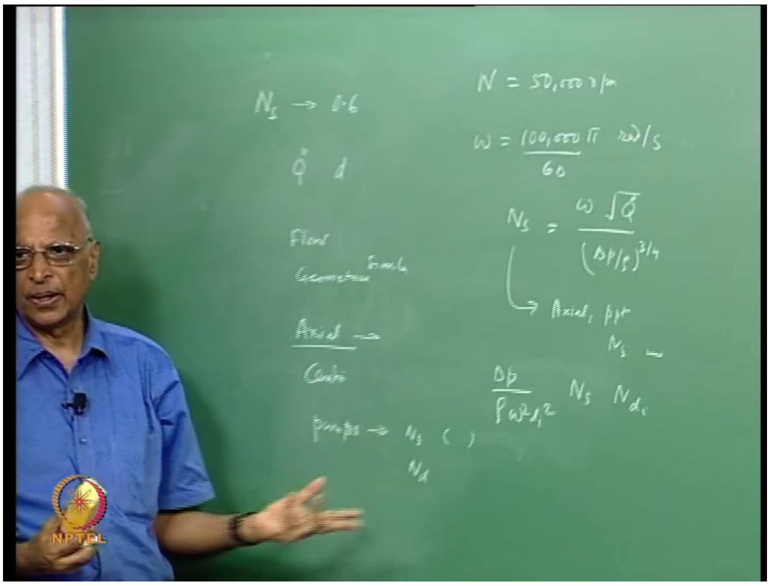


The first parameter I said $\pi_1 = \Delta p/ \rho\omega^2 di^2$. The second parameter $\pi_2 = \omega\sqrt{Q°}/(\Delta p/\rho)^{3/4}$, which call as specific speed.

We do the same analysis for finding out the non dimensional di as a function of $\Delta p/\rho$ and Q°. We will not do it in class. May be do it as a homework problem. We will get the value of π_3. We call it as specific diameter and it is di $(\Delta p/\rho)^{1/4}/\sqrt{Q°}$.

Well, these are the three non dimensional parameters. The performance of the pump can be expressed as π_1 which is the non dimensional pressure head and can be expressed as a function of π_2, the specific speed and π_3 the specific diameter. This is how we non dimensionalize the parameters of the turbo-pump. But, why did we non dimensionalize it?

(Refer Slide Time: 24:35)



Let us take one of the non dimensional parameters and see what is the impact and why we are doing all this? When we say the specific speed π_2 i.e., $\omega\sqrt{Q°}/(\Delta p/\rho)^{3/4}$ and if the specific speed of a turbo machine is something like let us say let us say 0.6; what does it denote? Similarly, if we say π_3 or specific diameter, what does it lead us into? Why is it so important?

This non dimensional parameter tells us for a given value of this diameter, if we were to scale up the diameter, we have to scale up the value of Q° and $\Delta p/\rho$ according to π_3. Similarly, at different values of speed, the flow in the pump, the geometrical characteristics of the pump will be similar at the same value of specific speed. In other words, for the same non dimensional number, that is the same specific speed, we can assume that the flow characteristics will be the same through it may be handling different density fluids at different speeds and flow rates.

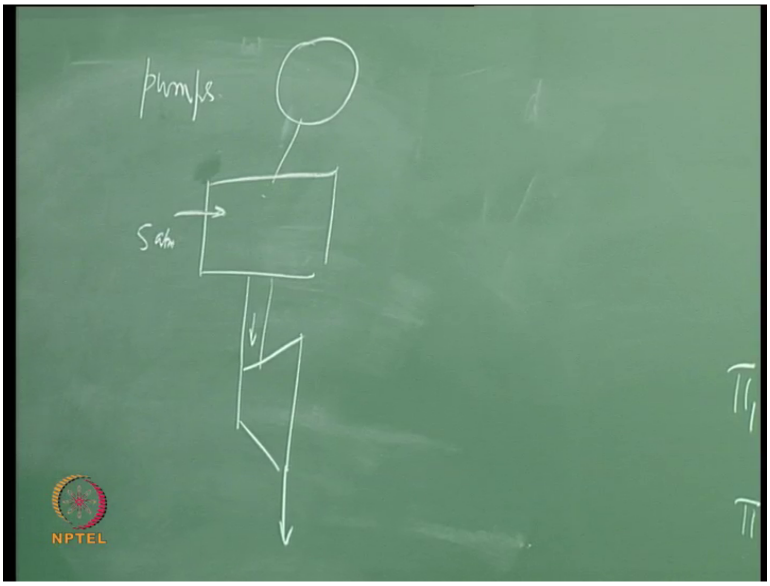
For a given axial flow pump handling a particular set of propellants, if we keep on varying the quantities and if we vary the size of it and if we get a given non dimensional number, the flow through it is invariant or similar. It shows that for a given type say axial or centrifugal pump, if the size is varied automatically Q° and D will get vary and speed will vary, but, if the the specific speed is same the flow characteristics and the geometrical similarity will be there. If one axial pump works for a given cryogenic propellant at a given speed, a scaled up version should also work at the same specific speed. The variations in design is such that for a given type the value of π_2 or specific speed Ns will between a small range of values.

If we were to say π_3, also called as Nd, that is the specific diameter it will have a small range of variables. Therefore, you know if we have to scale up a cryogenic pump still using the axial pump we will go ahead and design for this particular value of specific speed. Therefore, these non dimensional parameters are powerful because they allow us to determine the range of operation of a particular system like what we said was the speed of a pump may be fifty thousand rpm, may be therefore, ω is equal to let us say $100000\times\pi$ radians per minute or to convert it by radians per second I divide it by 60. We get so much radians per second and therefore, for this radians per second if we were to get the equivalent value of specific speed Ns and how did we get the value of Ns? We get ω for that particular machine or particular pump; we find out the flow rate, the pressure head developed by it and get the value of Ns.

And now, if we were to design another pump which has to cater for a much larger flow rate and a different size of it, if we use the same value of Ns. The nature of flow in the system that is the hydraulics in the pump and also the geometrical characteristics will be similar. And therefore, for a given type of pump let us say axial pump, for a given type of propellant the Ns will fall in a very small number may be 0.6 to 0.7. Therefore, these numbers are useful and also the performance can be written in terms of Ns, in terms of Nd, in terms of $\Delta p/\rho\omega^2 di^2$ and this is why the non dimensionalization is useful. Whenever we plot the results of turbo-pump, we always plot it as a function $\Delta p/\rho\omega^2 di^2$ versus the specific speed $\omega\sqrt{Q°}/(\Delta p/\rho)^{3/4}$and that is how the performance of pumps are expressed.

This brings us to the next part on the usefulness of the parameters.

(Refer Slide Time: 29:08)

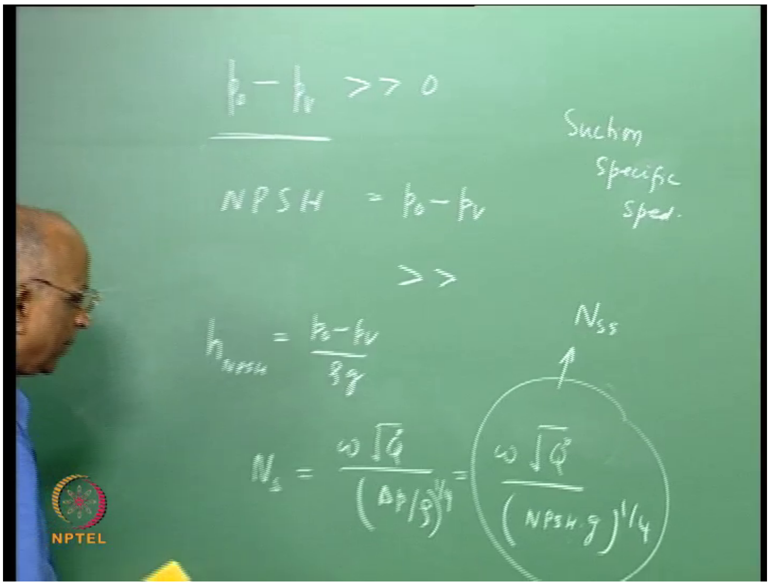


What are the problems with pumps? We take the propellant from a tank. We cannot have a high pressure in the tank. The maximum pressure here is let us say five atmospheres which is the upper limit. Now, we feed the propellant into the pump over here and I take the outlet at high pressures. This is inlet and this is outlet.

This means that there is a maximum pressure at which we can supply because Iwe have to carry a gas bottle here. If I have to increase the pressure we have to increase the mass of gas which is not desirable. Therefore, the pressure at the inlet to the pump cannot be high. Now if the pump is to rotate at very high speed the velocity of the blades will be high; if the velocity of the blade is high then the static pressure will be low. If the static pressure falls below the vapor pressure, bubbles of the vapor are formed and bubbles of vapor formed will harm the blade. It will immediately fail. We are rotating at high speed and the two phase flow will cause severe vibration and the blade gets damaged.

Therefore, the pump is subject to cavitation and in any pump it is necessary for us to reduce the likelihood of cavitation. How do we eliminate the possibilities of cavitation?

(Refer Slide Time: 30:38)

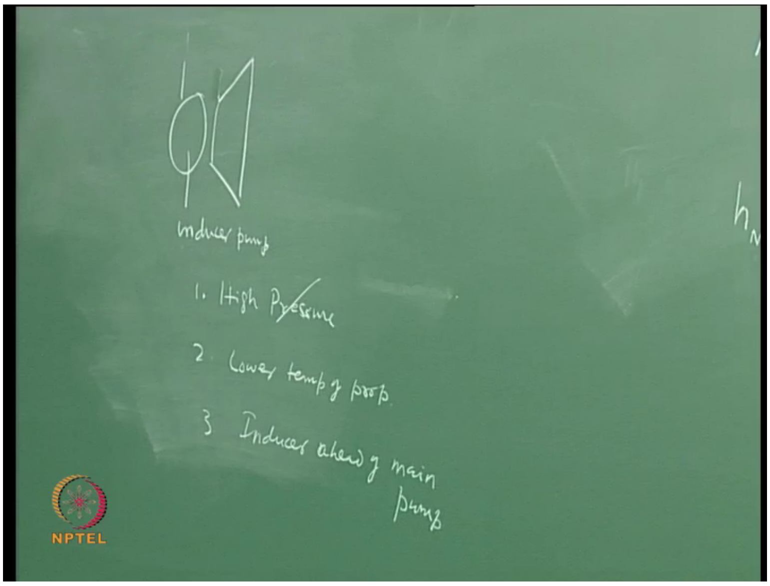


My supply pressure or the stagnation pressure at supply which we call as p_0 and this p_0, when it the maximum, could be about five atmosphere. This value − the vapor pressure should be a large number. But, this number depends on the speed of the pump. If ω is large since the vapor pressure pv is a property for a given propellant, what happens if the static pressure reduces to the value of vapor pressure and cavities would form in the flow or cavitation would start. This value p_0 −pv becomes an extremely important parameter and we call it as the net positive suction head: Net Positive Suction Head (NPSH). This given by p_0 − pv must be a large number for any pump.

Is it clear? I would like the net positive suction head that is the p_0 − the vapor pressure which we call as net positive suction head to be large. We can write this net positive suction pressure as head in terms of ρ and g as equal to (p_0 – pv)/ ρ g as the net positive suction head. To avoid cavitation, this head must be a reasonable positive value and if we were to substitute in the value of the non dimensional parameter π_2, we call it as suction specific speed. What was specific speed equal to? It was equal to $\omega\sqrt{Q}/(\Delta p/\rho)^{3/4}$. We substitute $\Delta p/\rho$ with the value we get is the specific suction speed of the pump.

This value is what is referred is denoted by Nss. That is we say the specific suction speed for preventing cavitation or we say this head must have a value greater than a threshold such that cavitation does not occur. This is equal to non dimensional number with respect to cavitation. We call it instead of writing it as Ns which was the specific speed, we say as suction specific peed Nss. Now, all what we are trying to say is cavitation is an important parameter in a turbo-pump and is to be avoided. We would like the net positive suction head to be large and therefore, this Nss gives you an idea of what we need to do to make this a large number.

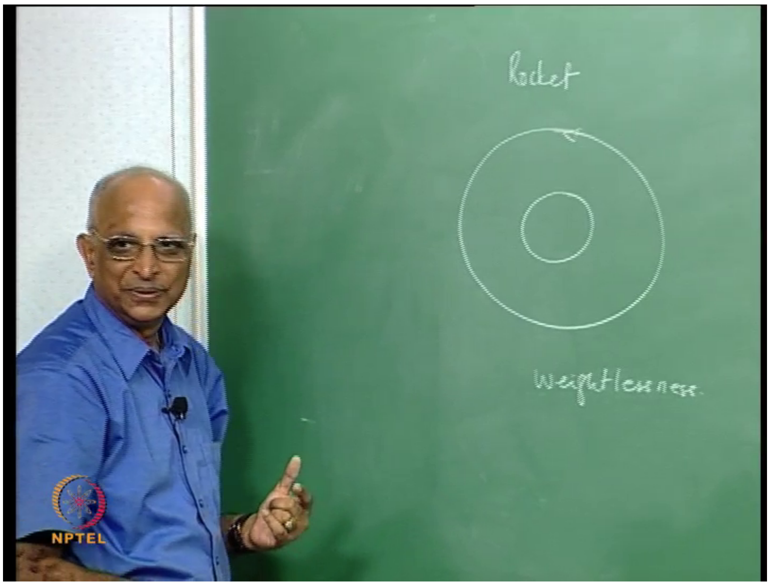
(Refer Slide Time: 34:09)



We have said that would like the value of $p_0 - p$ vapor pressure to be a large number. How can you make this? Either the tank pressure must be increased or else if I can sub cool the liquid propellant, if I cool my liquid propellant the vapor pressure comes down. We can then get a larger number for the net positive suction head. A third solution to the problem is before the pump we place another pump, which we call as an inducer pump. This rotates at much lower speeds and supplies the propellant at much higher pressures than the pressure from the tank to the main pump, which is rotating at very high spee therefore get a higher value of p_0. That means, we can improve the net positive suction head by following one or two of the above three strategies. Either provide high pressure tankages which is not the correct solution; second is lower the temperature of the propellants in which case we reduce the value of pv or we place something like an inducer ahead of the main pump.

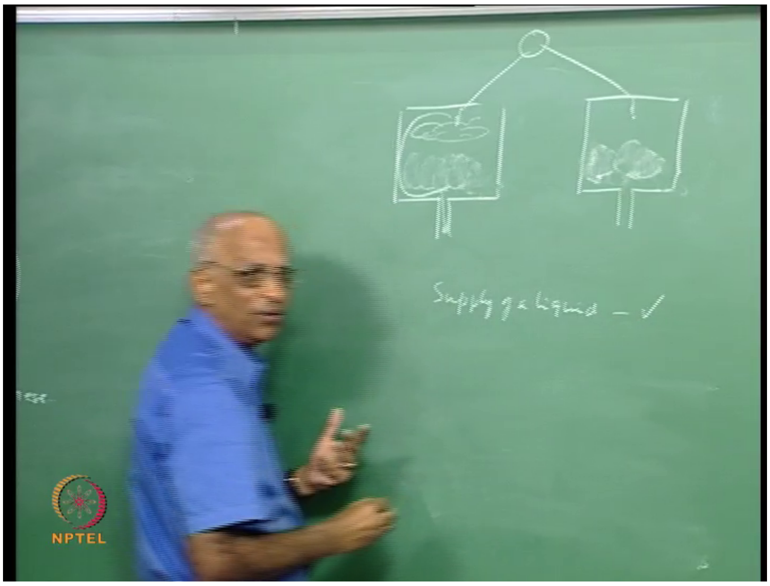
Therefore, people who work with liquid propellant rockets will talk of an inducer pump ahead of a pump and this is the reason why it is done. I think this is all about the turbines and pumps. We reduce the problem to one of non-dimensional representation. We talked in terms of a specific diameter, we talked in terms of a specific speed and said there will be similarity when the non dimensional parameters are the same and we will be able to quantify the performance and normally the performance is always expressed in terms of this non dimensional parameters.

(Refer Slide Time: 36:15)



I think with this background of turbines and pumps let us come to the last topic in liquid propellant rockets. We have a satellite going around the earth in some orbit or the other and we said that the motion of satellites in orbit is something like a freely falling bodies. We also told ourselves all freely falling bodies have a problem in that they are in a state of weightlessness in its own frame of reference.

(Refer Slide Time: 36:54)



Now, the question is we have a propellant tank may be a liquid fuel tank, an oxidizer fuel tank; well the liquid is at bottom of the tank. I have a drain port through which we are drawing the liquid.

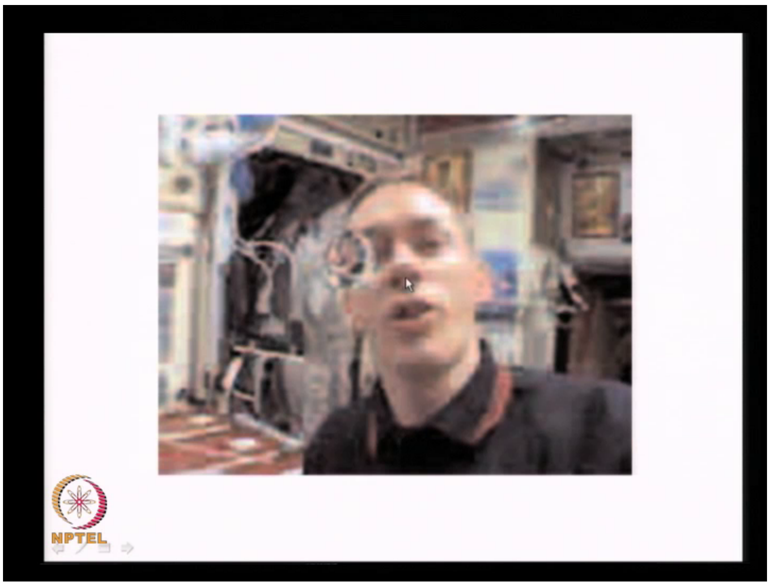
Similarly, if the rocket as it is going up with the satellite or when the rocket is moving up it sometimes coasts. This means there is no thrust, it is again in a state of reduced weight as it is not powered. The liquid in the tank, when is in a state of weightlessness, is not going to be at the bottom and it could float anywhere within the tank. If we supply a gas over it to pressurize it, liquid will not be expelled. We push the liquid using gas and only gas will come out through the drain port rather than the liquid. Therefore, supply of a liquid under the conditions of let us say weightlessness has to be taken care of and how do we do it? I thought let us illustrate it with some pictures available on the net.

(Refer Slide Time: 38:11)

The pictures are very illustrative. This one shows an astronaut in one of the space capsules in orbit.

He is trying to eat something. But, you know what he wants to eat is just freely floating. He cannot really access it until he physically pulls it. It is not going to fall because of the state of weightlessness.

(Refer Slide Time: 38:30)



How do you drink water in space craft? This is again of an astronaut. He is in the space station. He has a water here and he wants to drink water. There is no way the water can come to him. He has to literally catch the water drop, bring it to his mouth and drink. otherwise he just cannot drink.

(Refer Slide Time: 38:55)

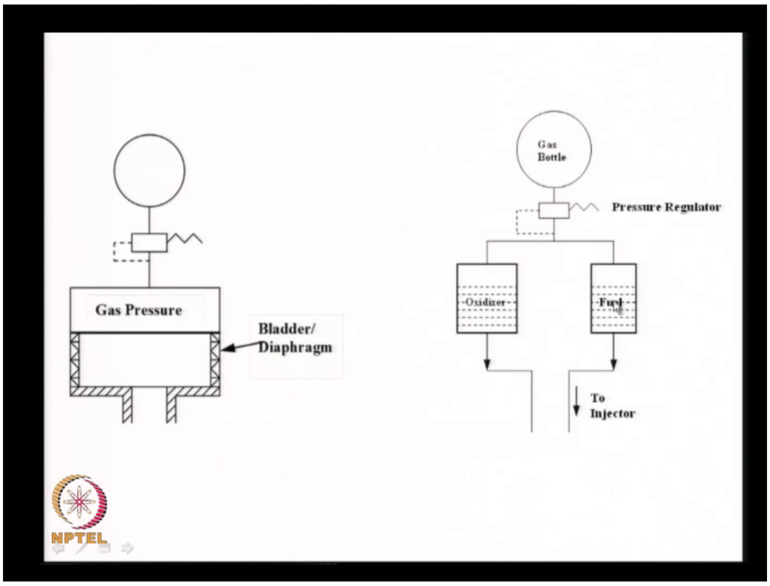
And this is the problem we have of weightlessness. You know, I thought all of us are concerned in some way or the other with the subject of combustion. This is how a candle flame looks like on ground. But, if we light the same candle in a state of 0 g that is weightlessness I get a beautiful picture like this.

That means you know there is no buoyancy because buoyancy depends on gravity. Since, there is no buoyancy the flame is beautifully a hemisphere over here. Let us now come back to our problem of whether we can supply propellants when in a state of weightlessness and that is something which we have to do.

(Refer Slide Time: 39:27)

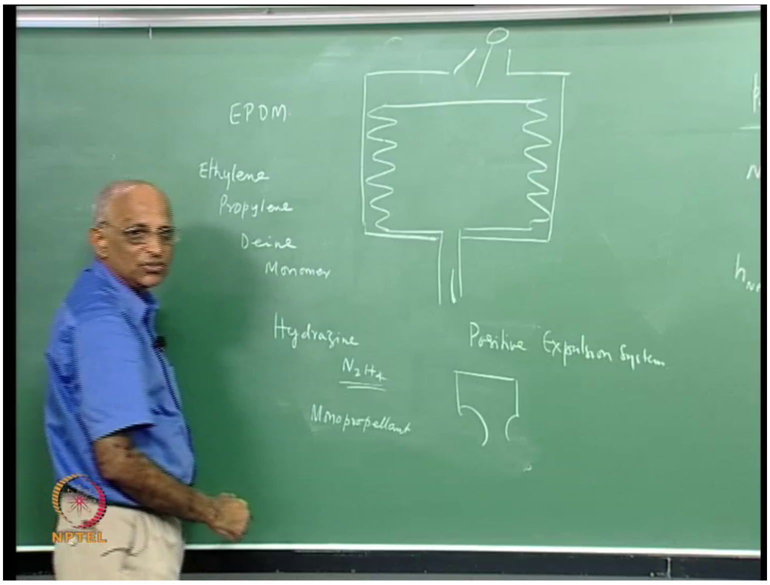
This slide shows water droplets on some leaves in the international space station. These plants were grown there and when you try to water them, you know see water bubbles this is the water drop on a leaf. This water drop does not have any weight. It has a certain mass, but the weight is zero. Therefore, you know you see the leaf which is supporting such a large quantity of water because it is weightless. It just does not have a weight by which it can fall down.

(Refer Slide Time: 40:08)



And therefore, we come back to our problem. We have a gas bottle, we have the oxidizer fuel and the fuel. Both are in the liquid state. When the flight is in a state of weightlessness, well oxidizer could be distributed in any way in the tank and we will not be able to supply it. One of the measures which was done in the early part of the rocket technology was we would have something like a diaphragm. What is a diaphragm? Well, let us let us sketch it out.

(Refer Slide Time: 40:53)



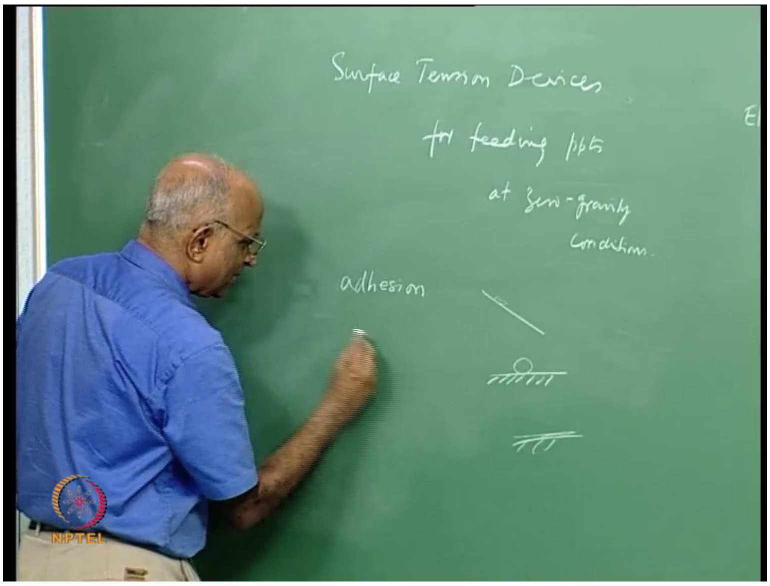
You know, you have something like an elastic material, like the foot ball bladder. Something made of rubber. You know something like the bellows that we have in the musical instrument harmonium which we compress by the diaphragm and squeeze out the air. I enclose the propellant completely within it and place it within the tank. Now, I pressurize the tank with a gas and the gas compresses the diaphragm and the diaphragm as it compresses, the propellant flows out. That means, I contain the liquid positively. That means, we have a positive expulsion system.

That means, we cannot leave the liquid free. We have the tankage, but, within the tank we must put a diaphragm and in the diaphragm, we store the liquid. There is no gas at all within the diapragm. W make sure there is no vapor at all and we positively push the propellant through and the fuel gets expelled into the chamber. That means, both the tanks will consist of diaphragms which is a positive expulsion system. Now, diaphragm must be a very flexible material. One of the material used is EPDM rubber is more or less universally used. What is this EPDM? It is a rubber type. It is ethylene propylene deine monomer.

Why this rubber is chosen is most of the upper stages or let us say the rockets which are used in spacecraft is that the fuel hydrazine or MMH (MMH is again mono-methyl hydrazine) which is again hydrazine based fuel. And this particular diaphragm material should not get dissolved in this hydrazine because if it gets dissolved even trace quantities would affect the performance of the rocket. We will study this may be in the next class wherein I will deal with monopropellant hydrazine rockets.

What happens is the trace of the bladder material will poison the catalyst used for combustion. The catalyst will degrade and therefore, the general tendency is to use EPDM rubber for the positive expulsion system. But, you see the positive expulsion system has its own problems. You are having something like this rubber material or diaphragm material and it occupies a volume with the result the useable space in the tank is not fully used. That means, the entire tank space cannot be filled with the liquid propellant. And we loose precious volume.

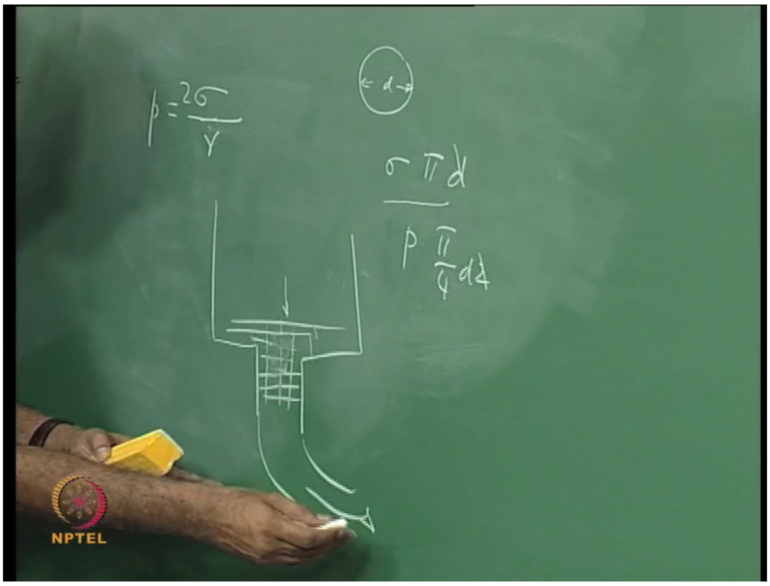
(Refer Slide Time: 44:08)



Therefore, what is the current trend and what the recent generation of satellites use? By recent I mean for the last 15 to 25 years or so, if not more. It is to use surface tension devices for feeding liquid propellants for feeding under zero or micro gravity conditions.

All of us know what surface tension is. A surface when wetted sticks to the liquid wetting it. Why does something have to stick to the surface? Well, you talk in term of adhesion. I have a surface of a metal. I put a mercury drop the mercury drop over it. It stays as a drop it does not smear on the surface. If I put water on a surface it smears. That means, I say surface adhesion takes place. In this case of mercury something like cohesion of the liquid takes place. We do not want cohesion, but, want the liquid to spread. It is not only the property of the liquid, but the properties of the surface of the material are equally important. Like for instance, water spreads on the surface in a glass tumbler or in a vessel, but the same water does not spread on a lotus leaf. That means, we are looking at surfaces and how do I make use of surface tension will be able to overcome the problem of feeding propellants under micro-gravity conditions.

(Refer Slide Time: 45:51)

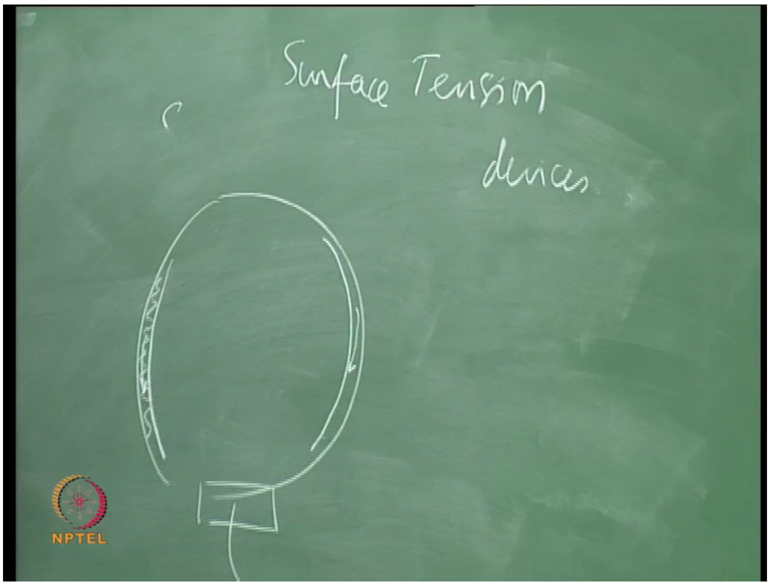


Well, I can think of the following. Let us do a small exercise. Supposing I make a sieve; that means, a series of thin wires placed crosswire. Let us say I place it in a cylindrical case and I dip it in water. The water is retained over here in the sieve. How is it retained? Let us say I have a series of sieves here and now I pour water the water just sticks to the surface. Now, I push air over here. May be there is a value of pressure drop across the sieve before which air cannot enter it. That means, I must overcome the surface tension pressure. If we were to write surface tension as units of Newton per meter and what does it do? It wets the surface. Let us take I take an individual hole in the sieve. The diameter is d the surface tension coefficient is σ. The surface tension coefficient is in Newton per meter. The surface tension force = $\pi \times d \times \sigma$ Newton.

Now, we push air into it. The force of pressure on this is equal to let us say the force of air which is equal to $\Delta p \times \pi/4 \times d^2$ while the surface tension force acts over the perimeter. This is $\sigma \times \pi \times d$. The particular diameter d that can hold a pressure equal to something like let us say d and d gets canceled, $\Delta p = 4 \times \sigma / d$ or $2\sigma/r$. comes on top over here. Therefore, if we can make a series of sieves or mesh and stack one over the other, it can be designed to prevent air from passing through it. In these meshes liquid is always present as long as it is wetted.

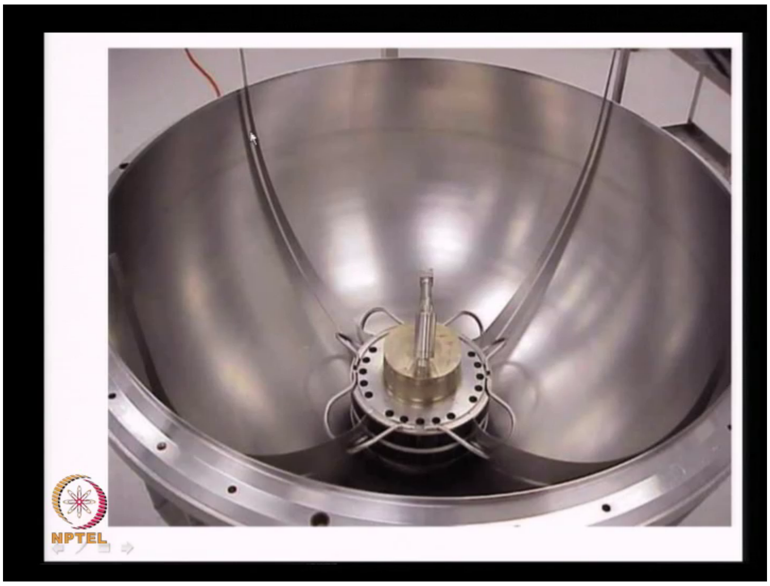
And therefore, you know what happens is that I make sure that the gas pressure will not permeate through and the gauze is always wet. Whenever I want to supply a propellant, the propellant is available. When I supply the propellant immediately a thrust gets generated and there is some force generated and thereafter the propellant settles down and wets the gauze. The gauze is placed in the drain port and this is the essential principle of surface tension devices for supplying liquid propellants at 0 gravity conditions.

(Refer Slide Time: 49:05)



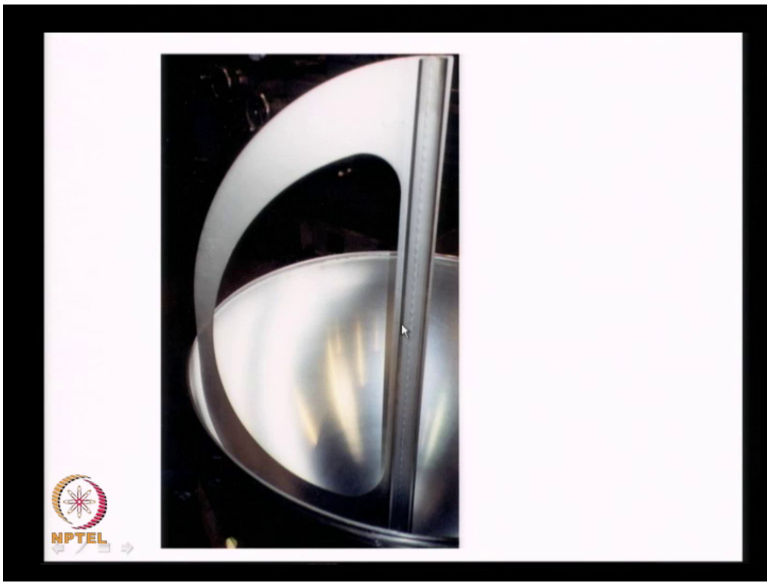
Let us take a look at some improved versions of them. We have a tank and by placing a series of ribs adjacent to the tank surface we can use it for a dynamic pumping. Let us say that we put some vanes at the surface and there is a small gap between the vane and the surface. We shape the veins such that the pressure at the lower end is lower than the pressure here. In other words the flow of propellant takes place and I collect it in a surface tension device here and supply it to the thrusters. Let us take a look at some of the arrangements used for spacecrafts.

(Refer Slide Time: 49:36)



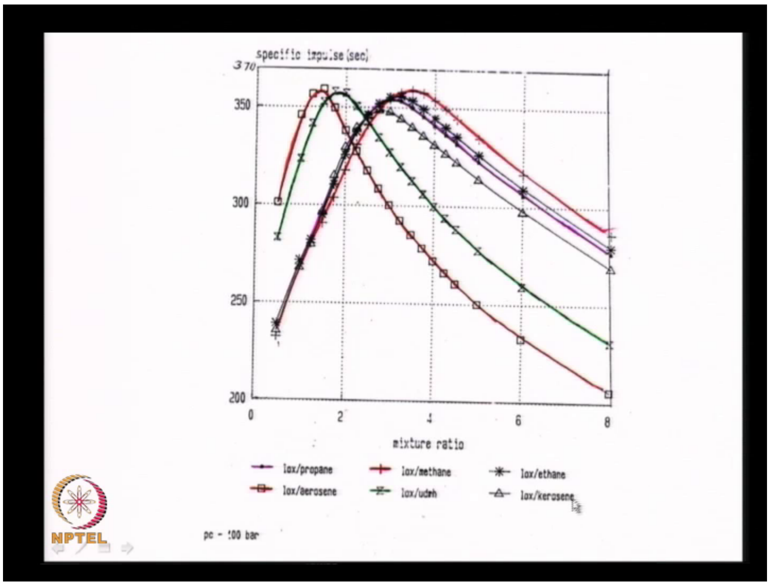
The propellant tank shown above is spherical. The propellant is retained in the gap between the vane and the tank inner surface. The vanes are shown here. The gap is so adjusted and the pressure varies in such a way that the propellant is fed to the drain port. The vanes are placed for collecting the propellants and supplying it. This is another view of it. This is the vane what I am talking of, this is the gap what I am talking of, this is where the sieve at the bottom which collects the propellant and feeds it into the chamber.

(Refer Slide Time: 49:58)



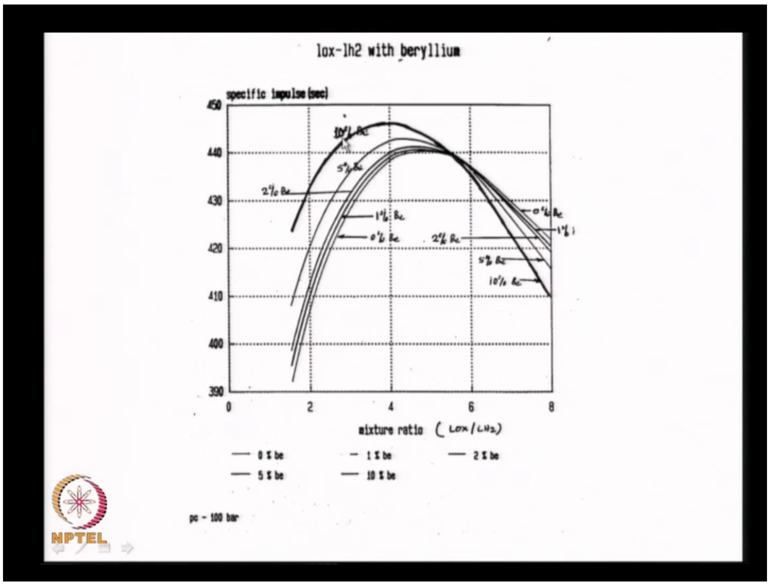
These devices have high values of expulsion efficiencies. Most of the propellant can be expelled unlike in the case of the positive expulsion system. This is all about surface tension devices. I think we have more or less covered the liquid propellant rockets; we considered the different elements, but, just to get into one small part of it

(Refer Slide Time: 50:35)



We talked in terms of specific impulse, we talked in terms of mixture ratio, we talked in terms of different propellants. The propellants which we did not consider were liquid propane, liquid methane and liquid ethane. When we compare the performance of liquid, oxygen and kerosene; we find kerosene has lower performance than these cryogenic fuels like liquid propane which is normally a gas; liquid methane is a gas and therefore, you know people are trying to work on whether they should use some of these propellants in future liquid propellant rockets.

(Refer Slide Time: 51:13)



But they are far from being operational. In the last slide, I wanted to bring out whether it is necessary to add metal powders to liquid propellants to enhance its performance. When we consider a solid propellant; we added metal to solid propellant to improve specific impulse.

But if we try the same procedure with liquids what happens is the molecular weight of the products goes up and putting metal in the propellant rather than improve the performance does not really give the advantage like you for solids. Therefore, metal in liquids does not seem to be a solution. The higher molecular mass of the exhaust and metals requiring some more time to burn are constraints. And sometimes the metal is converted into a liquid oxide oxide, but unless that oxide releases the heat within the nozzle the energy is not effectively released.

I think this is all about liquid propellants rockets. In the next class, we will discuss liquid monopropellant rockets and hybrid rockets and then get into the problem of combustion instability.