Rocket propulsion
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Lecture No. # 09
Theory of Nozzles

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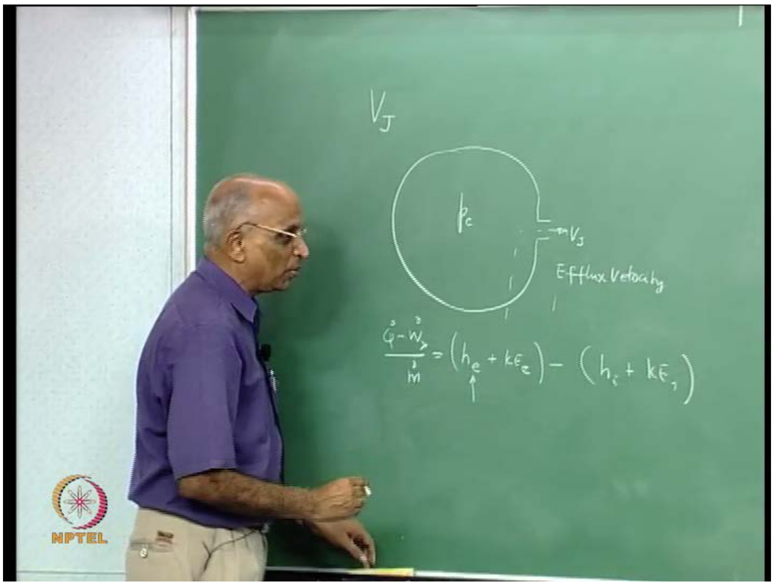

Good morning, you know in this class we will develop the equation for V J, as we left it in last class we told ourselves we have any high pressure container it has a chamber pressure likes P c, I have something like a hole or a went through which a hot gases are squatting out.

I want to find out the efflux velocity, which I call as jet velocity or we call it as efflux velocity V j, and this is what but how I before I do that since there was a question of specific impulse, and unit of specific impulse let just spent some 2 or 3 minutes on this issue.

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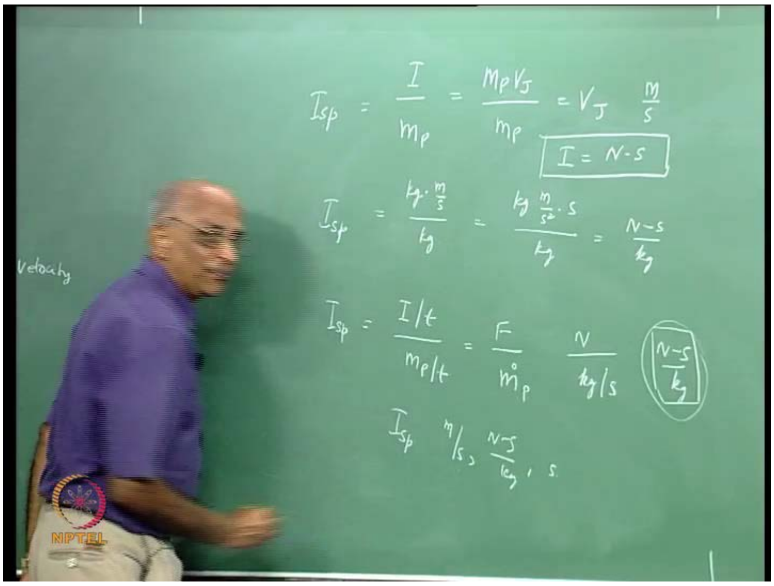

What was specific impulse we told our self's specific impulse is equal to I divided by the mass of the propellant, that is the impulse generated by M p mass of propellant, what is impulse change of momentum is equal to M p into the momentum V J divided by m p which is equal to V J, as per this equation the unit of specific impulse should be meter per second, which is same as the efflux velocity V j. But how did I define specific impulse I defined it as impulse for mass flow of propellant, in other words impulse has unit of momentum, change momentum, kilogram, meter per second divided by kilogram and when I say impulse I give a certain force over a given time; that means, I can write the change of momentum as equal to kilogram, meter, per second square into second divided by kilogram and this the force mass into acceleration is a force which I call as Newton second by kilogram. Therefore I also see that unit of specific impulse can be expressed in Newton second by kilogram.

So far so good let us go to the third one derive it instead of putting as impulse suppose in either to write the same expression for specific impulse as equal to impulse per unit time divided by mass flow rate of propellant per unit time. And what is impulse per unit time is force, force into time is impulse, in other words I have force divided by M p dot, in other words force as unit of Newton, mass flow rate of unit kilogram per second, therefore the unit of impulse specific impulse again comes out to be Newton second by kilogram.

Therefore, whether I express specific impulse as impulse per propellant mass or specific impulse as force per unit mass per rate I get a same unit as Newton second by kilogram, therefore the unit for specific impulse is Newton second by kilogram, the unit for impulse should have been I as equal to Newton into second, that is what we gives me the value of impulse kilogram meter per second as Newton second, therefore let us keeps the thing very clear impulse has unit of force into second Newton second, specific impulse has unit of Newton second by kilogram, but well there are many text books which specify the specific impulse not in meter per second, not in Newton second by kilogram, but other in second.

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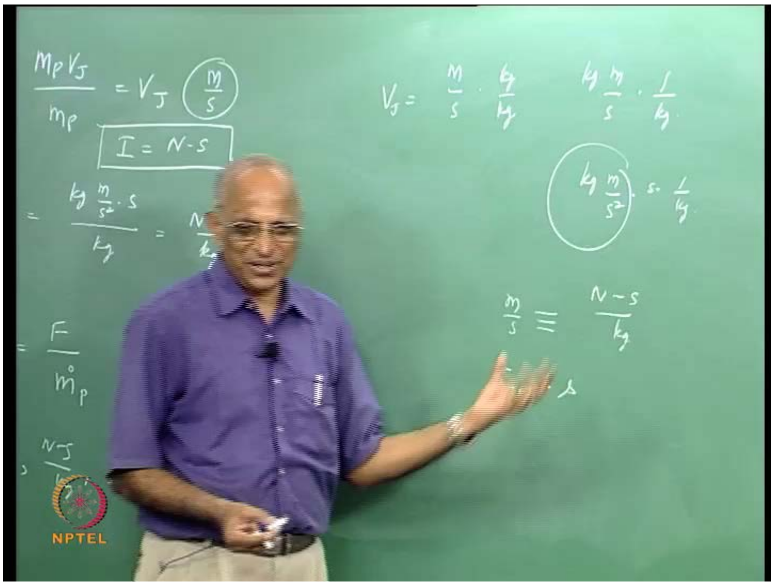

See when I say the specific impulse is so much meters per second, I could have also taken meter per second here straight here meter per second, I multiply both numerator and denominator by kilogram and kilogram, and what is it I get; I get the unit of V J as equal to kilogram meter per second, divided by kilogram now I again multiply the numerator and denominator by second which this gives me kilogram meter per second square into what do I get second per unit kilogram and this gives me Newton second by kilogram, therefore meter per second is actually identical to Newton second by kilogram, but there are either of the units is ok, but there his many text books which still continue to define specific impulse in terms of seconds.

Why do they use seconds in they also specify the force in kilogram or pounds, therefore pounds and pounds gets cancels second, therefore whenever somebody gives in second it is my duty to multiply by the conventional constant G c, and then use it in Newton second by kilogram, may be you all should go through it, but in this class we will always address specific impulse in Newton second by kilogram or in terms of meter per second both of which you have the same identical units.

See units are very important in engineering, you know without units we will be talking of something but getting of some other figure as it (( )), having said get back to our problem, we want to find the V J. We derive the equation for control volume we said q dot minus the work done by the particular rent let's say W x divided by let say m dot is equal to the enthalpy which is leaving, let say h e plus the kinetic energy which is leaving, we told ourselves that the change potential energy between this and this if the data is about the same is the same, therefore I can forgetter it, therefore I get a minus, h i plus the kinetic energy what is entering at I.

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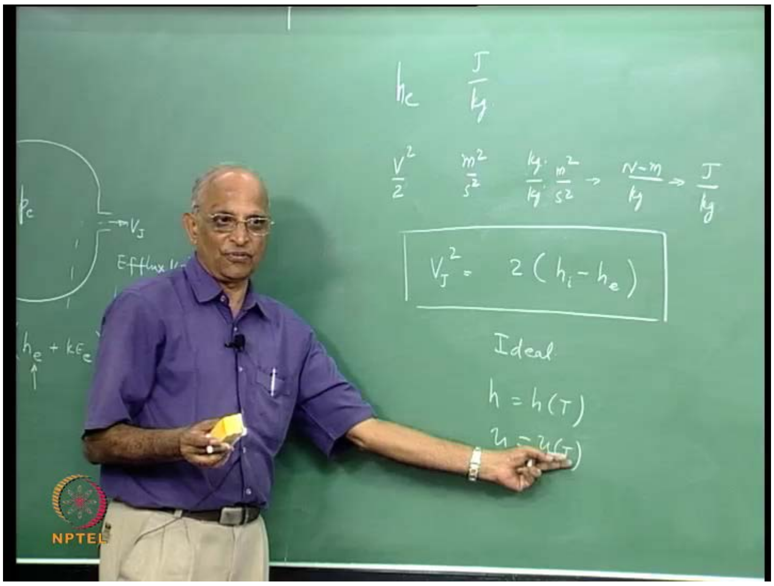

And we told ourselves we are to looking phi unit mass, this is enthalpy phi unit mass let's put it units clearly, the unit of h e is therefore joule per kilogram, the kinetic energy is equal to V square divided by 2 and that is equal to meter, square per second square and multiply numerator and dominator as usual by kilogram by kilogram meter square by second square, this is equal to kilogram meter square per second square; that means, Newton meter per kilogram, which is equal to joule per kilogram. Therefore the kinetic energy V square by two has units of joule per kilogram; that means we are taking per unit mass of the gas which is moving what is the kinetic energy.

Therefore let us puts things together we told our self's well it as adiabatic ignorers or adiabatic went, it is not something which is which can dilate and all that no if you were to apply the same problem to our heart warms, see heart also pumps our blood, but the valve is also something like flexible when we write the same equation for the control volume for the flow through blood through one of our valves in the body may be w x is not 0, may be that is what is to make modelling of the heart little more difficult compare to a vent over here. Therefore now let put's things together we have V J square which is equal to the exit velocity and that is equal to 2 of the enthalpy which is entering minus enthalpy with exiting the nozzle, and of course I had V J square divided by 2 and therefore I had h i minus h e over here is it all right.

Now, I want to solve this equation and I want make sure that I solve it in terms of the properties of this particular gas, and what are the gas properties could be the temperature, could be in the molecule mass, could be some other property which we need to consider. Now to be able to solve this I have to make further assumption, let up let me assume that the gas is ideal what is you mean that the gas is ideal, a gas is ideal when the enthalpy per unit mass or the specific enthalpy and specific internal energy are only functions of temperature, I think this definition are important let me just briefly go through, when the enthalpy is only a function of temperature and the internal energy is only a function of temperature we say that the gas is ideal.

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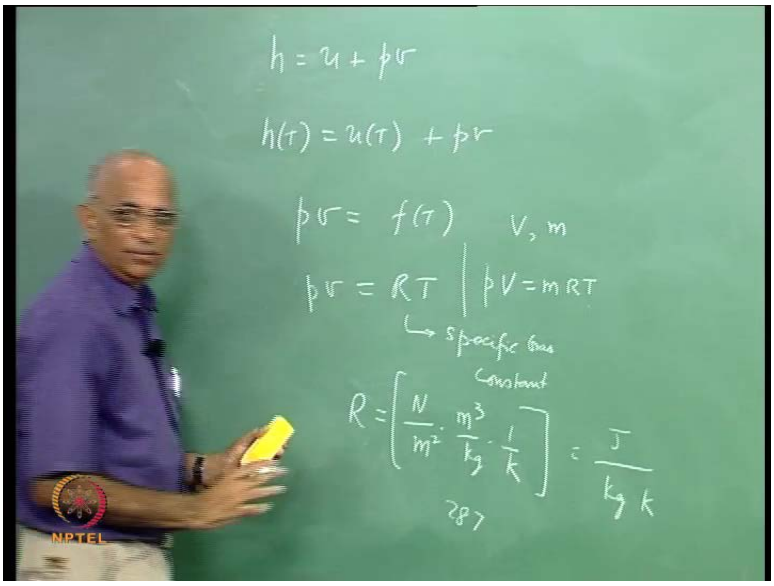

And what is the consequence of this, we have the definition that h minus u are rather we define enthalpy as equal to u plus p into specific volume, and therefore we find for an ideal gas h is function of temperature, internal energy is the function of temperature plus p v, are rather we get p into the specific volume is only a function of temperature, and therefore I write it as R T, and therefore an ideal gas for which enthalpy and internal energy are only the function of temperature has an equation of state, which specifies p v is equal to R T, and this R is what we call as specific gas constant, let us again just repeat what we said.

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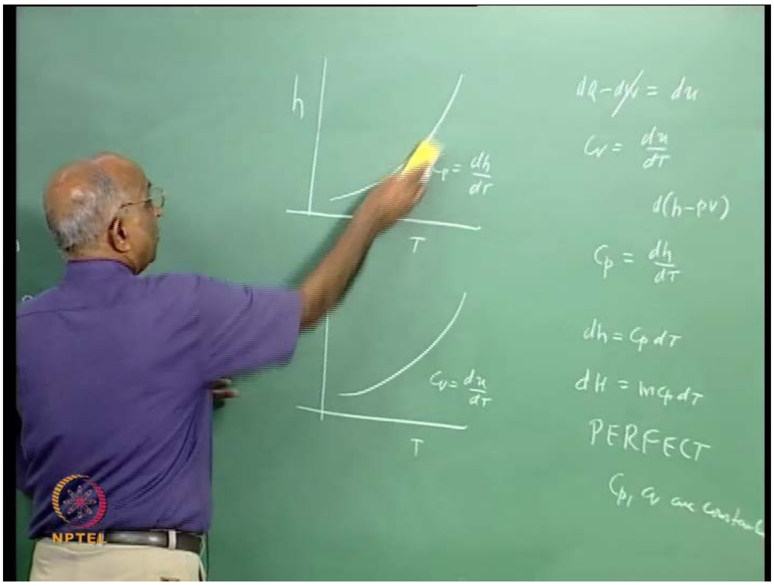

We told our self’s for an ideal gas may be h as a function of temperature is only a function of temperature, similarly u is function of temperature and now if I take the slope anywhere I get the value C p is equal to d h by d T and I get C v is equal to d u by d T. How did this come for any system we have d q minus d w is equal to d u, for a constant volume system work done is 0, therefore, heat require per unit temperature change per the unit mass is therefore the value C V is equal to d u by d T, that means is nothing; that means for a constant volume system work done is 0 I get this, for a constant pressure system what did we do we define we instead of writing d u.

I write now I have write as d of h minus p V and now I have p d v, v d p i have p d v over here it cancels of and I get C p is equal to d h by d T, therefore we are still considering an ideal gas specific gas constant R and what is a unit for R, let us put it down pressure, Newton, per meter square into volume, meter cube by kilogram by its specific volume, I have something like one over Kelvin come over here, Newton meter joule per kilogram, Kelvin; that means I have joule per kilogram Kelvin. Which for a air is something like a 287 is a value and it is specific to the gas, air has value 287 and may be C o 2 will have a lower value, may be helium may have a higher value, this is R defend depends on the type of gas which we use. So far So good therefore we say well I have the equation of this gas is given p V is equal to R T, or if I consider the volume of a gas v which has a certain mass in I can write the same equation p capital V is equal to m R T, and this is what we have been studying in thermodynamics is it alright,

Now let us go in forward now I ask myself see now I find when I look at a h is the function of temperature, u as a function of temperature, the curve is varying, C p is also a function of temperature, C p keeps varying and now if I have to write from this equation I write d h is equal to C p d T or rather the enthalpy of the mass of gas m capital H is equal to m C p into d T, now C p is going to change with temperature now my problem is going to become more than more complicated because I have to consider the C p variation with temperature.

Therefore, I put another idealisation and this idealisation I say that the gas is even better than ideal I call it as a prefect gas, and a perfect gas is one which C p and C V are constants in addition to the value of h being as a function of temperature we again put one more assumption and tell our self’s well the functional dependents is not like this, but the functional dependents is straight such that it constants u is constants and therefore C p is never constants this becomes my perfect gas.

Therefore, we will solve this equation assuming now let say a perfect gas and if I (( )) to assume a perfect gas (( )) let say p C the gas which is here at p C has a temperature T c, let the exit temperature at this plane be let us say T e, therefore now my job is clear I know my definition let me just quickly derive the value of V J.

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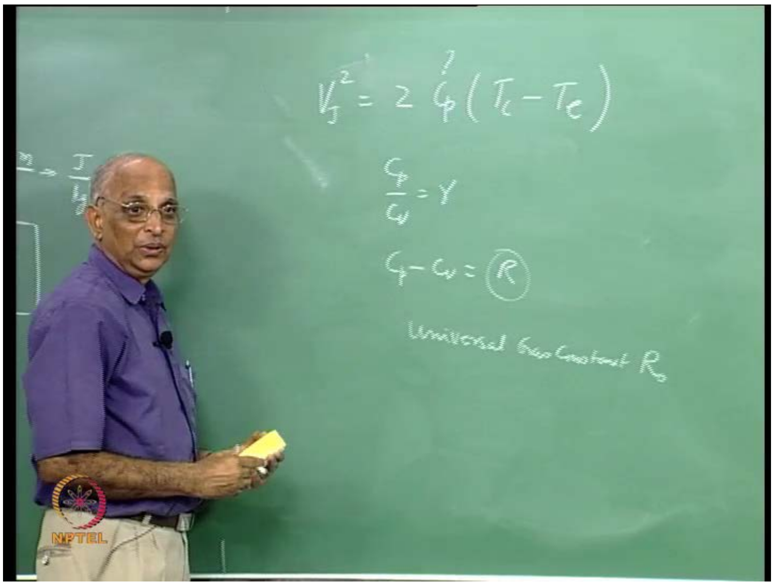

I now write V J square is equal to 2 of h i minus h e, C p is a constant is equal to 2 C p into the value h I minus h e, h i the temperature is T c, we should not confuse t c the exit temperature is T e, therefore it is equal to alright, now I want find out what is the value of c p, I want to know the properties of C p of gas in terms let us say the gas constants may be in terms of the a molecular terms of the gas, therefore I again go through and say well C p by C v is equal to gamma specific ate ratio, also we know from h minus u is equal to p V is equal to R T I get the expression C p minus C v is equal to r, how did this come h minus u is equal to p V which is equal to R T, I take differential d h by d T, d u by d T is equal to R, therefore it is equal to specific gas constant. Now I find R keeps changing with type of gas and supposing I keep changing the gas here and I have to change the value r why not I express the R in terms of universal gas constants, which is same for all gases namely R that is R 0.

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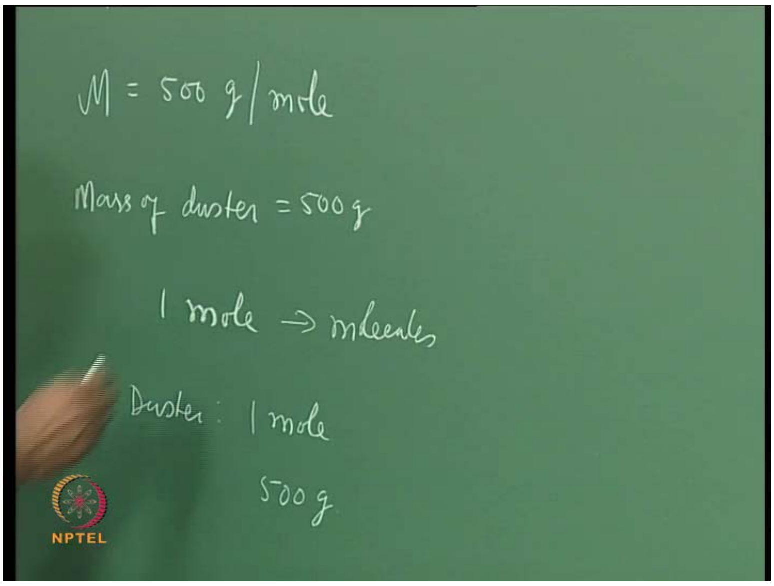

And now how do I define R 0 compare to r, let us again talk in terms of little more basics over here, what did we tell ourselves when we started this course, we told ourselves the quantity of matter we just express interims of kg, I have given matter and how do I say k g well somebody maybe in 1827 or 1830 he kept some mass in some lab in France servers which I say the 1 kg, and based on 1 k g I say this is a quantity of matter (( )) 2 kg, therefore quantity of matter is what I express in kg, but why the hell should be kg could be another unit, you know instead of saying that they let us say the mass of the duster is let us say 500 grams why not express it in some other unit, let us say the molecular mass be something like 500 grams per mole is the molecular mass of the wood of this particular duster, now is the molecular mass if the mass of the duster is equal to 500 grams.

Then I can as well say that this duster contain one mole of the substance, in other words be instead of defining the mass of this duster as 500 grams I can say the duster having consist 1 mole of the substance wood, therefore I can also define the duster in terms of a mole just as we define it in terms of 500 grams, getting back to some more details we must remember that this mole is different from the number of molecules, the no of molecules in 1 mole is what we call Avogadro’s number a v o.

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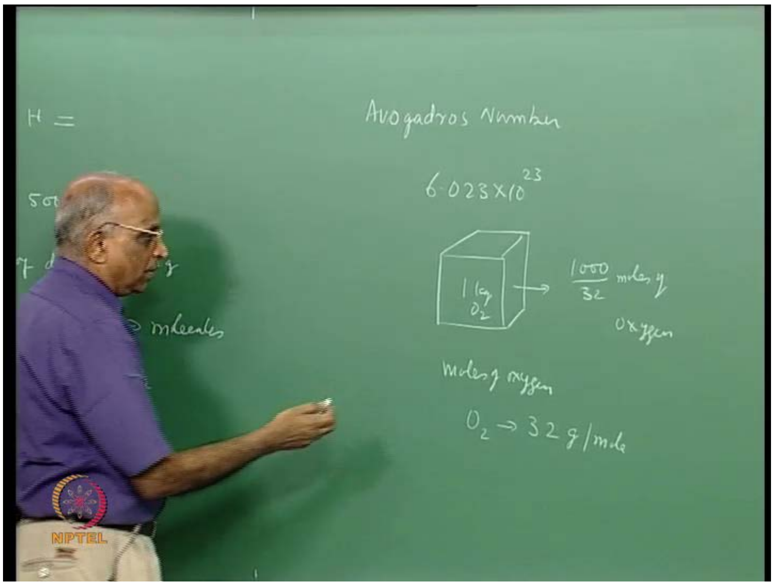

And the number of molecules in 1 mole is 6.023 into 10 to the power 23, in other words 1 mole of any substance has something like 6.023 into 10 to the power 23 molecules. Now we must be a little more clear and let me take one more example, supposing I consider let us say a box an empty box into which I put let us say 1 kg of oxygen, now instead of saying 1 kg of oxygen I did rather describe this oxygen in terms of moles of oxygen, we all know that the oxygen O 2 has a molecular weight a molecular mass of 32 grams per mole, therefore instead of saying 1 kg of oxygen.

I can as well say I have 1000 divided by 32 so much moles of oxygen. Therefore to clearly state the amount of matter which is there or amount of matter which is available I can express it either in mass or in terms of moles of substance. Now, therefore what we I just now do let as let as erase this part.

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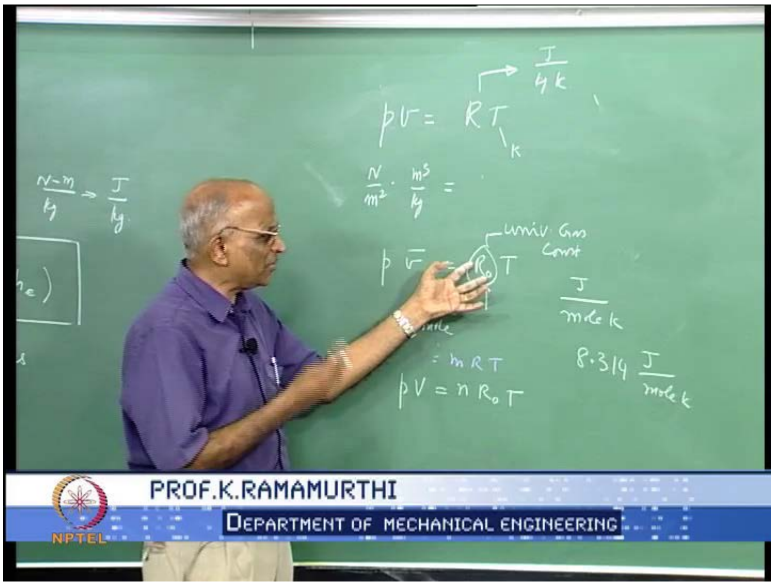

I give you the equation as saying p into the specific volume and p is a pressure as Newton per meter square, volume has units of meter cube by kilogram, as equal to R T, where R is the specific gas function R has units of joule per kilogram Kelvin and temperature has a unit of Kelvin.

Now instead of expressing this specific volume in meter cube by kilogram I can also write it as p into I write meter cube per mole, I just used this unit and if i write this my right hand side becomes R nought T where R nought for all gases the value is the same which I call this the universal gas constant, in other words I write p v is equal to n R 0 T instead of writing p v is equal to m R T, if I consider m in kilograms I have R T if I consider this term in mole I get the same value of R for all gases which now become a universal and I say R nought is universal gas constant which should have the units let us put the units together joule per mole Kelvin and the value is 8.314 joule per mole Kelvin. Therefore we just refresh ourselves little bit about thermodynamic, we say we are talking in terms of a perfect gas for which C v, C p are constants we also learn to distinguish between R and R nought which is very primary which is very essential, therefore now I can go back to this particular equation and then tell myself well we had also got this equation is equal to 2 C p of T c minus T and we said C p minus C v is R C p by C v is gamma.

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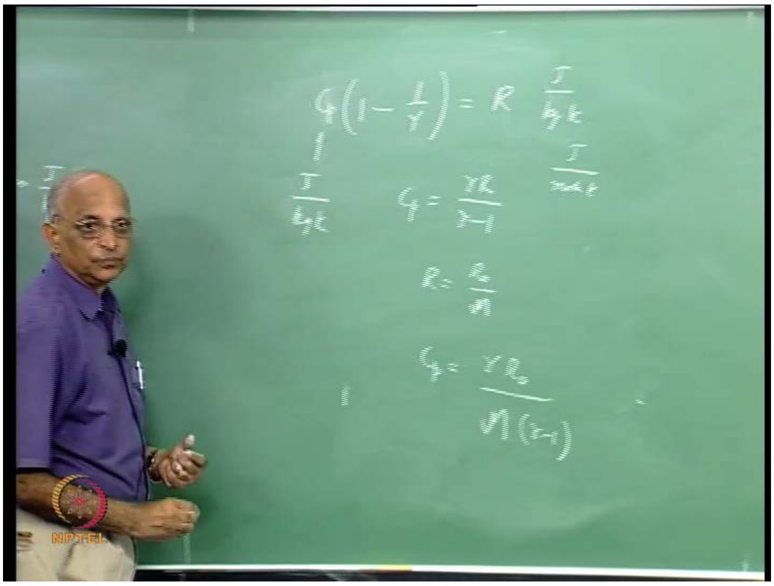

And therefore, I could write that same equation as C p into 1 minus C v by C p, C p by C v that is C p minus C v, C v comes 1 minus gamma is equal to specific gas constant R let us keeps the units well clear R has the unit of joule per kilogram Kelvin, C p has units heat require per unit mass per unit Kelvin, C p and R have same units and therefore I can write the value of C p as equal to gamma R by gamma minus 1, supposing I want to write it you know r keeps change in gas to gas, supposing I want to write in terms of molecular mass all what I do is instead of writing R in joule per kilogram I have to write R in terms of joule per mole Kelvin, therefore I just say R by comparing p V is equal to m R T, p V is equal to n R 0 T I get r is equal to R 0 by the molecular mass, where molecular mass in kilogram per mole are rather if I by to now simplify it I get the value of C p in joules per kilogram Kelvin as equal to gamma R nought by the molecular mass m into gamma minus 1. Any doubts here.

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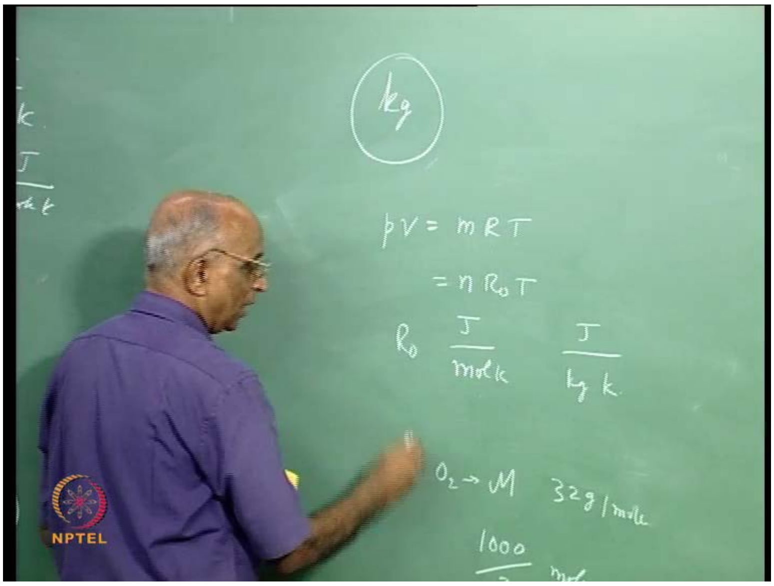

I just swallowed 1 or 2 small steps and what steps which I swallowed where we told ourselves we could write p v volume in meter cube is equal to m R T are rather this could also be return as n R 0 T, this joule per mole Kelvin, this is joule per kilo gram Kelvin and therefore to convert R to R nought I have to take the molecular mass that means r 0 divided by molecular mass is equal to this are rather R 0 is has the unit of joule per mole Kelvin.

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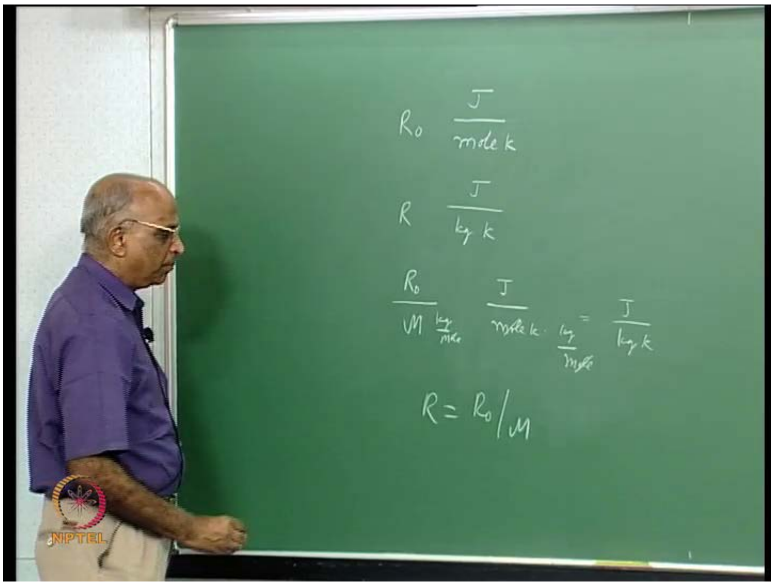

And if I have to convert joule per kilogram Kelvin into mole Kelvin if I have to convert the universal gas constant R nought whose unit is joule per mole Kelvin into a specific gas constant R whose unit is joule per kilogram Kelvin, I have to use that is R nought divided by the molecular mass of the particular gas I am interested in kilogram per mole or rather now I get joule per mole Kelvin into kilogram per mole; mole and mole get cancelled.

And the unit becomes joule per kilogram Kelvin which is the specific gas constant, therefore we have R is equal to R nought divided by the molecular mass of the particular substance.

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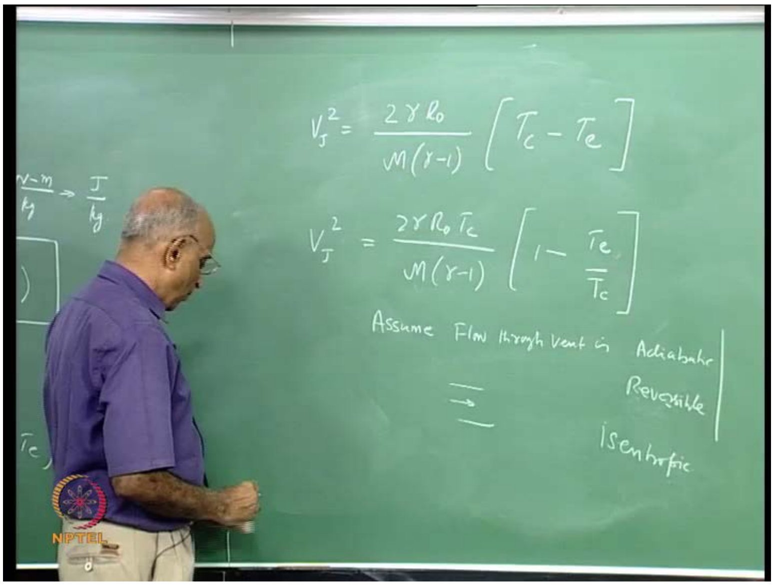

Therefore, let us now substitutes this and if I (( )) substitutes the hole expression here what is it I get V J square is equal to 2 I have gamma r 0 divided by I get the value molecular mass into gamma minus 1.

And now I get the value of T c minus T e, let me take T c into this particular bracket I get 2 gamma R nought keeps (( )) units clear, joule per mole Kelvin into T c divided by molecular mass of the gas, kilogram per mole into gamma minus 1 into I have 1 minus T e by T c, this is it going to be (( )) square of the efflux velocity or jet velocity, see at time to make little more assumption on the motion of the gas because for me you know the temperature of the gas in that particular balloon or a container can be known, but I do not know what is the exit temperature, but I know the exit pressure I would like to convert it, therefore let us assume the next set assumption or assumption, assume flow through the vent or flow through the hole is adiabatic, well we had already assumed it we said q is equal to 0, therefore as a corollary a flow through the vent is adiabatic, but let us make 1 more small assumption.

Let us assume that the flow through the particular vent is quit slow, what do I mean by slow I mean its quit slow slow enough such that the flow is reversible, what do you mean the flow is reversible in other words the flow is not so fast that it cannot retrace back it goes through the series of equilibrium states and therefore I say that the flow through the vent is adiabatic and reversible or rather the word is isentropic.

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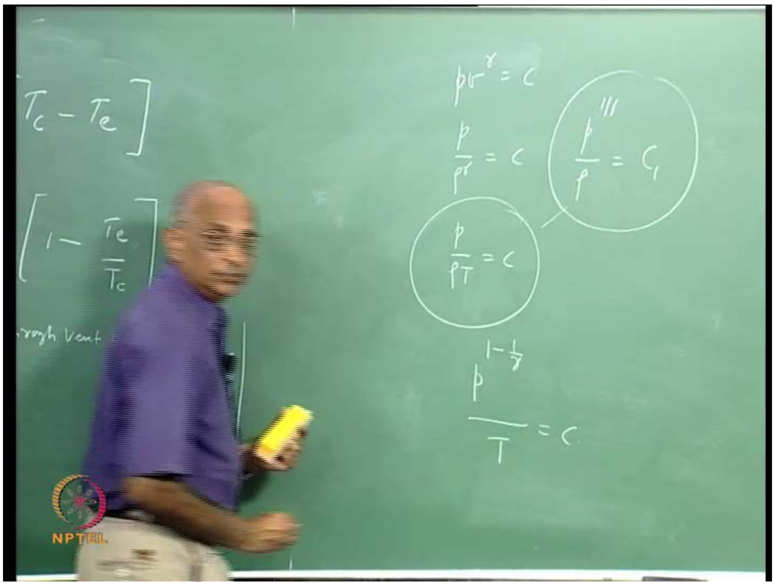

And if I have the isentropic flow well done equation of state for or the equation for the process involving this isentropic process is going to be p v to the power gamma is constant are rather i have p into rho to the power gamma constant, but I know that the ideal gas or a perfect gas may be ideal perfect gas is better than the ideal gas I have p by row T I is a constant, equation of state and therefore based on this I can write the same equation as p 1 over the gamma divided by row is again another constant let us say c 1, I just take the gamma through it on both sides and now I compare this equation along with this equation, and I say I take this equation and divided by this particular equation and now I get the value as p to the power 1 minus 1 over gamma, row gets cancelled divided by T is a constant.

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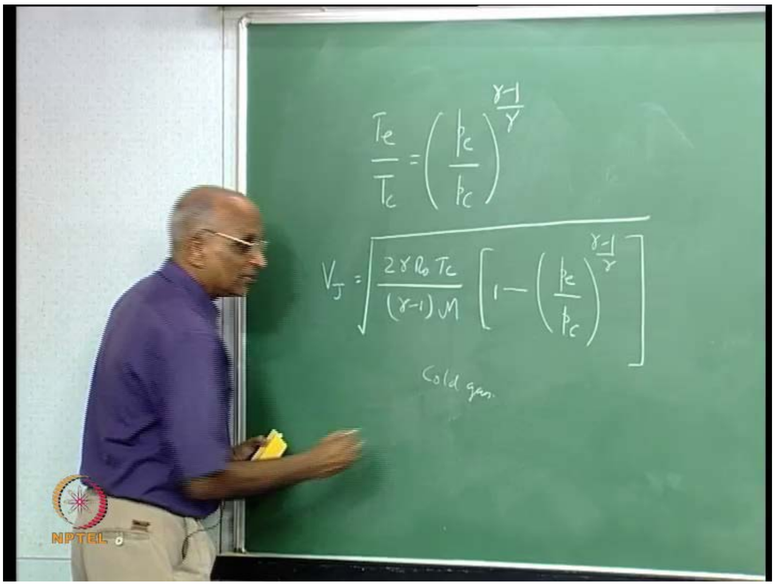

And therefore, now I can write the equation as the value of T e by T c is equal to may be based on that equation T e by T c is equal to p e by p c to the power gamma minus 1 by gamma, gamma minus 1 by gamma divided by T; T goes on top I have T e I have p e here p e by p c is equal to T e by T c.

Therefore, what happens to my jet velocity, now I get my expression for jet velocity is equal to 2 gamma R nought T c divided by gamma minus 1 into the molecular mass of the gas into 1 minus the value of p e by p c to the power gamma minus 1 by gamma, so many meters per second and this is the expression for the efflux jet velocity. That means we are b seen able to derive and what were the assumption for perfect gas, the vent is adiabatic it is the reversible flow it is a slow flow and that gives me the jet velocity as so much meters per second, if this expression if the reason for this expression is clear maybe we can we all we have to do describe this equation or draw conclusions based on this equation and that is what I will be doing in the next couple of minutes, but is it clear how we get the jet velocity, see its quit simple it is just a simple algebraic manipulation, the only assumption which we made is flow through the vent is adiabatic and also reversible because we set as a slow process.

You know this 2 assumption we must keep in mind because I will try to relax it as go along, now let us discuses it out; when we get a high value of V J? When the temperature of my balloon or air is very high, and what is tells me? it tells me if I use something like a cold gas such something like

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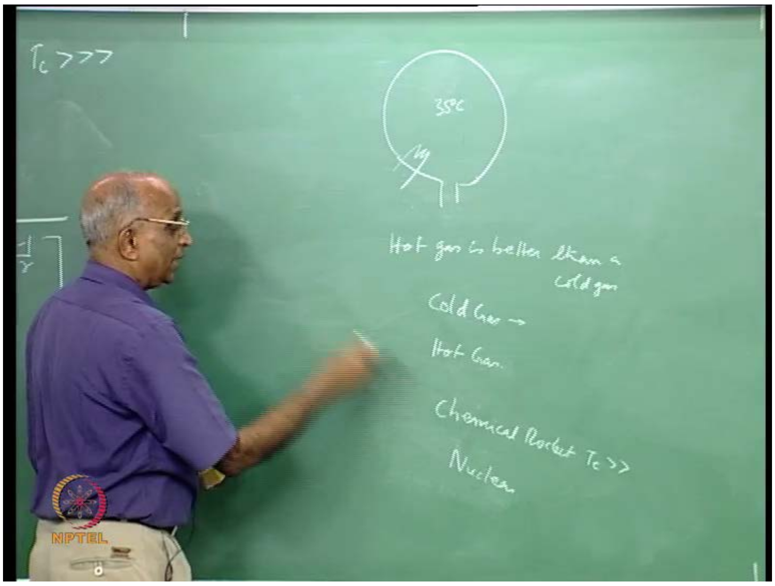

let us say I take the same balloon I use as rocket, my balloon over here, I have this particular vent over here, I have the balloon which was initially air at 35 degree centigrade; that means if my temperature is small, I do not get a very high value of V J, if I can increase this temperature in some way I can get a much higher V J, and that is why a hot gas is better than a cold gas. I could have a cold gas rocket, I could have a hot gas rocket but hot gas is definitely better. Therefore, first thing we say is maybe T c has highest possible, but is this some limitation well the material must withstand the high temperature and therefore there is a limits to this temperature, we normally use temperature of 3000 to 4000 Kelvin this is the type of temperature. And how do we generate it? We burn fuel and oxygen which we call as propellants; that mean we use chemical reactions to generate high temperature and high value of T c.

Therefore, a rocket to be a cold gas rocket, could be a hot gas rocket, could be a chemical rocket and inner chemical rocket you generate high temperature with chemical reactions, in a hot gas rocket maybe I could put resistance wire heat the gases and allow the gases to come, it becomes a hot gas rockets or I make something hot and push it out or if I use a cold gas I just use a cold gas, mind you cold gas rockets are also used in satellites are something were an I cannot I cannot allow chemical reactions to takes place, I just allow gas in a chamber and allow the gas into expand and I can get a thrust. And do you know could also have nuclear reactions, and if nuclear reactions I can get a even higher temperature, I can get a higher jet velocity, and you have classification of rocket cold gas rocket, hot gas rocket, chemical reaction rocket, nuclear rockets may be will have to keep on going, therefore we say well temperature is the one of the primary causes let us take look at a any other parameter, let us take at the exit pressure,

If exit pressure is very small vacuum well this becomes small therefore, may be then I would like to say p e must be small, or if my exit pressure it cannot be small I can set p c must be large; that means I if I can store gas a very high pressure I can get a higher value of (( )), in other words the ratio p e by p c must be small are rather the chamber pressure must be high the exit pressure must be small, second conclusion from this equation is there any other conclusion I can draw.

Let us take a look at the molecular mass of the gases which are exhausted, it tells me directly V J is equal to 1 over under root of m; that means, if I can have a gas which is very light molecular mass like hydrogen or let say helium well my V J will be higher, but how do I get a light gas let us take a example.

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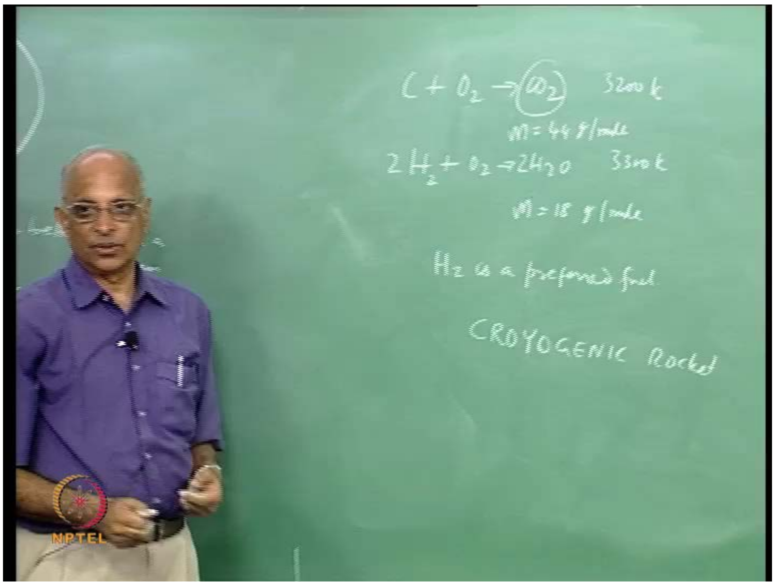

Supposing I have a chemical rocket in which I take carbon, I burn it with oxygen and I get product combustion of carbon dioxide, C plus half O 2 or c plus O 2 why why why should I make it clumsy, complete combustion stock metric, I have another rocket were in I have H plus O 2 giving me H2O (( )) 2 H 2 plus O 2 gives me 2 H 2 O, now let us let us what is the difference in these 2 rockets, this gives me a temperature in oxygen of around 3200 Kelvin, this gives me around 3300 Kelvin at the same pressure conditions, therefore temperature is not very much different, now I look at the molecular mass of carbon dioxide the molecular mass is equal to 12 plus 32; 44 gram per mole.

For water the molecular mass is 16 plus 2; 18, in other words if I burn hydrogen and oxygen I get a very low molecular mass and my V J which is directly proportional to the under root of m will therefore be large and that is why we find hydrogen is a proffered fuel, any amount I have a solid propellant; I would like my solid propellant is contains as much hydrogen as possible, or if I have a liquid propellant to carry hydrogen is difficult, I liquefied hydrogen at low temperatures and that is what makes cryogenic rocket to have better performance. In fact if I buy to give your number the V J for the cryogenic rocket is around 4600 Newton second by kilogram, where as for an ordinary fuel it is of the order of 3500 Newton second by kilogram, you get immense benefit out of this under reason being only the value of molecular mass.

Therefore I think you must be very clear let us put one temperature 2 p e 3 mass which must be as low as possible, can you say what must gamma know? We left with one small thing others are we have already discuss, should gamma be small or large and if so why?

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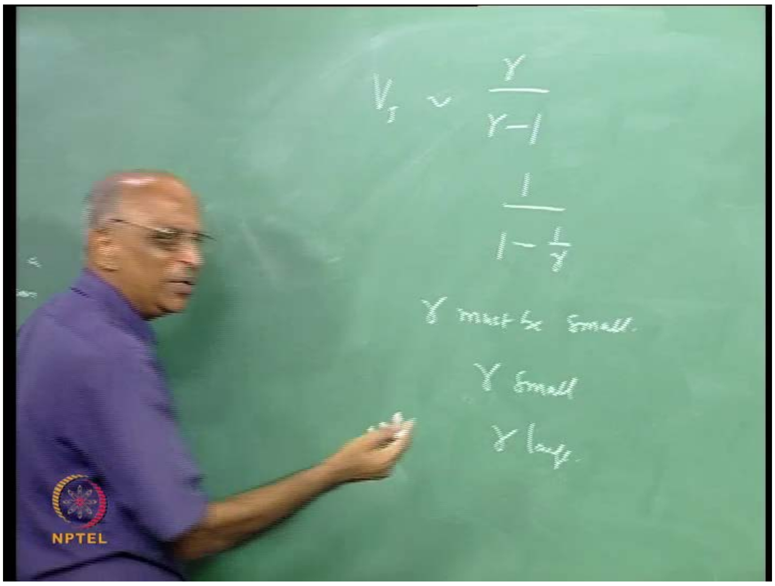

Yes what do you find V J goes as gamma over gamma minus 1 under (( )) of course, therefore well would you like a small value of gamma or large value of gamma, let us divide numerator and denominator by gamma 1 by 1 minus 1 over gamma, therefore I find if I have the smaller value of gamma I subtract a larger number, a small value is preferable because gamma must be small. Because if gamma is small I subtract my larger quantity and my denominator comes down and my numerator goes up V J is larger.

Therefore I also tell myself well gamma must be a small, but you know do I what is the sensitivity of gamma is directly proportional to m here it is gamma by gamma minus 1 gamma is not very much affecting. Let us take an example; how do I make gamma small, how do I make gamma large, how does gamma depends on the gas? We tell ourselves yeah we go through some examples

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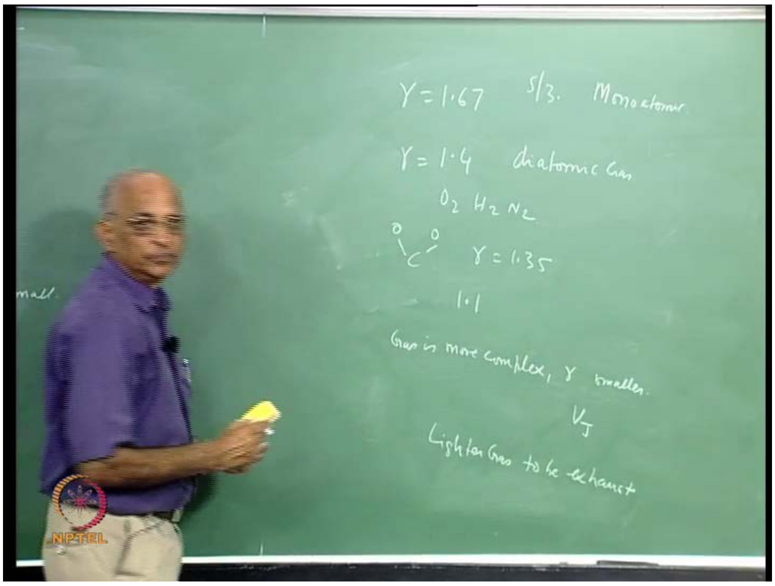

We tell ourselves well helium; which is a mono atomic gas has a value of gamma equal to 1.67 are rather which is equal to 5 by 3, if I take air gamma is equal to 1.4, if I take nitrogen or oxygen is 1.4, it is a diatomic gas, it is a mono atomic gas this is true for oxygen, hydrogen, nitrogen and all that, the gas becomes more and more complicated.

Let us say C O 2; gamma is around 1.35 or something, and I make the gas extremely complicated like I have Freon molecule is used as refrigerant, gamma is the order of 1.1; that means ask the molecular mass of the gas increases the gamma becomes smaller, now what is it am telling if the molecule or if the gas is more complex say gamma is smaller, and therefore the influence on V J is V J will be better.

But if I look at the molecular mass; I tell myself if the exhaust if the molecular mass is small then I get a smaller value is just contradictory, therefore the role of molecular mass and gamma is just the opposite, but it so happens the effect of gamma is much smaller, and therefore we would still like to have a lighter gas to be exhausted out or to be part of the efflux, maybe I will just repeat the four salient conclusion which I draw from this particular jet velocity equation.

What were the things well the temperature of the gases must be as high as possible, the ratio p e by p c must be small are rather the ratio of the chamber pressure to the exit pressure as must be large as possible, 3 molecular mass of the gas which is coming out must be as small as possible, last we would like gamma to be small, but this gamma being small contradicts the requirements of the small molecular mass, and therefore we do not really pay so much attention to gamma, well these are the conclusions which we draw from the equation.

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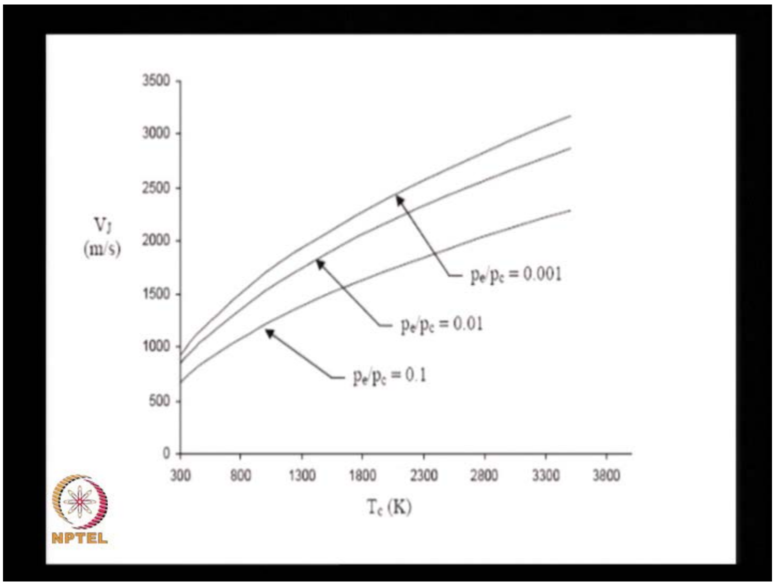

Let we quickly go through the conclusions on the slide, because I plotted the equations for different values of temperature, well let me go through the first one over here as u see I have plotted the value of V J is meters per second as the function of temperature, the temperature varies from 300 to 3800 Kelvin, and this the range of chemical rockets is of the order of may be something like 3000 to 4000 Kelvin, much lower than 4000, and therefore I restrict myself in 3800 here. I also plot for different values of p e by p c you find as the value of p e, p c is decreases I get the higher value of jet velocity, and this the conclusion which we looked at the equation drew.

Let us now come back and ask ourselves If I have let us say a gras at a low temperature like a cold gas rocket, and if I have a cold gas rocket if I increase the value of or if I decrease the value of p e by p c from 0.1 to 0.001 I do not really get much benefit, where as if I have a high temperature rocket T c is high I get much larger benefit, therefore if I were to design cold gas rocket I can make a small I do not need to really expand it much I can have a lower chamber pressure.

Therefore the forth conclusion I draw is may be for a cold gas rocket let us write put it down this are an important conclusion, for a cold gas rocket for which T c is quite small we do not really require a small value of p e by p c.

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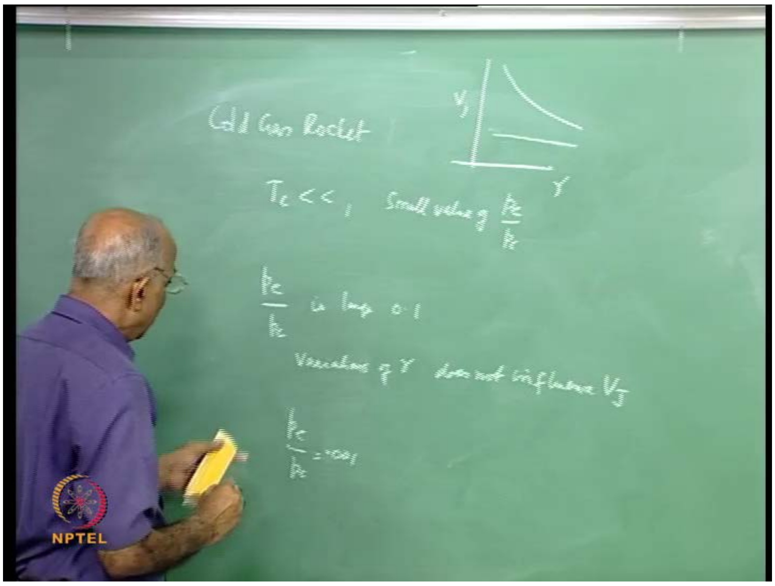

Because you find when the temperature is small, the gain what I got in going to this to this is only this much, you know I expand it out so much I increase pressure p c so much but still I do not get benefit, where as if I have really a high temperature chemical rocket this gives me higher temperature and much better. In the next one I plot the value of the jet velocity in meter per second as a function of the molecular mass, I find when the molecular mass is small I get the value of V J which is higher, and of course the same trend continuous, this is at a mean temperature of 3000 Kelvin, and therefore this tell me very clearly that as the molecular mass is smaller I get a higher value of V J here, this is the second one here.

The last one where in I show the value of gamma; here we show the value of V J as a function of gamma what I find is at a low value of p e by p c of 0.1, or at a value of p e by p c is 0.1 gamma really does not influence, I find that the curve is quite flat, it is independent of gamma as it were, whereas when the value of p e by p c is quite small of the order of 001, I find as gamma increases I get a smaller value or rather the conclusions which we drew was as gamma decreases as the value of V J increases, it is seemed to be more valuable or to be seemed more at a smaller value p e by p c.

Whereas when I have a higher value of p e by p c the value of gamma is small, in other words let us write it out, when the value of p e by p c is let us say large, that is when we consider 0.1 effect of gamma that is variation in the gamma does not influence.

Whereas when I had the value of p e by p c of border of 0.001, what happen when you looked at the curve? The curve was like this with respect to gamma this is V J, when the value of p e by p c was of the order of 0.1 it was flat, and therefore what does it tell you? If I have a something like a rocket for which the expansion ratio is not very high like a cold gas rocket, I can even use helium helium as gamma of 1.67, weather I use helium or I use air of 1.4 it really does not make things worse, and therefore a cold gas rocket normally uses a light gas like helium, and helium has low molecular mass; molecular mass gas is around 4 gram per mole, and therefore I get the benefit of the molecular mass and I do not lose any effect due to gamma [over here].

Therefore what is it I have done so far, all what we done in this classes we derived this particular equation, we looked at the effect of temperature, molecular mass, expansion ratio and also gamma on V J, we told ourselves for a cold gas rocket for which p c need not be very high, the effect of gamma is not dominant, but if I where to look at the effect of temperature in a chemical rocket for which temperature is high, I can operate at a much lower value of p e by p c and gamma effects will also becomes significant. Therefore by now we must be very clear that if where to have a choice of propellants for my rocket, I must have propellants which will generates a high temperature a low molecular mass gases, which if I can operate with high temp high pressure I will be much better of gamma, I do not have much control but gamma is not very controlling provided the pressure ratio is not too low; that means p e by p c much not be a very low number.

I think this is all about this jet velocity, I think all the conclusions from this we have to now relate to choice of propellants, and this is how starts dealing with solid propellant rockets, chemical propellant rockets and other forms of rockets. In the next class what I will do is see our aim has been to get a high value of the jet velocity, now the question is should I have the vent is straight, what must be the shape of this vent which we give me a high value of velocity, in other words I am getting into the chapter of nozzle, shaping of nozzle, what are the problems in the nozzle and that is what we will address in the next class thank you.