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Aerospace Propulsion
Liquid Rocket – Nozzle Cooling I

Lecture 32

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

In the last class we were discussing about liquid rocket engines and we have seen, what are the different kinds of feed system possible then what the classification of liquid rocket engines is. Now one of the things that I said in the last class about liquid rocket engines is that in this case the thrust chamber is the one where the combustion takes place and the thrust chamber and the propellant storage are differentiated.

A propellant stored elsewhere and brought into the thrust chamber by a feed system and then in the thrust chamber combustion takes place. Now because of this if you look at the volume of the liquid rocket motor as such it is a very small volume and therefore if you look at the amount of heat released the energy release density per unit volume is very high in liquid rocket engines.

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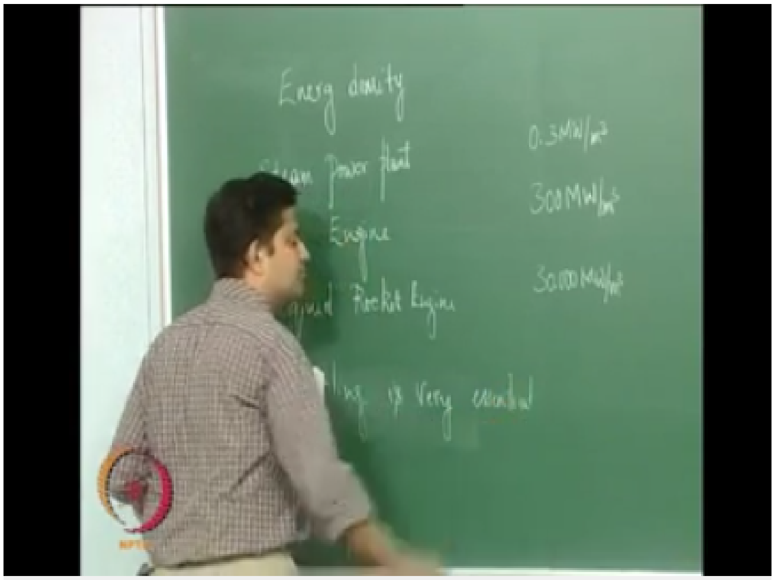

In fact if you were to compare energy density of different systems firstly a steam power plant then jet engine and lastly liquid rocket engine. You will find that this is somewhere around 0 point 3 megawatt per m^3 and this goes to something like 300 megawatt/m^3 and this is something like 30,000 megawatt per m^3. So it is a very large heat release per unit volume that is taking place in a liquid rocket motor.

As a consequence if you do not cool it appropriately it could meltdown the entire rocket motor within a few seconds okay, so in a liquid rocket motor cooling is very essential are supposed to this in a solid rocket motor, if you look at it the propellant itself in a sense if it is a port burning configuration the propellant itself protects the walls. So there is no need to insulate the truss a rocket motor chamber whereas only the nozzle needs some kind of thermal protection and a solid rocket motor. Whereas in a liquid rocket motor both the thrust chamber as well as the nozzle both of them need cooling.

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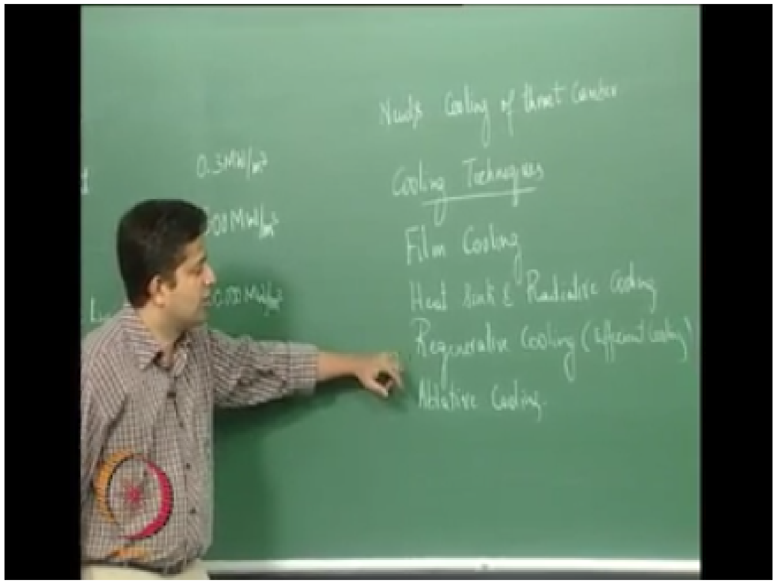

Now before we look at which is the area that has the highest heat transfer all that let us look at the different cooling techniques that are adopted in liquid rocket motors or in general in all rocket motors. Firstly there is something known as film cooling then there is a heat sink and regenerative cooling and lastly ablative cooling; these are the four techniques that are used in all kinds of rocket motors in order to cool the system. As we discussed the other day regenerative cooling is a very efficient way of cooling okay.

Primarily because whatever heat is lost to the walls a significant portion of it is brought back into the system okay, so this has very little heat loss to the surroundings whereas the others are not so efficient as this. So there is a very efficient way of cooling in a solid rocket motor only these two are used whereas in a liquid rocket motor in a sense you can all use all of these okay, primarily because in a solid rocket motor you do not have any other liquid to circulate around and cool the system.

In one sense the heat transfer in a liquid rocket engine is a very tough problem to crack because if you look at any other application which requires cooling, one of the advantage you have is you can choose the kind of coolant you want. So therefore you can do a very good job with it right here you are not given that freedom to choose the coolant you have essentially if it is a monopropellant system only one liquid or if it is a by propellant system two liquids and you have to choose one of them as a coolant.

And in addition to that you do not have a control on the flow rate the flow rate is also fixed because that is what it gets fed into the engine, so that is also fixed the coolant properties are fixed. So and the coolant type is also fixed so it is a very what should I say a very tough problem for a liquid rocket motor cooling. As I said we will look at where the heat flux is maximum because that is the region which needs to be cooled much more than the other regions.So let us look at where what portion of the rocket motor gets the highest heat flux.

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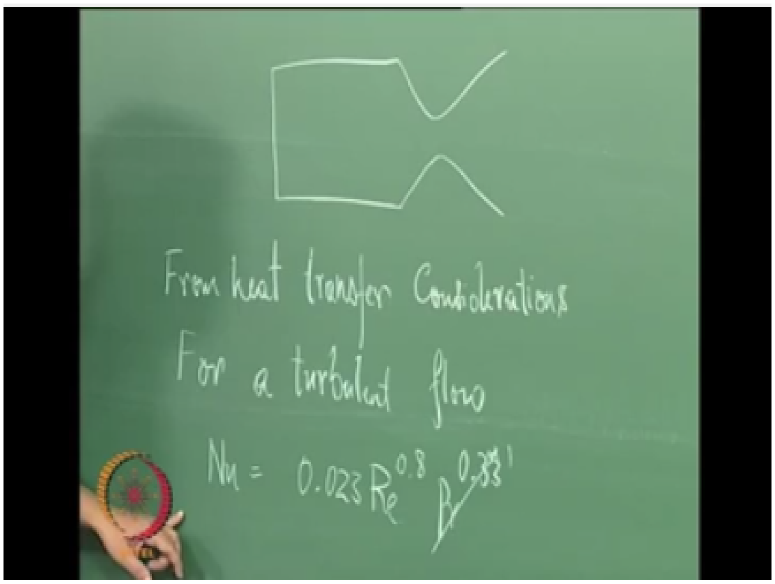

Intuitively where do you think should be the highest heat flux why right, no if you look at see we are looking at convective heat transfer facility if you look at this where do you think the mass flux would be highest? It is at the throat and that is where you will find that the heating will be or the heat transfer coefficient will be the highest okay. So let us try and derive that let us say we have a rocket motor like this then from our heat transfer we had seen earlier while of dealing with erosive burning that from heat transfer considerations.

This flow if you take a look at some low thrust liquid rocket motors the flow in the chamber could be laminar in certain regions okay but the flow in the nozzle is always turbulent okay, so for a turbulent flow we are going to deal with the nozzle first primarily because this is something that is common to all kinds of rocket motors and then we will see how what we need to do for the entire liquid rocket motor okay.

So for a turbulent flow we have seen earlier that we can write nusselt number as and we had said that the Reynolds number for most gases that we deal with is of the order of somewhere around 0.71 and if this is raised to a fractional power this gets very close to one and we could kind of neglect this as this is very close to one. So if you write the nusselt number in this fashion then we can further simplify it because we know nusselt number is nothing but.

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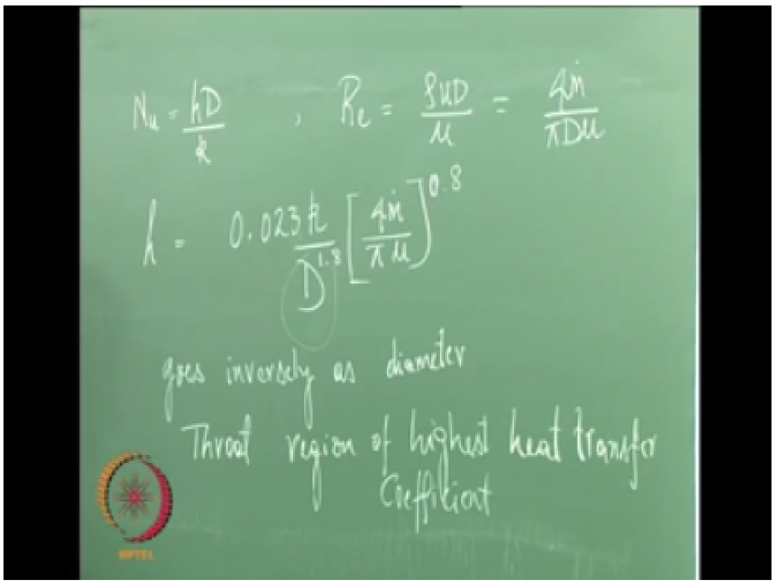

Okay and we also know Reynolds number is nothing but $\rho u/\mu$ or in terms of mass flow rate it is 4M./ IDM you the reason for expressing this in terms of mass flow rate this if you look at the flow through a chopped nozzle which is always going to be the case in rocket motors the mass flow rate at any section is the same right, it is a constant so it is better to write it in terms of M. the Reynolds number we will see that we can find out certain things better.

So if you use this then we can write h = 0.023 okay, so from this relationship we see very clearly that it is a very strong function of the diameter okay and it goes as deep our one bar 1.8 so if the diameters are small that is where the highest heat transfer coefficient is going to be, so the throat is the region where you have maximum heat transfer coefficient. So we know that the throat is the region of highest heat transfer coefficient and if we were to calculate the heat flux that is coming back to the surface we can do that like this okay.

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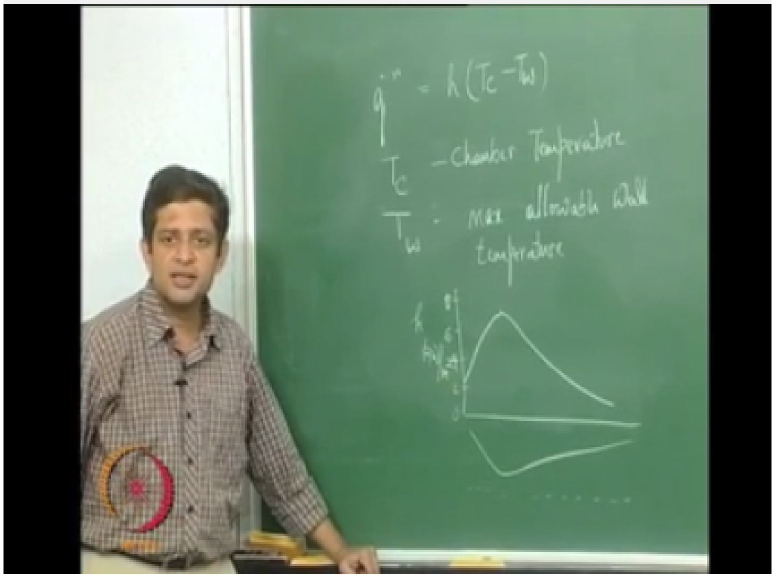

Q.” that is a heat flux right will be = h xT_C - T_1 where T_C is the chamber temperature and T wall as the maximum allowable wall temperature okay. So depending on this T wall and T_C you will have Q.” righ, now if we were to plot what is the heat convective heat that is transferred to the surface and where you have the highest heat transfer coefficient if we were to plot that we will have a plot like this, where in on the x-axis you have a nozzle along the axis and on they-axis you have a chain kilo watt per meter ^{2}.

Goes like this so you can see that the throat is the highest and as we go away from the throat it again drops because the flux is reducing. Now we can also recast this equation in terms of pressure by using the following that we know that for a choked flow.

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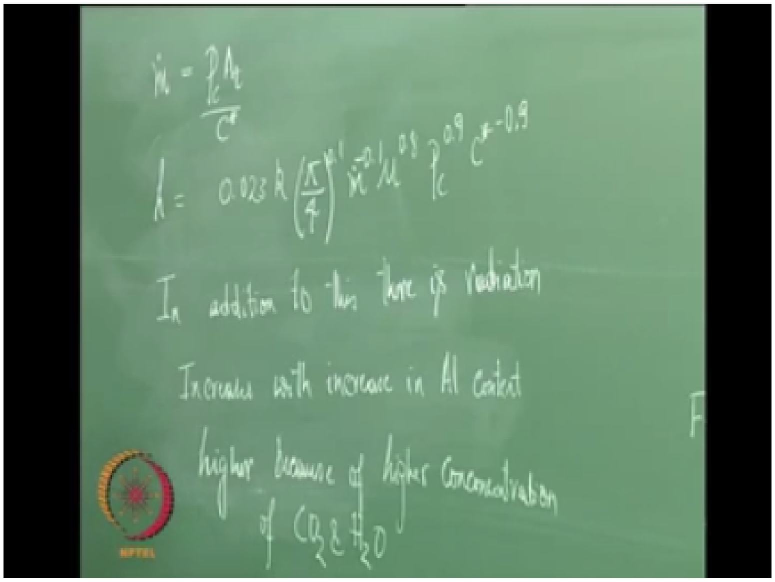

The mass flow rate through the nozzle is given by P_C 80 by C* so using this we can recast this and write it in terms of pressure equation as which is equal to okay, so you see that if you want to operate the rocket motor at a very high pressure then you need to have very good material to withstand the kind of heat flux because, this is now a very strong function of chamber pressure okay higher the chamber pressure higher will be the heat flux back to the wall and unless you have a material that can resist very high temperatures the engine will not be able to function okay.

Now this is what we have looked at is only one part of how the heat gets transferred back to the walls that is by convection, in addition to this there is radiation if you look at a composite propellants solid rocket motor, it will have something like 18% of aluminum right if you remember we said this propellant cannot be used in tactical missiles because of its high heat signature, which also means that the radiation heat flux in these motors will be higher if there is a larger fraction of aluminum.

So the radiation heat transfer increases with increase in aluminum content and we also know that carbon dioxide and hydrogen are called greenhouse gases right, the reason is they tend to absorb radiation right and in essence they prevent the cooling of the atmosphere right. The earth rear ad its back heat to the space which gets absorbed by the co_2 and h_2O, now if you look at what is the gas composition in the exhaust of a rocket motor it is going to be rich in both these compounds or right.

So you will have both co_2 and h_2o in the exhaust and they add to the radiative heat transfer which one a sorry this is M. if you have replaced yes I agree but if you look at that equation it is $M.^{0.8}$ and if you look at this equation this is nothing to do with diameter right. So if i take $M.^{0.9}$e then x π d ^{2} d ^{2} will become 1.8 and therefore that will get cancelled out so that is why it has no diameter dependence and it was only mass flow rate dependence.

So if you look at this radiation is significant if you have a solid rocket motor because of the aluminum content and also you have co_2 and h_2o. So typically the radiative heat transfer part is something like 10 to 30% of the convective heat transfer.

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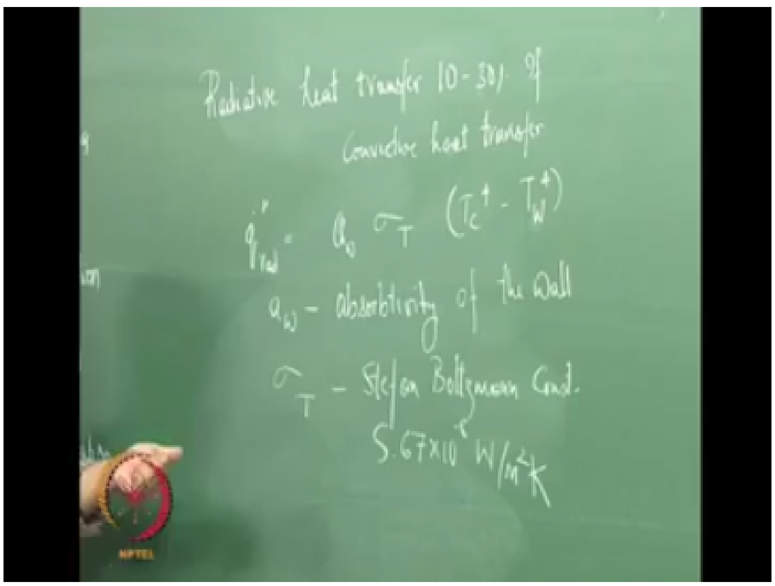

You okay and we can estimate it by the following relationship $T_C{}^4$ where it a_w is the absorptive of the wall and σ_T Stefan Boltzmann constant this is something like 5.6 7 x 10 $^{-8m2}$ okay and then T_C is the this is let me make it consistent with the earlier notation this is T wall T_C is the chamber temperature and T wall is the wall temperature. So if now realize that this is something like 10 30% the higher being when aluminum is present.

Now we understood that the throat is the region of maximum heat transfer and this requires cooling, so let us look at the various cooling techniques that we discussed earlier and firstly let us consider this film cooling.

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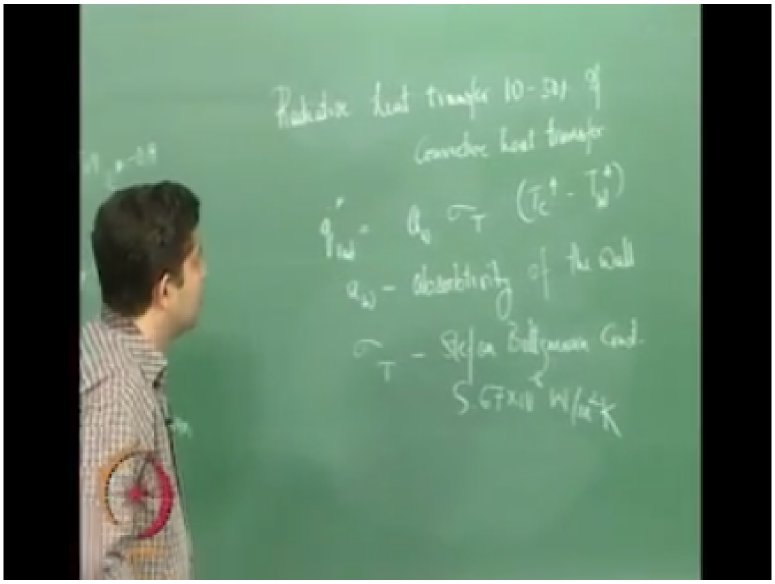

Film cooling if you look at it is the most inefficient process simply because what is done in film cooling is you inject fuel along the walls of the liquid rocket motor. So that as it goes through the motor it gets evaporated and therefore protects the material right so in a sense this does not strictly take part in the combustion that portion is kind of lost for useful energy release. So therefore you will find that if you calculate Isp it will be less because of this okay.

And you so as I said you inject a thin layer along the wall and as this air operates it absorbs the heat that is being coming in from the gas phase and therefore protects the wall right although this has been known to be very inefficient it is in a sense very widely used, simply because even in systems that have regenerative cooling it has been known to be used, a good example is the setting for of f1 engine on setting for ok it has a LOX kerosene system and kerosene is used for regenerative cooling also.

In addition to that they do use film cooling primarily because it gives you that kind of buffer right or it in essence you have redundancy over other forms of heat being taken up okay and that is why it is very popular although it is not very efficient. Now the reason for our if you look at it you are injecting film on the one right will it get mixed and burn up that is a possibility also right but people have noticed this does not happen simply because if you take any cross-section and draw the temperature profile in a liquid rocket motor.

You will always find something like this that it will have a profile like this which you can trace it back to the fuel and oxidizer injectors, so the temperature profiles are depending on where the fuel and oxidizer injectors are you will have a higher temperature okay. In the other regions it will be lower and if you are aware of something called as pattern factor that is used in aircraft engines aircraft gas turbine combustors okay how good the temperature distribution is?

If you take any cross section you will you would want it to be very uniform right but in this case it is not uniform and therefore there is a in essence very little mixing that is taking place and which is good for this kind of film cooling, if there was a lot of mixing this film cooling would have been very ineffective okay. So the reason for film cooling being effective is that if you look at the fuel and oxidizer jets let us say this is fueled this is oxidizer because they are injected at sufficiently high velocities.

The momentum of these carry forward and you will have jets of high temperature and in between you will also have jets of I mean regions of low temperature and therefore this kind of film cooling works and as I said earlier in some low thrust liquid rocket motors you could have a certain region in the combustion chamber which is laminar and other regions could be turbulent we looked at how to take care of things if the flow is turbulent. For a laminar casino is given by 0.5 where ReT if you look at the Reynolds number you need some diameter to be given to the Reynolds number or it is based on a certain diameter.

Ret indicates Reynolds number based on throat so this is about film cooling then let us look at the next cooling technique that we discussed namely, the heats ink and radioactive cooling.

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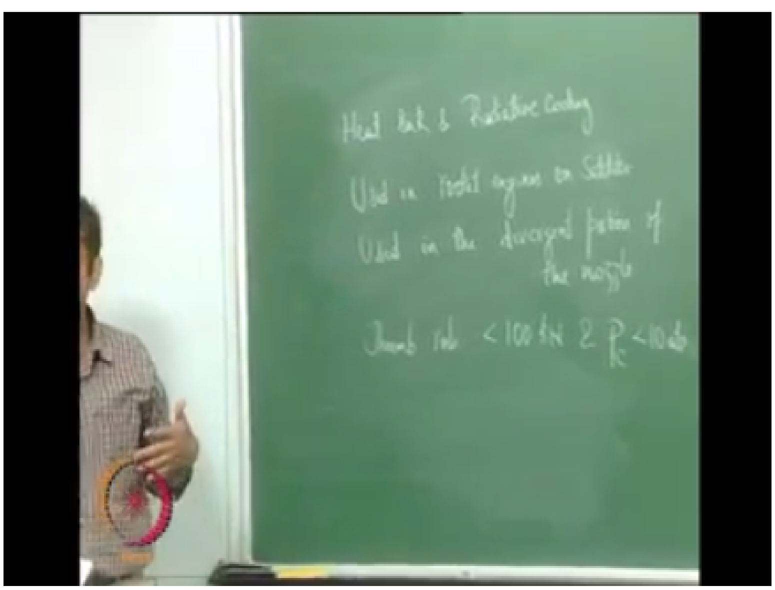

Now this type of cooling is very popular in satellite applications simply because you do not need to expend anything to do this, if you design a motor based on this it takes care of itself this is also used in if you look at film cooling you need to kind of use a particular fluid that is carried on board to achieve the cooling. In this case there is no such requirement and therefore it is quite popular in satellite applications and also this is used in the divergent position of the nozzle.

If you look at what happens in the divergent portion we said that the heat transfer coefficient drops after the throat, so in this region you could actually use radiative cooling in order to ensure that the temperatures do not go beyond a particular limit. As a thumb rule typically this is used for motors with less than 100 kilo Newton trust and chamber pressures not exceeding 10 atmospheres if you look at satellite applications I said they are very small thruster's right very small clusters and they are pulsed.

So in a sense if you are looking at any of the other cooling techniques right it will be a little difficult because when you are pulsing it if you have regenerative cooling or other things then there could be starting issues, so you do not want that and therefore this is quite popular as i said in satellite applications but this has also been known to be used on a certain other engines primarily a significant chooses there in the vikas inject that is there on Pslv although the thrust is not below this mark it still uses it and because engine to cool the divergent portion of the nozzle.

So as the name itself suggests it is something like a heat sink right so it should be able to absorb this energy and hold it and also the other part is radioactive cooling, so if you look at how the heat is coming in and how the heat is going out.

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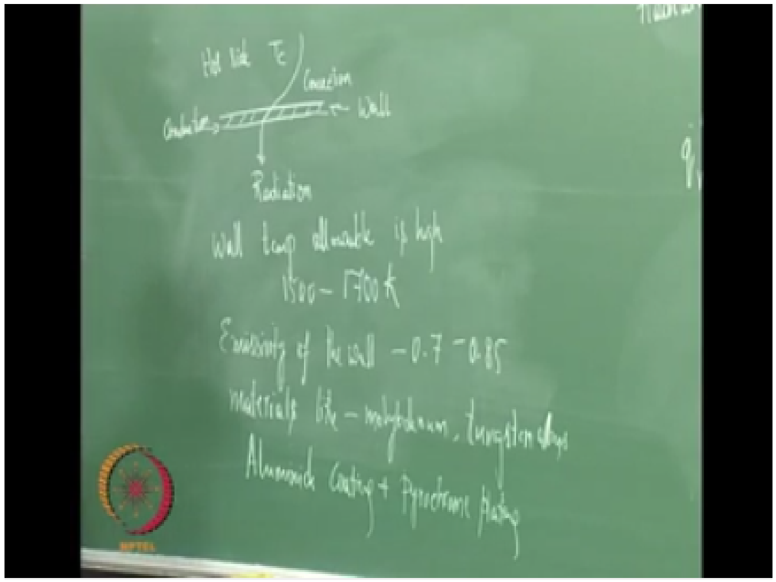

Let us say if this were the wall of the motor rocket engine, now let us say this is the hot side right then you have T_C here you have convection and in the wall you have conduction and outside is variation. Now if you remember the equation that we have written here for radiation it is very clear if you want to have the radiative heat flux higher than the temperatures must be higher right it is a very strong function of temperature. So therefore this should be high so in a sense here you need to have material that have the capability of withstanding very high temperatures okay.

So because you want the radiation to be higher what is the other thing that you want to be higher in that equation, if you look at this absorptive in this case it will be the emissivity of the wall okay the emissivity of the wall should be higher and it is typically around 0.8 or varies from 0.72 0.85 and in order to achieve this special materials like molybdenum, then tungsten alloys are used it is also given some kind of coating, so as to ensure that the emissivity is higher. So it is given aluminize coating plus pyro chrome plating in order to ensure that there is a high emissivity.

Now if you look at this figure here we said that there is convection from the hot gas side and in the wall that is conduction and outside there is radiation, this is like a series connection right this is like a series connection and if we were to write the equations for this. So what is there in series connection is the heat flux has to be the same right because there is a series connection in a series correction connection in electrical circuits a current is the same here heat flux is the same.

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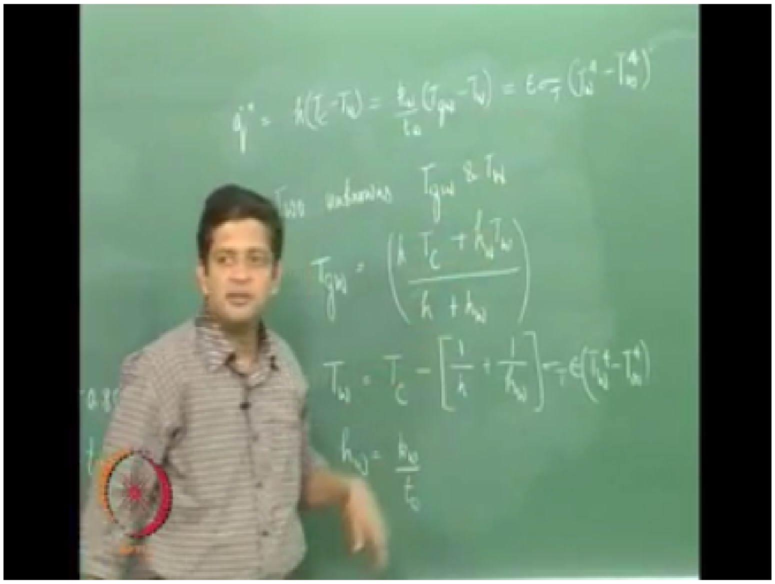

You got " HGH T_C - T wall is = wall okay here let me call this temperature as T_G wall and this temperature as T wall and the ambient or the far-field temperature as $T\infty$ okay, so there is heat transfer by convection that is given by this then in the wall there is conduction heat transfer given by this and outside to the ambient there is radiation given by this. Now if you look at this equation how many unknowns are there T_C will be known to you depending on what kind of propellants you are using what is the pressure and what is the flow rate right.

Then $T\ \infty$ is also known so there are two unknowns namely T_G wall and t work and we can solve for this from these equations and we will get T_G wall as Ag T_C + h T_W one minute okay where h whole is nothing but a vole by t wall if you look at the units of convective heat transfer coefficient and thermal conductivity thermal conductivity will have a meter term and the denominator.

So if you divided by a length scale then you will get both the units to be the same so you can write in this fashion and so you can get these two temperatures in this way okay so now we know both this and this so therefore we can calculate what is the heat flux that is coming into the material and what is being transferred out now which one T_C - sorry 1 minute T_C - T_G wall thank you this is T_G wall this ist1.

So if you look at it there is a connection between T_C and T_G wall T_G wall is on the gas side and T wall is on the other side so there is conduction between T_G wall and t wall and then there is radiation okay when we will stop here and in the next class look at the other modes of heat transfer namely regenerative cooling and ablative coding okay thank you.

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