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Aerospace Propulsion
Liquid Rocket – Nozzle Cooling I

Lecture 32

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In the last class we had looked at film cooling right and we said it was a very inefficient way of cooling built at us as I said it is still preferred because it gives you that redundancy in the design. Now let us look at perhaps the most efficient way of cooling that is the regenerative cooling.

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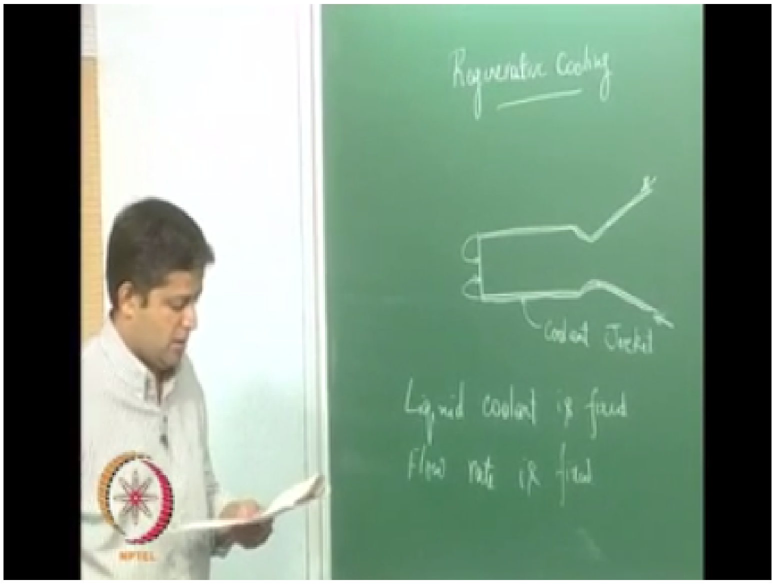

Now in this method as I earlier said if you have a liquid rocket motor there is a coolant jacket okay and the one of the two liquids is made to come in through this end and it will come out through, the injector right went through that end and you will come and get into the rocket motor like this. Now as it moves along it picks up the heat from the hot gases that is here and puts it back in and therefore in essence this mimics the adiabatic wall that we had made an assumption of okay.

So as I said they were very efficient but the trouble with this cooling is it is a very challenging problem simply because I do not have a choice on the coolant type, for example in most other applications like IC engines and other engines you are free to choose the type of coolant that you want right and you will choose the best coolant oils like castor oil and other things but here I do not have that choice, I have to use one of the two liquids.

So the liquid coolant is fixed and its flow rate is also fixed that is if the engine has a particular press then I can back calculate the mass flow rate and depending on the O by F ratio I know what is the flow rate of fuel and oxidizer. So it cannot exceed that flow rate right so that is also fixed and due to this the design of such a coolant system is very difficult. Now there are a few things that are under the control of the designer.

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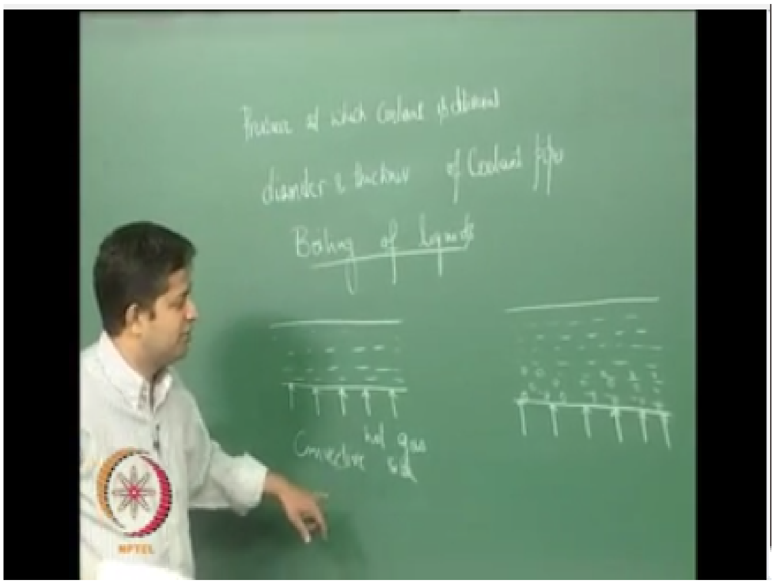

They are one is the pressure at which coolant is delivered; the other thing is this is strictly not true simply because you design the engine fertile certain pressure right. You can decide on how much of over that pressure you can give when the coolant chambers okay it is not as strict this thing but still there is some flexibility in it and the other thing that is under the control is our diameter or geometry of coolant pipes.

If you remember while deriving our equations for heat transfer in turbulent flow the diameter of the pipe played a very crucial role, so that is under the control of the designer and the thickness of the should you are put diameter and thickness is under the control of the designer. So with this we have to go ahead and design this coolant pipes now there are many options that are available as such for designing this these are shown in this figure here.

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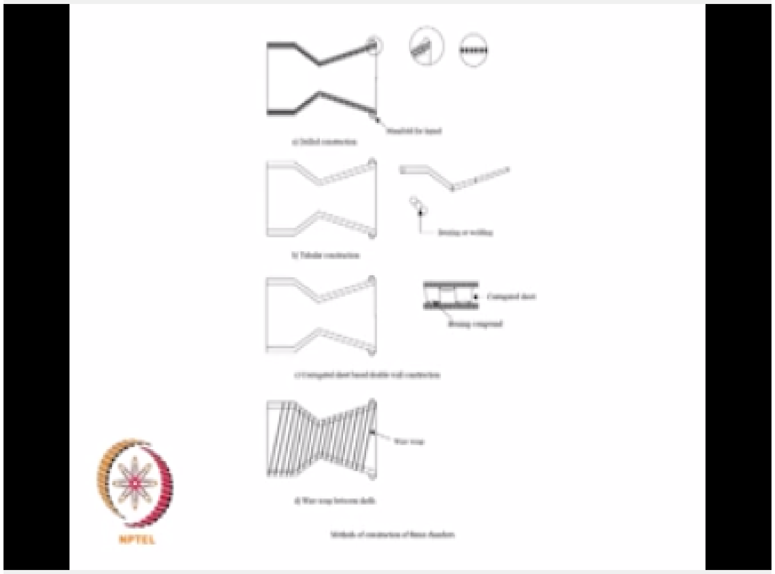

If you look at the first one it is something known as a drilled construction, if you see the view here there are a lot of holes that are drilled in the wall okay and these holes are going right up from here to beheading okay. Now other one problem with this as you move from the divergent person to the throat the diameter is decreasing right, so if you have X number of holes here the same X number should be there at the throat which means that the diameters need to shrink at the throat which is not very easy to sometimes fabricate okay or you need to have such a design wherein the size of the holes remains the same.

But they are more well spaced as it comes out in the same okay, so that is fabrication is a very difficult part in this then you have something known as a tubular construction this is a lot better than the earlier one. Here what you are doing is you have two layers okay one is the chamber that is the inner layer, on top effect you have pipes that are braced okay. So in a sense you can decide on the type size pipe size as you go from the divergent portion to the throat and to the head end this is under in some sense a lot more controllable then the other one.

And then you will have an outer skin on top of this the pipes are braised or welded together, so as to keep them in contact otherwise you will have development of hot spots in certain regions where there is no liquid coolant, then the other this is probably the most best of all the designs that is instead of having pipes if you have a corrugated sheet okay, it is something like this you have sheets that will make the coolant channels. The sheets are such that you can make the coolant channels based on this I itself and then there braced such that they are in position and then again you have a top covering layer.

So this shape changes also from the divergent portion to the throat the size shrinks at the throat and then again becomes larger this is probably one of the better designs because it offers you ease of fabrication in some sense, then there is something known as wire wrapped which is scarcely used that is you wrap wire around the nozzle itself. So that the coolant moves along these lines but the trouble with this is you cannot even if you wrap the worse there is going to be some gap between them okay.

That is going to lead to some kind of hotspot generation there, so it is not such a good design because you cannot cover the entire region with this kind of an arrangement okay. Now I would like to draw your attention to something that you have already learnt you were learnt that heat flux from the gas phase side is maximum at the throat right. So you need to ensure that this region is cooled appropriate otherwise there is a lot of heat coming in and if you do not cool it you might tend to damage this.

And in addition to this you have learned that the heat transfer coefficient changes from here to here and again here to here it is a Maximum here and then it goes down on both sides. So hG is very right the heat transfer coefficient coming or the heat flux coming in from the gas phase is very you have to keep that in mind and you have to also know certain things about how cool inch behave, we will go through that in a minute that is. I am sure most of you have done this boiled water sometime or the other right.

What do you see when you boil water and then have you ever left the vessel on this τ itself for some time you know and forgotten to take switch off the gas or something what happens then yeah, what happens to the vessel it could get burned right that is the same thing that is going to happen here too if we do not take appropriate care. We will see how that happens firstly if you look at the boiling of the liquid there are a few regimes of boiling, firstly you have something known as convective boiling that is if you have heating from this side.

Let us say this is the hot gas side that is you are looking at some region here and there is liquid in the pipe when you heat it at the beginning you have seen this that this portion becomes hotter and tends to rise up right and therefore it tends to carry the heat from this surface to somewhere inside okay. So heat is being transported from the wall to the fluid inside fine this is a by convection, so this is known as convective boiling then there is something known as nucleate boiling.

That is again you have the hot gas side and the heat flux coming in okay as you rightly said after some time bubbles begin to appear at the bottom of the surface. So locally the liquid boils and the bubbles rise up and as they rise up they transport the heat from the wall to the fluid inside and then they collapse okay because they are becoming cooler, so therefore they collapse again become a liquid in this way the heat is being transferred from the wall to the fluid inside. This is probably a very efficient way of transferring heat from the surface to the fluid inside.

Now there is a third regime of boiling this is known as nucleate boiling there is a third regime of boiling namely of film Boiling.
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Again you have heat flux from the bottom, so what happens is after some time if you supply the heat beyond this stage right these bubbles tend to get from more frequently right there are large number of bubbles and these bubbles tend to coalesce right come together and form something known as a film. So there is a thin film of a vapor that is formed close to the surface, now we all know this that the heat transfer or the thermal conductivity of vapor is an order of magnitude lesser than the liquid okay.

So the heat transferred from the wall to the fluid gets reduced because there is a layer of gas that is there and that in some sense resist the transfer of heat, so in a sense if you keep transferring this heat the wall temperature tends to rise up and this is very detrimental. Now if you plot this in a graph with the U." as the y axis and d wall liquid as the x-axis okay you can see all these three regimes like this firstly you will have a convective boiling, that is the heat flux or Rises linearly as the world temperature.

That is if you keep on increasing the world temperature this also arises up linearly beyond some point the rise is very steep and this is convective this regime is nucleate okay the slope is drastically different here in this regime and if you look at the wall temperatures for this will be something like tea boiling plus 3250^0 centigrade very small temperature rise above the boiling point and you will be able to transfer a lot of heat to the fluid okay. What happens beyond this is what is known as a film boiling and they are actually the heat flux drops and it only comes back to this level at something like DB + 400 to 600 centigrade.

That is you need to increase the temperature a lot more to get the same kind of heat flux okay if we do not transfer the heat from this region to the fluid what happens is the temperature of the wall tends to increase and it could reach the temperature wear in remember this is also under a lot of stress because of the high pressure inside the chamber, so it could reach a point where in it could break, so you would want that right. So you have to ensure that at the throat there is nucleate boil ok or some wherein this region.

Just before nucleate boiling if it goes into this region it could be very detrimental right because there is a lot of heat flux that is coming in and that heat is not being taken out, so the temperature of the wall keeps on rising so and that could break open the motor. So that is why this is such a challenging problem in heat transfer see if you keep on heating right it becomes a film if you look at viscosity of the gases viscosity of the gases increases with temperature okay and if you look at Renault number of gases is close to one.

Renault number indicates the ratio of momentum transfer to heat transfer right, so the thermal conductivity also goes the same okay this is a molecular diffusion phenomena so the thermal conductivity also keeps on increasing. So it only it has to reach very high temperatures for the thermal conductivity to come to the same right. Now in addition to this we need to remember that the pressures inside encountered inside the combustion chamber of a rocket motor are very high right the temperatures are also very high.

So there is something known as critical pressure and critical temperature right you remember from your thermodynamics studied earlier that.

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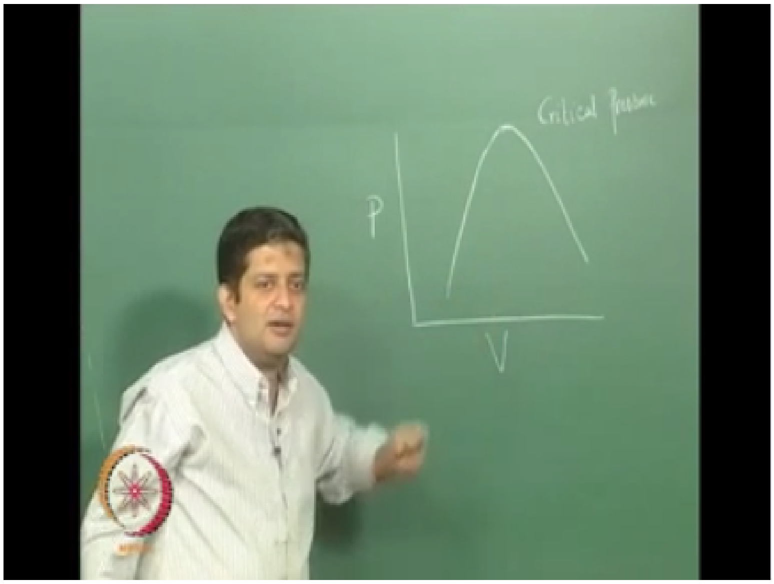

If we have a P_V diagram for a pure substance right it will go something like this and this point is called a critical pressure, now at the critical pressure and temperature then there is no distinction that you can make between liquid and gas phase both of them coexist okay. So because the pressure is encountered in the rocket motor or so high we need to be aware of this also right, so if you look at as I said earlier if you look at Space Shuttle main engine the combustion chamber pressure is somewhere around 200bar and somewhere inside the coolant channels it could go beyond 300 bar okay.

So very high pressures, so if you have temperatures also in that region then you will probably encounter this region and based on this we can make a map of critical temperature versus critical pressure as shown here.

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If you plot critical pressure versus critical temperature this is T critical let us say this is P critical now you divide the region into four parts right and let us call this in this if the pressures are below critical pressure and the temperature is also below critical temperature, there is a distinct liquid and a vapor phase right. So in this region there is a liquid and vapor this region as supercritical liquid this is supercritical gas this region is gasps a now why do we need to in essence worry about this is?

Simply because if you are wanting to design the system coolant regenerative cooling system what we need to know is the properties of the liquid in a particular temperature and pressure and we need to know whether it is a gas a supercritical liquid or something else in that region right, otherwise we might determine property somewhere else and use it something else then we could be under designing, over designing and we could probably get into trouble. So we need to know which region it is there and in the coolant channel what happens to pressure and temperature as you move along the coolant channel.

The temperature will increase right and there is a pressure drop because these are very small channels through which the fluid has to flow at very high flow rates, so the pressure drop will be that temperature will increase. So in essence you will depending on which region you are your curve will have a negative slope right, so let us look at which of the coolants and what is there you know critical points and if you use them at some pressures how do they move okay.

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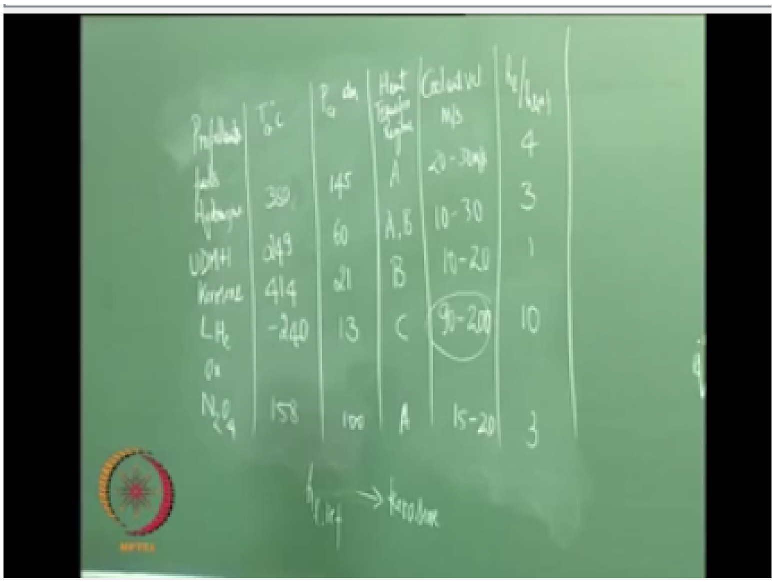

Propellants	T_c °C	P_c atm	Heat Transfer Regime	Coolant vel m/s	h_l/h_{ref}
Hydrazine	380	145	A	20-30 m/s	4
UDMH	249	60	A, B	10-30	3
Kerosene	414	21	B	10-20	1
LH_2	-240	13	C	90-200	10
Ox					
N_2O_4	158	100	A	15-20	3

$h_{l,ref} \rightarrow$ kerosene

The last column is the heat transfer coefficient of the liquid to the heat transfer coefficient of a reference liquid, what is used as a reference liquid is kerosene okay, kerosene is used here as a reference liquid. One of the biggest challenges of using a kerosene locks engine right kerosene locks engine is you know to put it differently, if you look at the Soyuz craft it has probably more than a thousand missions right thousand missions and this has been used to take people and equipment to the space station.

Now why is that being chosen as simply because it uses for most of its this thing a kerosene lock system which is very cheap among all the propellants, this is probably the cheapest. Now kerosene locks although it is very cheap one of the trouble with kerosene lock system is that if you use kerosene as a coolant right what happens is there is something known as coking kerosene remember is a hydrocarbon right it has hydrogen and carbon at some temperature the carbon tends to get deposited.

And this might block the coolant channels because these cooling channels are themselves very fine and that is a very serious problem to overcome in development of these engines. So kerosene is chosen as the reference fluid and let us look at the sum of the propellants firstly the fuels hydrazine or Nh4 then the other one is un symmetric died methyl hydrazine you DMH then kerosene then liquid hydrogen among oxidizers will pick n 24. Now the critical temperature for hydrazine is around three ET centigrade 380^0 centigrade and the critical pressure is somewhere around 145.

So if you are using typically with hydrazine and you UDMH you do not go to very high-pressures it is somewhere in the region of 70 to 80 bar in the chamber, so upstream of that could be lower than this critical pressure. So the heat transfer regime would be in a that is here okay so there is a distinct liquid and A vapor phase and as the coolant moves from the nozzle end towards the head in it traces a path like this okay the cooling velocities are something like 30 meters per second and the HL x HL references for that is it is 4times effective than kerosene then UDMH this is 249 and this comes down to 60.

So this could be in either A or B and the velocity would be something like 10 to 30 and this is three times as effective as kerosene itself will be one the HL x HL reference this is 414 kerosene the critical pressure is very low right it is somewhere around 21. So you will most likely end up above this critical pressure so it is in most cases in this regime and moves in this direction, then LH to remember liquid hydrogen is a gas at ambient conditions and only if you super cool it will go to liquid state.

So the critical temperature is very low minus 240s centigrade and critical pressure is something like 13 atmosphere this will be sorry, in see now it could start somewhere here and go in to see okay because it is if you look at the critical temperature this is also very low this is also very low right. So you could end up with C and therefore if you notice this is very high because it has changed its state from liquid to a gas, so the flow velocities are very high right and therefore its cooling properties are also very high.

It has ten times more effective than kerosene right and in 20 for the numbers something like this 158 this is 100 it will be a gas if you look at liquid hydrogen liquid oxygen injectors the hydrogen is coming in as a gas which is why we are going to have swirl injectors for this kind of a system we will discuss that when we discuss injectors it will be a gas. Now it is also important for us to kind of know that what is the properties that are desired of a coolant you will have two fluids onboard right.

One and oxidizer 1f fuel if you are looking at a buy propellant system which one among them to use as a coolant is, the question typically the choice is invariably a few simply because if you look at its properties what is it that you desire of a coolant firstly it is C_P should be very high I specific heat capacity should be very high, that is if you have a higher C_P let us compare air and water okay for the same amount of heat that you pump into both these systems the C_P of water and the density of water is also very high.

So therefore it is something like C_P is four times density is thousand times so if you pump in four 1000 kilo joules the water temperature will go up by one degree whereas the air temperature will go up much more right. So that is something that you need to keep in mind when you look at what kind of coolant to use C_P and thermal conductivity are something that is important and similarly you the table for so you have to choose a liquid that has a higher C_P and probably higher thermal conductivity and which obviously in most cases happens to be a fear.

Now if we have to look at the analysis of the heat transfer let us see this is the wall and this is hot gas side so there is T_C this is hot gas this is liquid and this here is the wall there is heat transfer by convection on this side in the wall that is conduction and here again you have convection right. So there are there is one that is P_C in the hot gas side and let me call this temperature as T wall gas liquid and let me call this temperature as T_N okay. So what are the temperatures that are known and what are the temperatures that are unknown.

And what are the equations to use, again this is a series connection right, so the heat flux is going to be the same so you have a Q ." must be = hg into T_C -T w g this must be = K_W / T_W = H_L twl - T_N okay, this we have seen we could write it as H_W right. Now there is a radiative heat transfer also coming in from the gas phase side which could be significant you could absorb this in this but you need to be careful in deciding on the edgy it has to also a confirm if the radiation part is significant it also a set of account for the radiation part okay fine.

Now how many unknowns are there we will know this part pc we will know what about t wall g we do not know this and the wall L we do not know and T_L also we do not know right, so there are three unknowns okay and we have only two equations. So how do we solve this? Now before we get into that we have seen how to estimate this part right hg we know how to get it we said its turbulent flow and therefore we based it on Reynolds number right.

And this part is conduction if we know the wall property thermal conductivity of the wall we can evaluate this part if you look at this is again flow through a tunnel but this is a liquid okay Reynolds number of the liquid is not something close to one that you can strike off okay. So you need to have Reynolds number also, so HMU would be again the flow is turbulent because this is a confined flow and the transition Reynolds number is somewhere around 2,300 right flow through tubes and the tube diameters are very small.

Although if you look at this here the velocities may not be too large but the channel diameters are very small, so therefore the flow would be turbulent, you okay we can estimate the H_L in this fashion and then solving these two equations we can rewrite expressions .

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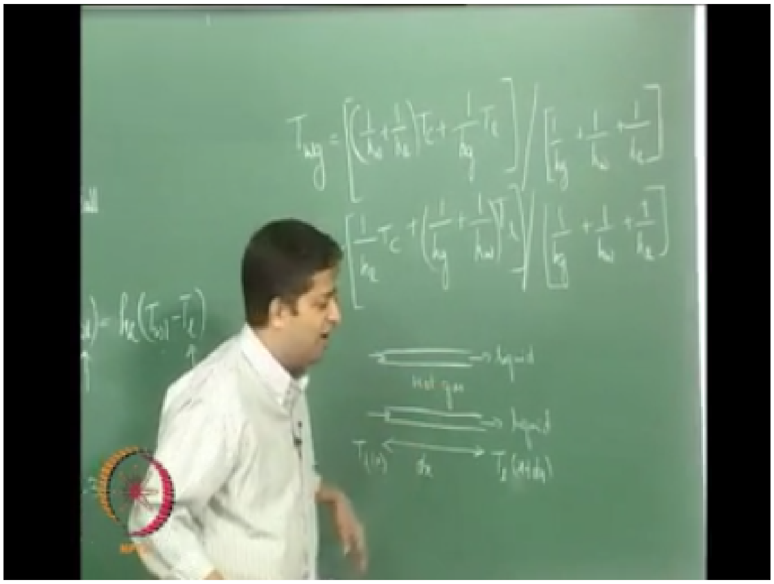

For t wall gas you and t wall n also we can get and so if you got expressions for t wall land t was G, now we do not know how to take care of the other one right if you remember your basic energy transfer fundamentals this is nothing but a pipe flow right you have a pipe flow right and there is a coolant jacket fine so if I consider a very small elemental area D_X right. Then what i know is let us say this is then at x then i will call this P_L x + Δ x a.

So here you have hot gas and this is liquid know there is a certain heat that is being transferred from here to here and you can write the energy balance for that.

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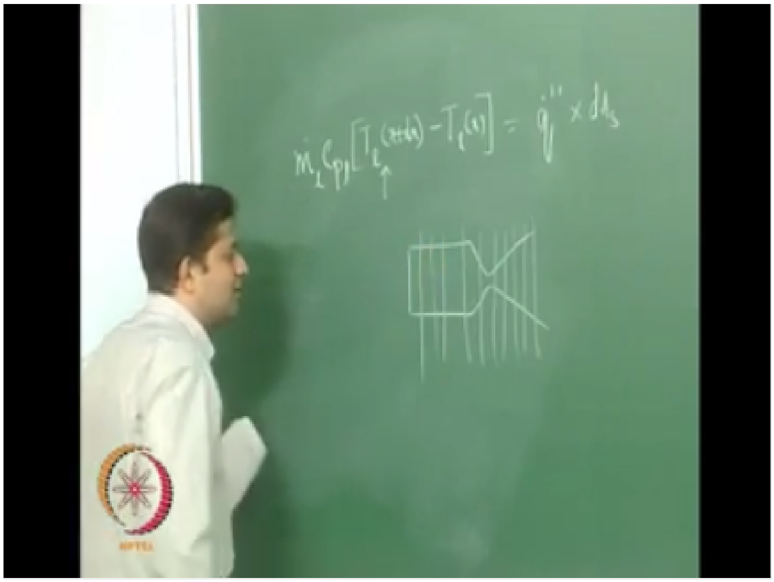

As M. l/cpl T_L X + D_X - T_L of X this must be = the heat flux coming in that is Q. "into the das is the surface are a alright that is perimeter into DX fine πd into DX so if you take a very small elemental area and you need to also remember that at the entry to the coolant pipe you know the temperature right. So you will know the temperature there and that is let me assume that to be this point if you know this then from this equation right.

You know at the entry point you can calculate T wallet corresponding to that okay and if you know T wall L from this you can calculate Q ." and you will know the area. So you can calculate the heat that is coming in fine you know M. dot so you know $C_{P.}$ So the only unknown would be this so you can evaluate this then if you evaluate this becomes.

The next entry temperature, so you can go on and proceed in steps from the nozzle end towards that is you need to divide the motor into sections from the nozzle end towards. The head end okay and proceed in this direction then you will be able to get all the temperatures okay fine this clear we will stop here will continue in the next class thank you.

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