Heat Transfer
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Lecture - 59
Shell & tube heat exchangers

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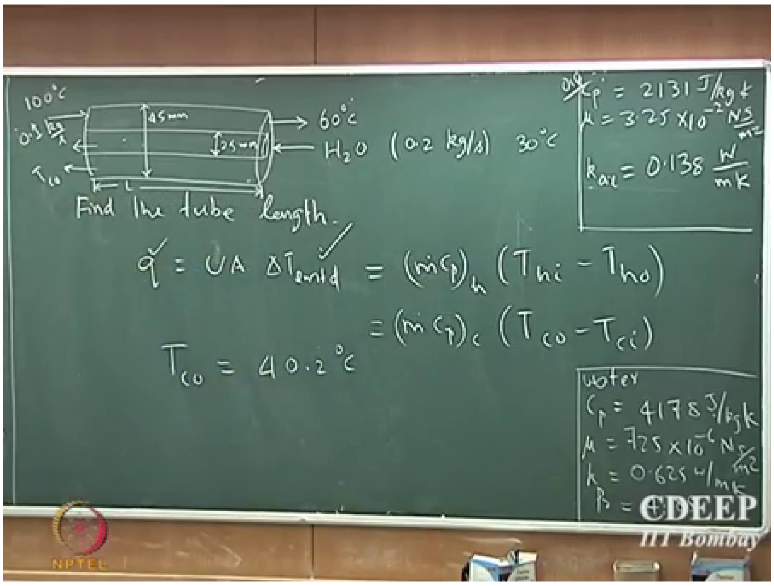

So, let us look at an example problem so suppose if we have a concentric cube which is what you had in your lab experiment, but this example is slightly different from the experiment that you have done in the lab. So, the diameter of the inner tube is 25 millimeter and the diameter of the outer tube is 45 millimeter. And you have oil which is flowing at 0.1 Kg's per second at 100 degree C in the outer chamber and the oil leaves at 60 degree.

So, clearly that is the hot fluid and we have cold fluid which is flowing through the inside of the tube which is water and flowing at 0.2 k g per second, mass fluid at 30 degrees that is what is given to you and some properties are given; we will come to that later.

So, the question is find the tube length; find the tube length. So, how do we address this problem? We need to find the tube length, we need to find the length of the heat exchanger so that is L that is what we need to find anybody how do we start? Yeah.

Student: (Refer Time: 02:03).

Yes we want to find q. So, if we know q q is U A delta T l m td. So, if we know U we know delta T l m t d and q we should be able to find the area. So, the area will tell me from area we should be able to find out what is the length of the heat exchanger? What are the properties that we know already, what are the quantities that we already know? Yeah do we know q? Yes we know this is equal to m dot C p hot fluid into T h i minus T h o taking calculate that we know that delta T l m d we know that, how? Ok.

So, we do not know what is the outlet temperature of the cold fluid, but we know m dot C p h at steady state this should be equal to m dot C p of cold fluid T C o minus T C i. So, from here equating these two we should be able to find out what T C o is. The first exercise is find T C o and T C o is about 14.2 o C I did not list the property.

So, C p of oil is 2131 Joule per k g Kelvin, this oil the viscosity is 3.25 into 10 power minus 2 Newton second per meter square and the conductivity of oil is 0.138 watt per meter Kelvin ok. And that is for water that is for water is C p s 4178 joule per k g Kelvin.

And we have mu is 725 into square and the conductivity is 0.645 watt per meter Kelvin and Prandtl number is given, Prandtl number is 4.85 so that is Prandtl number so all the properties are given. So, we can immediately find out what is T C o? So, we know q, we know delta we know delta T, l m T d ok. So, we need to find you the universal heat transfer coefficient how do we do this?

Student: (Refer Time: 05:00) ok.

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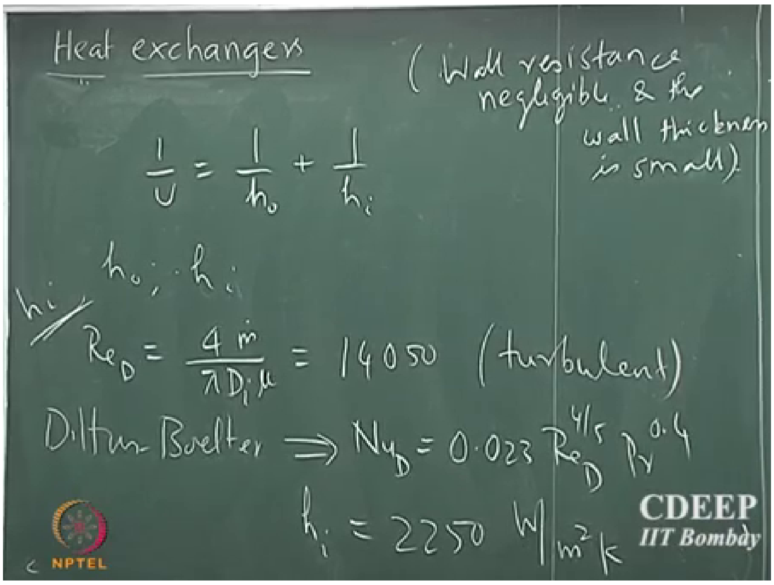

Heat exchangers

(Wall resistance negligible & the wall thickness is small)

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_i}$$

h_o ; h_i

h_i

$$Re_D = \frac{4\dot{m}}{\pi D_i \mu} = 14050 \text{ (turbulent)}$$

Dittus-Boelter $\Rightarrow Nu_D = 0.023\, Re_D^{4/5}\, Pr^{0.4}$

$h_i = 2250\ W/m^2 K$

So 1 over U is 1 over h naught plus 1 over h i. So, I am assuming that wall resistance is negligible and the wall thickness is small ok. So, assume that the wall thickness is small, so assume that the outside and the inside area of the tube which is present inside are approximately the same

Student: (Refer Time: 05:52).

So, now we need to know what is h naught? So now we need to know what is h I how do we find them? We can get the correlations; so, the Reynolds number, so the Reynolds number would be for the inside will be 4 m dot by pi d i into mu so that is about 14050. So, this is for the inside ok.

To calculate h i the Reynolds number of the flow which is flowing through the inside tube it is about 14000 or so clearly it is a turbulent flow which correlation should be used Dittus Boelter correlation, so that is what you used in your lab, use the Dittus Boelter and that is NUB it is 0.23 R e D to the power of 4 by 5 Prandtl to the power of 0.4. So, from here we find out that the heat transport coefficient h i is 2250 watt per meter square 2 k, so that is the inside heat transfer coefficient. And then similarly we can find the outside heat transport coefficient.

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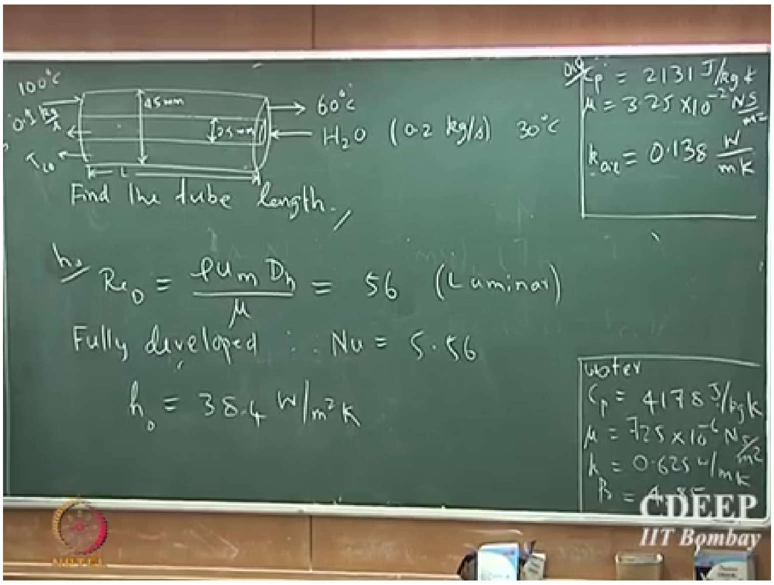

Find the tube length.

h_o: $Re_D = \frac{\rho u_m D_h}{\mu} = 56$ (Laminar)

Fully developed ∴ $Nu = 5.56$

$h_o = 38.4\ W/m^2K$

Oil
$C_p = 2131\ J/kg\,K$
$\mu = 3.25 \times 10^{-2}\ Ns/m^2$
$k_{oil} = 0.138\ \frac{W}{mK}$

water
$C_p = 4178\ J/kg\,K$
$\mu = 725 \times 10^{-6}\ Ns/m^2$
$k = 0.625\ W/mK$
$P_r =$

So, that is for h o and it is an annulus. So, the R e D Reynolds number is given by rho U m into divided by mu so that is the effective diameter. We find that and so that will be about 56, it is the laminar flow; remember that we did not look at the correlation for concentric cylinders. So, one could actually do that it is there in the text, but we did not go over it in this course for want of time d h is the effective diameter between the two.

So, you look at the so you know what is the area of area of flow correct. So, pi d the outer diameter minus the inner diameter so using that you can find out what the h is. So, so that if we assume laminar flow and you assume fully developed condition. So, the Nusselt number is constant for that and it is about 5.56 that is the Nusselt number for that system. And from here we can find out h o is 38.4 watt per meter square Kelvin, because the heat transport coefficient for the exterior of this cube ok. And so now we know you we know delta T l m T d and we know q. So, we can easily plug it in the expression.

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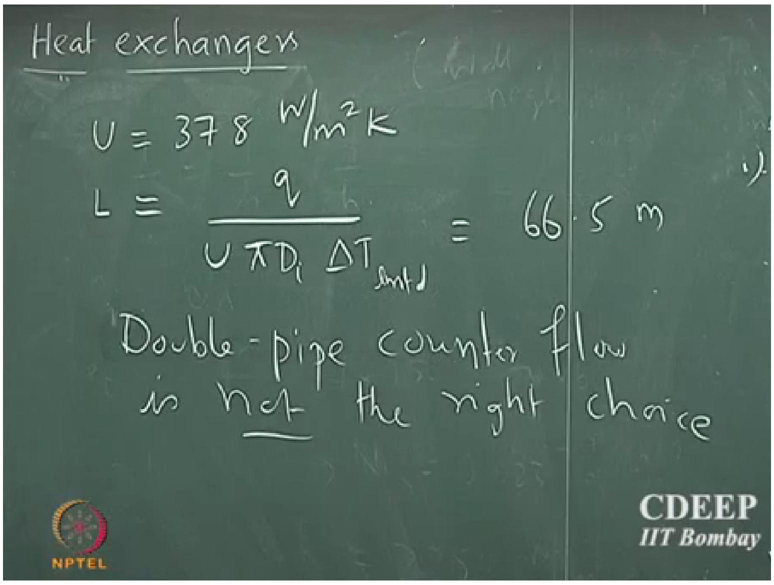

Heat exchangers

$U = 378\ W/m^2K$

$$L = \frac{q}{U \pi D_i \Delta T_{lmtd}} = 66.5\ m$$

Double-pipe counter flow is not the right choice

So, U is 378 watt per meter square Kelvin, and L is given by q divided by U into pi into D into delta T l m t d, so that is given by 66.5 meter is that a reasonable number 66.5 yes no, not at all. We have a tube which is 25 millimeter there is just 2.5 centimeters, which is this much this much and it is 66.5 Why is the prediction wrong? The wrong prediction right why? So, cannot have a heat exchanger with the 66 meters.

So, what is wrong? It is 2.25 millimeters that is 2 and a half centimeters that is as much and you have a 66 meters long; is it possible to flow water with a reasonable price will have a huge pressure drop, it is a completely unreasonable number. So, how do we handle this? So what will be the first question that you would ask if you get such kind of unreasonable numbers?

What are the different types of heat exchangers? The first question I would say we have never used this kind of a configuration. You would require 66 meters of construction if you want to use this kind of a heat exchanger for exchange and this is a pretty realistic system where the temperature difference not unreasonable, and water is a constant water is a very normal fluid which is used for heat exchange.

If you look at any industrial process it is like you conserve water you convert it into steam when you want to cool some fluid and use that steam to heat something else. So, water is a very constant fluid that is normal fluid which is used in the industry for heating and cooling purposes, so that is not an unreasonable fluid.

The real problem is this is the wrong configuration, never use a double pipe counter flow is not the correct choice it is not the right choice for this problem. It is a good choice may be a good choice for some other fluid, but definitely not for this system; you really need a different type of heat exchanger to actually achieve this extent of heat transport for the conditions that is given; if counter flow is worst parallel flow is even worse it is more worse.

So, you never want to use any of these double pipe configurations or such kind of a heat transport problem, so, this is where you know using these correlations and trying to estimate the design plays an important role. If you do not estimate what should be the approximate length or the dimensions of the heat exchanger; you would never be able to decide whether you are doing an efficient job here.

So, you will end up making a very expensive heat exchanger, but you are just not getting the best out of it, so that is an important point alight. So, what we will do next is we look at some special cases; I will just sketch some of the temperature profiles and then we will move on to a log mean temperature difference for shell and tube heat exchangers ok.

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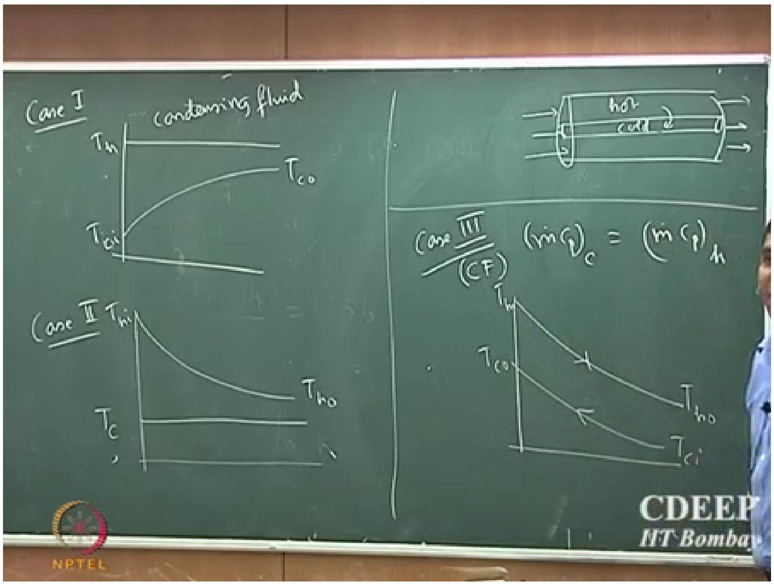

So, the first case we look at where you have condensing steam or condensing fluid in one of the chambers. So, if you have a double pipe heat exchanger, so you have a double pipe heat exchanger you have some fluid which is flowing through these two chambers.

Student: (Refer Time: 13:31).

Ok and you could always have a hot fluid it is basically a of condensing fluid. So, the temperature of the fluid inside the heat exchanger will remind approximately constant, because it is the latent heat which is actually being used to heat up the fluid which is flowing through the internal tube ok. So, supposing if this is my hot fluid and this is my cold fluid. So, the hot fluid it liberates the latent heat with this vessel by changing its own phase, and that heat is now transported to the cold fluid which is being heated up.

So, therefore so supposing if I have a parallel flow, so that is my hot fluid inlet and that will be my cold fluid outlet temperature. So, you can have a situation where the temperature is almost constant in the one of the chambers and that is a typical case when you have a condensing fluid.

What is the opposite of that? Cold fluid evaporating sort of obvious to guess that; you will have a cold fluid which is evaporating you can which is at a constant temperature and you have a hot fluid which is actually being cooled. And this is the T C is at a constant temperature because it is being evaporated or being boiled for example, so that is a special case.

And the third one a little bit more interesting; a little bit more interesting is a situation where you have the capacities are constant or equal the cold fluid is equal to m dot C p of a hot fluid. So, you can always have two different fluids and you can adjust the mass flow rate of the fluid to that m dot C p is same for both the chambers you can always do that ok.

Now, what will be the temperature profile let us say it is a counter flow, I want to draw the temperature profile for this heat exchanger delta T is gone, so that is easy to guess, so you will have a constant delta t. So, supposing if this is hot fluid T h o T h i T C i and T C o because the capacities are equal ok. So, q is m dot C p into the temperature difference between the two inlet and the outlet and similarly for the hot fluid.

And so one could guess that the temperature difference along the heat exchanger will actually be constant, what is delta T l m t d here. Remember the expression for delta T l m t d delta T l m t d is delta T at one location minus delta T at the second location divided by Lon of the ratio.

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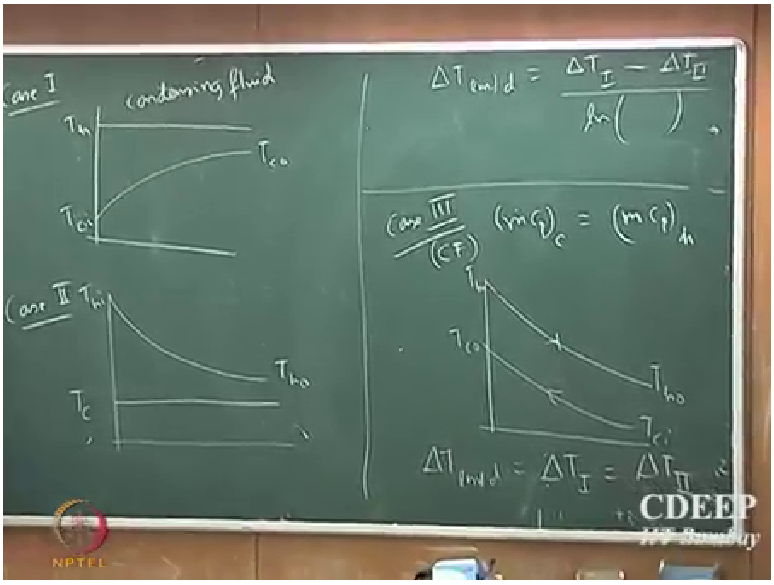

What is that? So, this is the expression for delta T l m t d we know that and we know that the temperature difference remains constant. So, what is the delta T l m t d that we should use this is not the one cannot be this cannot be this. So, what is the problem with 0 by 0 you cannot have this so, what is the delta T here? It is delta T actual itself ok.

So, if you actually go the go and do the derivation of the delta T l m t d is rigorously by assuming that these two are constants. You will find out that delta T l m t d is equal to basically what it means is that you do not require a log mean temperature difference to characterize this problem.

So, the temperature difference that you should use is either of these two so that plays an important role in designing your heat exchanger. If you can actually design your mass flow rate such that the m dot C p of the cold and the hot fluid are same. Then you have got an important property; you are able to now predict what is the temperature profile inside the heat exchanger; which we cannot do on all the other cases, we do not know what is the exact temperature profile note that all these are just sketches.

So, in this case we should be able to predict or we should be able to estimate what is the approximate temperature difference at every location inside the heat exchanger that plays an important role in heat exchanger design ok. So, the correct temperature difference that you should use is the actual temperature difference either at the inlet or the exit of the heat exchanger.

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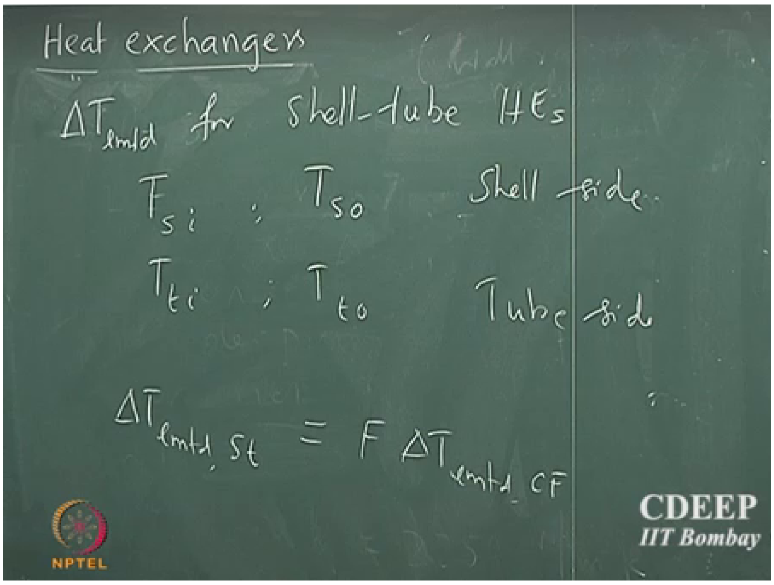

Heat exchangers

ΔT_{lmtd} for Shell-tube HEs

T_{si} ; T_{so} Shell side

T_{ti} ; T_{to} Tube side

$$\Delta T_{lmtd, St} = F \Delta T_{lmtd, CF}$$

So, next we are going to look at what is the delta T l m t d for shell and tube heat exchanger ok. So, here the nomenclature I will use this when I put S it stands for temperature on the shell side and S i stands for the ins shell side temperature at the inlet to the shell and T S o stands for the shell side temperature of the stream that is actually going out of the shell side. And similarly small t i and small t o ok; so, this stands for the shell side fluid and this is for the cube side fluid for the cube side flied ok.

So, now it turns out that the delta T l m t d for a shell tube heat exchanger it is basically some fraction of the delta T l m t d for counter flow ok, delta T l m t d for a counter flow which is exactly at the same temperatures ok. So, it turns out that it is a certain fraction of that, but what I am going to simply sketch is water going to what is this fraction F and from practical point of view how can you use this F in estimating the delta T l m t d for a shell and tube heat exchanger ok, so in order to do that we need to define two quantities ok.

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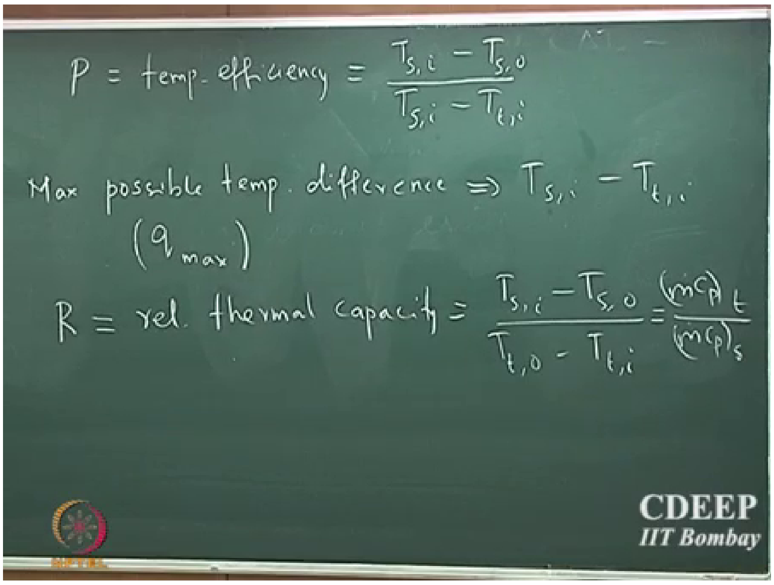

$$P = \text{temp. efficiency} = \frac{T_{s,i} - T_{s,o}}{T_{s,i} - T_{t,i}}$$

$$\text{Max possible temp. difference} \Rightarrow T_{s,i} - T_{t,i}$$

$$(q_{max})$$

$$R = \text{rel. thermal capacity} = \frac{T_{s,i} - T_{s,o}}{T_{t,o} - T_{t,i}} = \frac{(\dot{m}c_p)_t}{(\dot{m}c_p)_s}$$

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So one is called the P which is a thing called the thermal efficiency or the temperature efficiency defined as the and that is given by the difference in the shell side temperatures divided by the maximum temperature difference ok.

Now I would like you to stare at the denominator of this expression here this is the first time you are seeing a difference between the inlet temperatures of two different streams ok. So, the maximum possible temperature difference the maximum possible temperature difference is T s i minus T t i, where s stands for the shell side and t stands for the t stands for the tube side the difference in the inlet temperatures, is the maximum possible temperature difference in the heat exchanger that is the theoretical maximum ok.

Now in fact in a short while we are right when we go to epsilon NTU method we actually be using this concept of maximum possible temperature difference to define a quantity called maximum; theoretical maximum possible heat transport. So, we have not looked at that so far we are going to see how to define or how to find out what is the maximum possible heat transfer rate ok. So, far all we know is what is the net heat transport rate in the hot fluid, we know what is the net heat transport rate in the cold fluid, which is equal when it is a steady state, but we do not know what is the theoretical maximum possible.

So, only if we know what that is we will be able to define some sort of efficiencies. So, here the temperature efficiency means the difference in the inlet and the outlet temperature of the shell side fluid divided by the maximum possible temperature difference ok. And then one needs to define another quantity called R which is the relative thermal capacity. So, that is sort of easy to realize what it is from the definition basically the ratio of the capacities or it is defined as T s i minus T s o divided by T t o minus T t i.

Here we have assumed that the shell side fluid has hot fluid and the tube side fluid has a cold fluid. So, it does not matter how it is because the minus minus will always cancel out. So, that should be equal to m dot C p of the tube side fluid divided by m dot C p of the shell side fluid once again assuming steady state condition ok.

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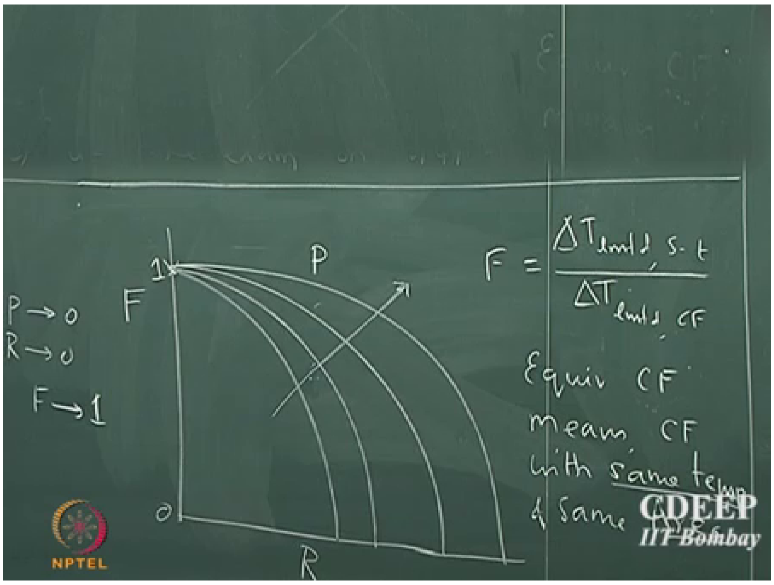

So this factor f which is basically the delta T l m t d of the shell tube heat exchanger divided by delta T l m t d of a counter flow equivalent counter flow ok. So, if I sketch the graph between the R which is the relative thermal capacity ok. So, what I would see for a fixed P so note that these expressions have all been derived they are not going to look at these expressions in this course, but the general behavior is for a given specified P for a specified value of P.

So, what you get is this kind of a profile where F goes from what is the range for F? 0 to 1. The same temperatures you just have a counter flow configuration that is all the area is same. So, the net area or that net heat transport area that you have is matched with the counter flow the corresponding area.

So, what it means by saying equivalent counter flow; counter flow with same temperatures and same area that is very important same temperatures and same area ok. So, now, as P is decreased ok, so this is the what is found is this is a kind of profile that you will get for this fraction F ok. So, as you decrease P you will go closer to the origin.

So, now what it simply means and note that everything all of these they start from 1 ok, all the expressions for different values of P they all start from 1 ok. So, which simply means that when P goes to 0, and R goes to 0 or R goes to 0 either of these two the F will tend to F will go to 1 ok, so, which means that the limits for Helen tube heat exchanger.

In fact, this actually comes from the expression for the delta T l m t d, but what is important here for the course point of view is to realize that the upper bound for the delta T l m t d of a shell and tube heat exchanger is essentially that of the delta T l m t d equivalent delta T l m t d of an equivalent counter flow configuration which has same temperature and same area ok.

In fact, the same area is not relevant from the calculation point of view, but you must understand that that is very important ok. Because to remember that for calculating delta T you really do not need area you only need the temperature differences, but it is important to say that when it is equivalent counter flow; it means that the area of heat transport is also maintained similar. Otherwise you cannot expect the same temperature difference to occur in a real situation.

So, so this has been worked out so this kind of graph has been worked out for all kinds of shell and tube configuration. So, we will not go over all of them, but all these graphs are all available they are all available in tabular form.

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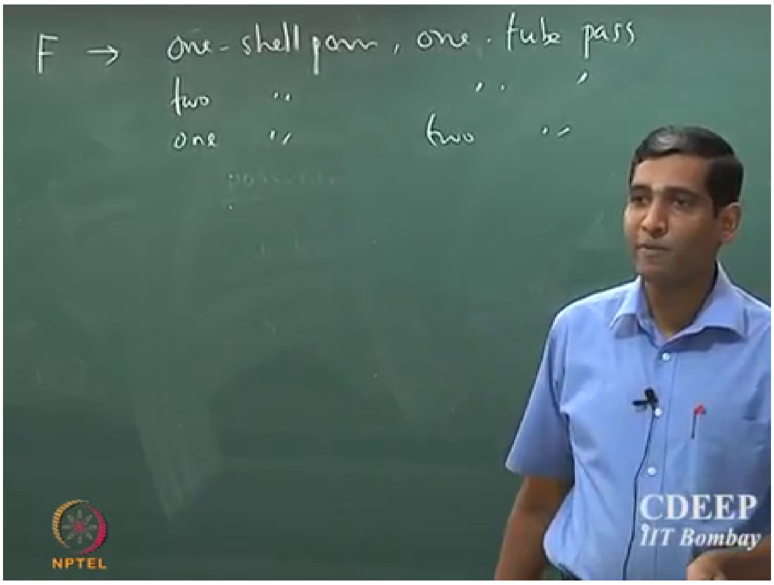

So, the F is available for one shell pass, one tube pass. It is available for two shell passes. One tube pass is available for one, shell passes two tube passes for all kinds of configuration for which this fraction F is available it is all it has all been worked out and nice table or tabular forms are available, they are all available in terms of graph.

So, it is very easy to find these numbers and it is routinely used in industrial setting; remember that shell and tube heat exchanger is actually the workhorse of heat exchange process in any industry. Most of us heat exchangers you will see will be of that configuration. So, this has been worked out for almost all possible combinations of shell and tube heat exchangers and there is no need to go over it again and again,.

But it is just important to realize that it is the fraction of the counter flow and counter flow is like the upper limit for shell and tube heat exchanger that is correct. So, it has both co current and parallel; now what is turns out is that the co current operator and the counter current flow is the best mode right because for as smallest area you can have maximum heat transport. So, that is why counter flow is like the upper limit for shell and tube.