**Process Equipment Design**
**Prof. Shabina Khanam**
**Department of Chemical Engineering**
**Indian Institute of Technology – Roorkee**

**Lecture –31**
**Design of Reboiler-5**

Hello everyone. I welcome you all in 7th week of the course Process Equipment Design. If you remember the 6th week of this course there we have discussed design of reboilers and as far as design is concerned we have considered detailed design of kettle reboiler as well as vertical thermosyphon reboiler and we have classified the reboilers and further we have seen that how to select the proper reboiler according to the operating conditions.

So, in this lecture we will discuss design of reboiler with some example so that you can understand the procedure for designing of these reboilers properly. So, here again we will discuss design of kettle reboiler as well as thermosyphon reboiler. So, let us start with example 1.

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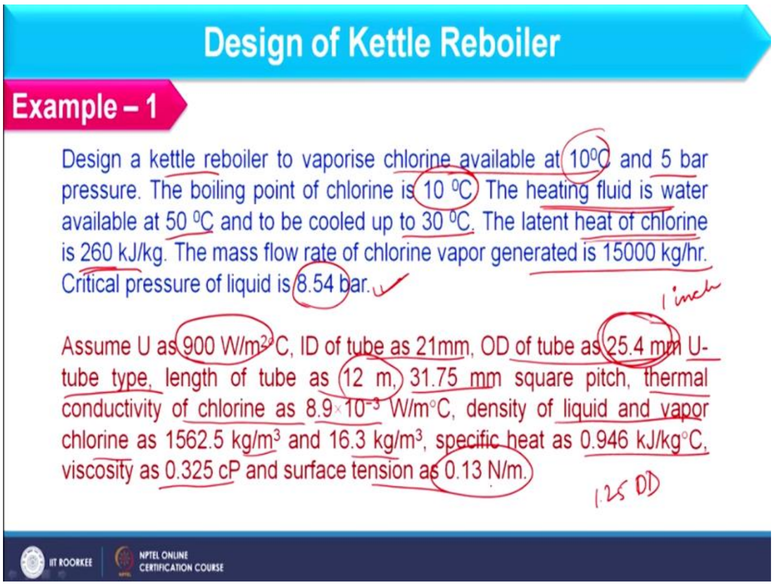


So, you see in this example we have to design a kettle reboiler to vapourize chlorine which is available at 10 degree Celsius and which is available and 5 bar pressure. Boiling point of the chlorine is 10 degree Celsius. So, you see here boiling point of the chlorine as well as chlorine availability both are at same temperature and that is boiling point. What is the meaning of this that when the chlorine is entering into the kettle reboiler no sensible heating is required only the vapourization will take place.

So, to heat the chlorine we use water which is available at 50 degree Celsius and which is cooled up to 30 degree Celsius by providing its heat to the chlorine. So, latent heat of chlorine is 260 kilojoule per kg and mass flow rate of chlorine vapour generated is 15,000 kg per hour. So, you see here we have to generate 15,000 kg per hour of chlorine vapour with the help of water.

Usually we consider steam as a heating media, but in this case because chlorine boiling point temperature is very low so we can use any other heating source and for that purpose water we are using. And as far as critical pressure of the liquid is concerned that is basically 8.54 bar and this is the critical pressure for chlorine. And further we are assuming that initial overall heat transfer coefficient is 900, ID of the tube is 21 mm, OD of the tube is 25.4 mm.

So, if you know this value this is nothing, but 1 inch. And we are using U tubes and length of each tube is 12 meter. So this 12 meter is the total length of the U tube and further we have 31.75 mm square pitch. So, if you see what is the relation in pitch as well as OD. So, if you consider this it is nothing, but 1.25 into OD. So, this is 1.25 OD and arrangement is square. And further we have thermal conductivity of the chlorine as 8.9 10 is the power – 3 watt per meter degree Celsius.

Density of liquid and vapour chlorine are given like this and this. Further, we have specific heat of the chlorine like this, viscosity is given and finally we have the surface tension so you see all properties are given to us. So, let us start the design of kettle reboiler. Now, if you recall the lectures which we have covered in 6th week and if you recall the design procedure for kettle reboiler what is the first step? The first step is obviously to find out heat duty.

In fact, whatever heat transfer equipment we have discussed so far as for a shell and tube heat exchanger is concerned condenser and now we are discussing the reboiler. The first step in each case is to find out the heat duty because complete design depends on that how much heat duty we are dealing with. So, in the case of reboiler heat duty you can find out depending upon how much vapour you are generating.

So, in this problem around 15,000 kg per hour of vapour of chlorine is generated and latent heat of the chlorine is given to us. So, we can simply multiply them to find out heat duty.

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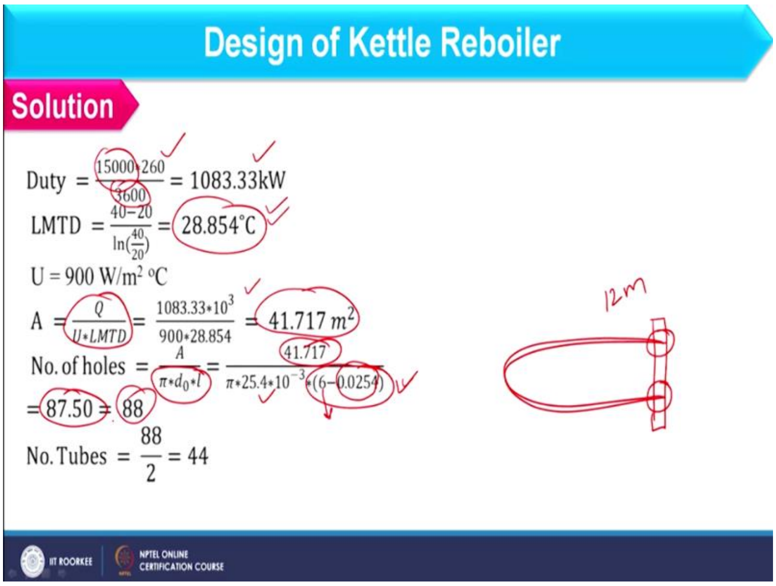


So, if you consider here heat duty is 1083.33 kilowatt where 15,000 kg per hour and that we have converted into seconds and 260 was the latent heat if you recall the example. Further, we have to find out log mean temperature difference because if you consider the temperature profile in chlorine side chlorine is entering at 10 degree Celsius and that is nothing, but the boiling point of the chlorine.

So we have isothermal condition in shell side where boiling is taking place. However, in tube side we have variation in temperature from 50 to 30 where water is available. So, you see in this case we will never come across a situation where temperature cross will take place. So, here only LMTD will work without considering F t correction factor and you know that how to find out LMTD and the value of that LMTD is 28.854.

So, I know the heat duty, I know LMTD value and overall heat transfer coefficient initial guess is given to us as 900 watt per meter square degree Celsius. So, we can simply find out heat transfer area. So, as far as heat transfer area is concerned we can use this expression and putting values of these parameters we can find out heat transfer area as 41.717 meter square. So, once I am having the heat transfer area we should find out the number of tubes.

And for that purpose we can have two procedures. First is if I am considering total length of the tube this is the U tube which enters twice into tube sheet. So, if you see if here tube sheet is there and this is basically the U tube and total length of the U tube is given as 12 meter so that is the complete length which enters twice into tube sheet. So, if I have to find out effective length we have to deduct thickness of tube sheet into 2 from the total length.

However, you can have a different approach here also like if I consider half length of the tube and that should be 6 meters and if I am considering that length it will enter only once to the tube sheet. So, in that way I have find out the heat transfer area of a single tube and then we can find out number of tubes so let us see. Now as far as area of single tube is concerned that should be pi d 0 L effective.

So d 0 is given to us as 1 inch or 25.4 mm and this is nothing, but the effective length where I have considered half of the length and this is basically tube sheet thickness. Usually we consider tube sheet thickness as 25 mm, but here because OD of the tube is more than 25 mm we should consider OD of the tube is equal to tube sheet thickness. So, in this way we have found out tube sheet thickness as 25.4 mm.

So, considering all these values as well as total heat transfer area we can find out number of tubes as 87.5 which should be 88. Now what is this 88 is number of tube or number of holes? If I am considering half of the length that is the length of 1 lakh of U tube it means whatever number of tubes I am considering that is nothing, but the number of holes because so many holes I have to make in tube sheet.

Now, if I consider the number of U tube that should be just half of the number of holes. Otherwise what you could do 12 meter was the total length you should deduct twice of tube sheet thickness from that length and you can find out number of tubes and whatever number of tubes you can obtain just multiply that by 2 to find out number of holes. So, in that way we can carry out the calculation.

Now, once I am having number of tube what is the next step? If you recall the procedure of kettle reboiler we have to find out actual tube count and so the bundle diameter and as far as actual tube count is concerned we have to refer certain standard tables and these tables are table C series which is available in R.W. Serth book in appendix C.

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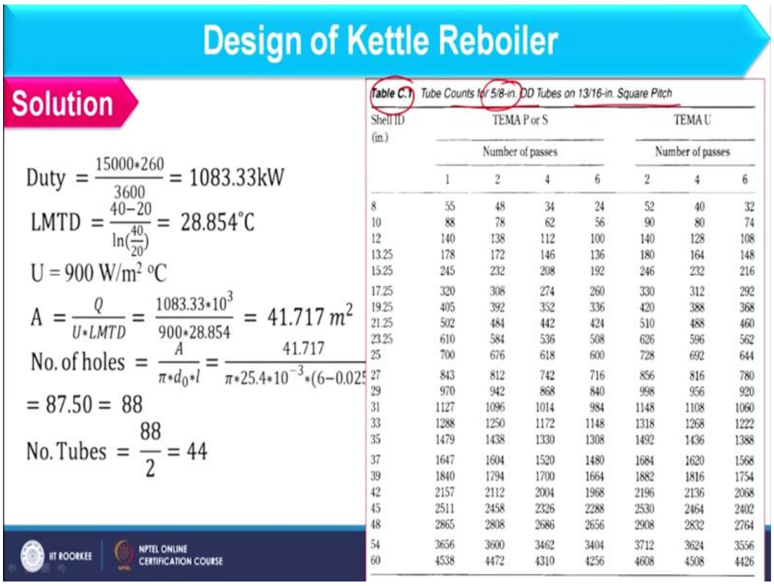


So, let us see table C 1 first. So, if you focus on table C 1 it is given tube count for 5 / 8 inch OD tubes on 13 / 16 inch square pitch. So, if you see OD of the tube is not 1 inch as we are given in this problem so this table will not work for me.

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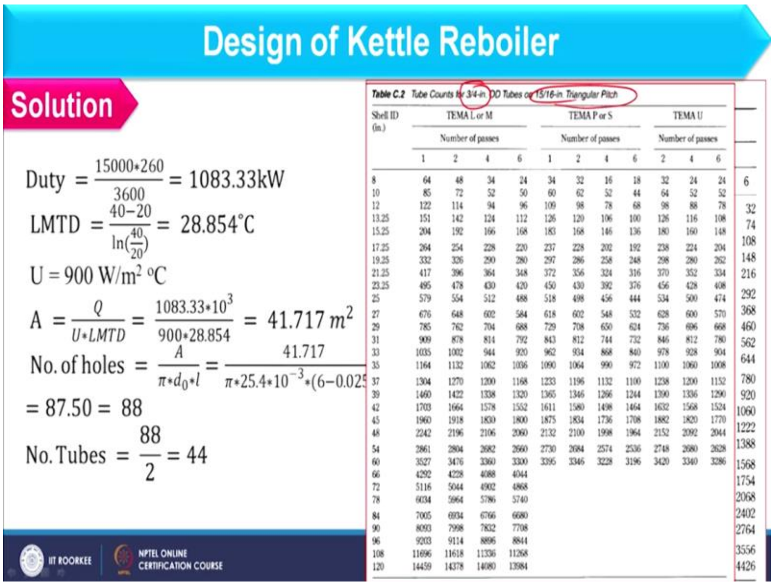


So, let us focus on other tables. So, here I am having table C 2 which says that tube OD is 3 / 4 inch and 15 / 16 inch triangular pitch. So, it will also not work for me.

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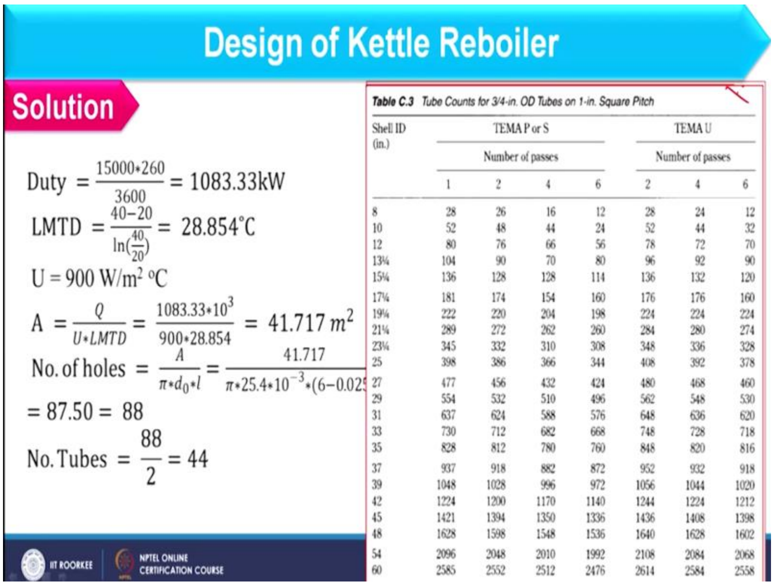


And then we will focus on table C 3. So, if you see the table C 3 it is for 3 / 4 inch OD and 1 inch square pitch. So, here this also will not work for me.

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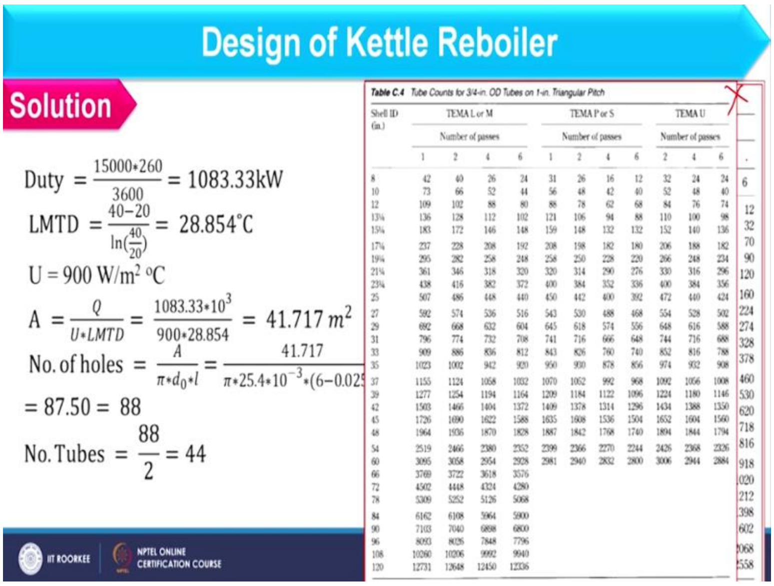


I will focus on table C 4 and it is for 3 / 4 inch OD and 1 inch square pitch. So, obviously this will also not work for me.

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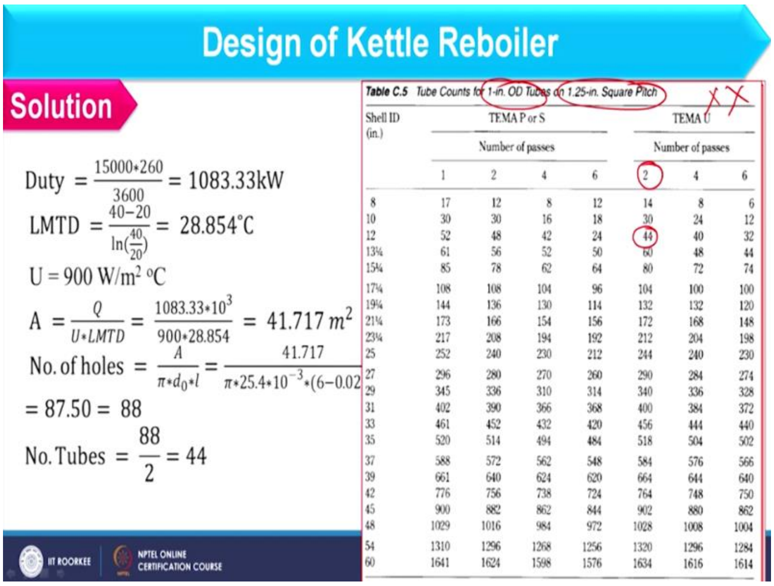


And further we have table C 5 where OD is 1 inch and 1.25 inch square pitch is given. So, as per the specification this table is suitable for me. So, let us see the actual tube count in this table. Here, I am having U tube and number of tubes we have obtained as 44 and passes are 2. So, if you see here I am having 44 tubes. So, in this case whatever number of tubes we have calculated the same number of tube is available in standard table.

Otherwise what you could do whatever number of tubes you will obtain just take next value which is available in this table. In this table means table C series. So, here I am having 44 tubes and corresponding to this 44 tube shell ID is given as 12 inches and as you remember the last week lectures the bundle diameter should be slightly lesser than the shell dia and for that purpose we usually deduct 0.25 inches from this shell ID.

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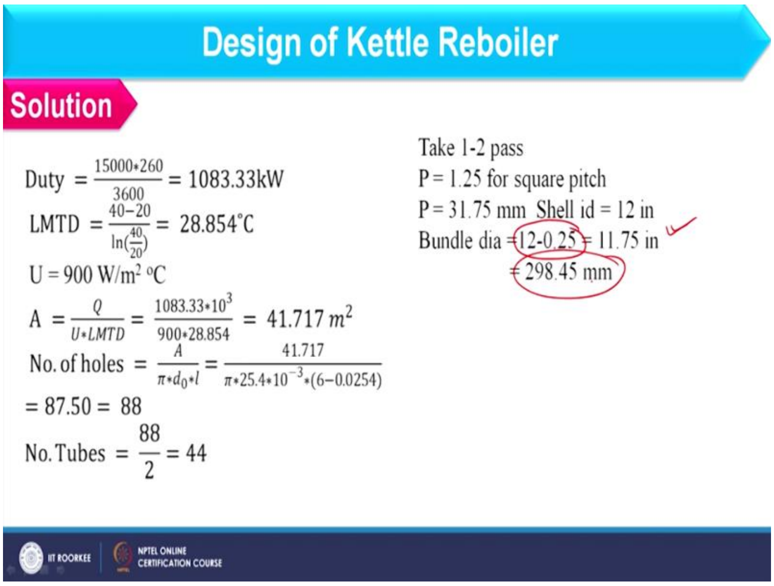

So, considering this we can find out bundle diameter as 12 inch – 0.25 so that is 11.75 inches conversion you can make in mm. So, in this way we can find out bundle diameter. So, next step is to find out heat transfer coefficient in shell side as well as in tube side. So, if you remember the heat transfer mechanism that is nothing, but the pool boiling. So, we will consider nucleate boiling correlation over here and in this problem we are given the critical pressure. So, accordingly we will choose the expression.

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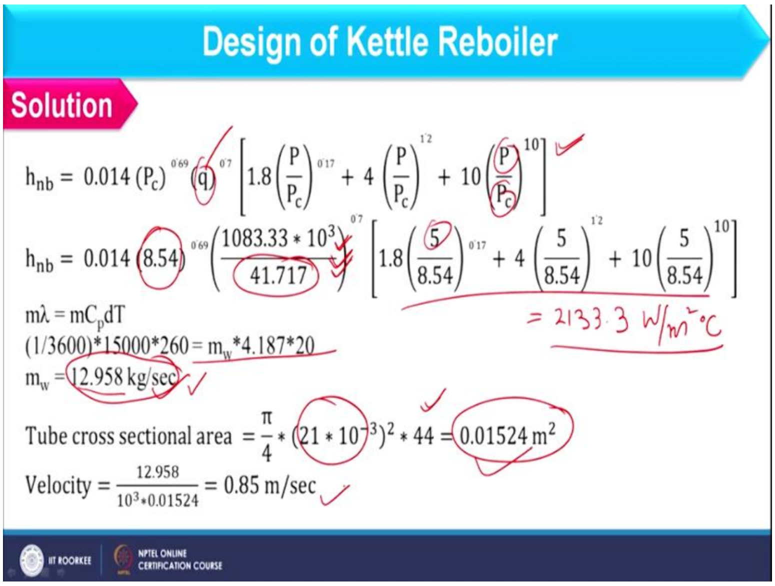


So, here we have the expression depending upon the critical pressure as well as the operating pressure along with the flux. So, what is this flux? This flux is nothing, but the heat duty divided by the heat transfer area. In this case whatever number of tubes you have obtained the same number of tube you can find in standard table C. However, if it will not happen then what you have to do?

If whatever number of tube you will see in table C that number of tubes are more than whatever you have calculated, so in that case you have to find out revised area. Revised area how you can find out because you know the area of one tube into number of tubes. So, based on that revised area you should consider and accordingly you have to find out the flux. Flux calculation is very simple heat duty divided by heat transfer area.

So, here I am having flux as 1083.33 into 10 is to the power 3 watt divided by the heat transfer area. So, this is the simple calculation for flux. Critical pressure for chlorine is given to us and operating pressure also. So considering these parameters you can find out h nb value which should come as 2133.3 watt per meter square degree Celsius sorry I forget to write the value over here, but you can see the value as like this.

Now once you have the heat transfer coefficient in shell side we have to find out heat transfer coefficient in tube side where water is flowing. So, a particular expression related to water is known to you, you have to find out velocity and for that you have to find out area per pass and then you can find out heat transfer coefficient in tube side. So, let us start the calculation for that.

And here first of all we have to find out the flow rate of water and that we can find out by making energy balance simply. So, mass flow rate of water you can obtain as 12.958 kg per second and tube cross sectional area how you can find out you already know the internal diameter of the tube and pi / 4 into di square should be the cross sectional area of one tube into number of tubes you already know.

So, area per pass is like 0.01524 meter square. Now once you have this mass flow rate you can find out volumetric flow that should be divisible by area per pass and then you can find out velocity as 0.85 meter per second. So, here whatever velocity you will obtain just take this value as it is. We should not meet that in a permissible limit because we are dealing with 1-2 pass.

And usually in kettle reboiler passes are 1-2 if you recall the design procedure. So, in this way we can find out the velocity.

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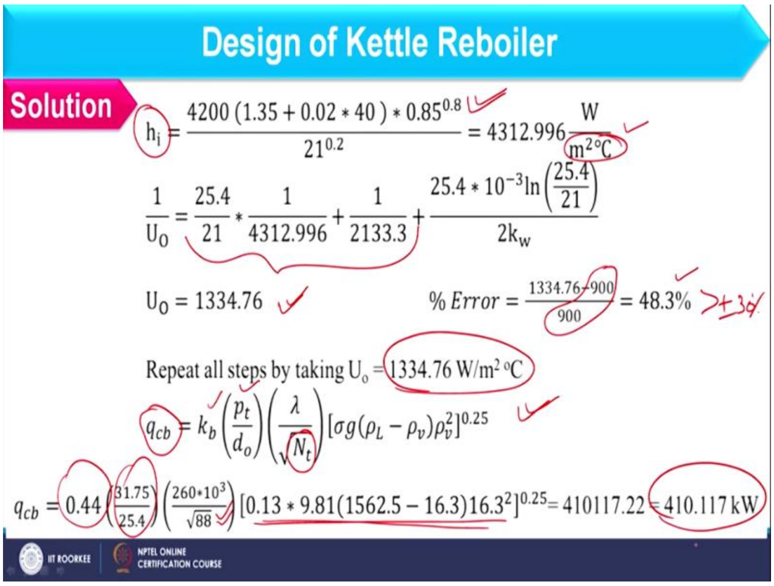


And so I can find out heat transfer coefficient in tube side considering this expression and so the value comes out as 4312.996 watt per meter square degree Celsius. So, as you have the value of h i as well as h 0 you can find out overall heat transfer coefficient calculation and in this problem dirt factors of two fluids are not given to us along with this thermal conductivity of tube material is also not known to me.

So, we will eliminate the three terms considering dirt factor as well as thermal conductivity of the material. So, based on these two term which includes h i as well as h o we can find out overall heat transfer coefficient value as 1334.76 watt per meter square degree Celsius and when you compare this with the initial guess you can find error as 48.3% which is more than plus minus 30%.

So, ideally we should take a repetition of all values depending upon U value as 1334.76, but for now we are considering the same problem and we are proceeding further because this is the repeat calculation and I hope you can do that calculation on your own, but in ideal case we should take the repeat. So, for now we are considering same value of U 0 as we have obtained and next step is to check critical flux value.

So, to find critical flux value we will use this expression where q cb is the critical flux in kettle reboiler and here you see all parameters so k b value should be 0.44 and pt is the pitch and d 0 is the OD of the tube, values you know already and here we have to see that what is the N t? N t is usually we represent for number of tubes, but here I am considering N t as number of holes.

So, here N t value should be 88 as you can see here. So, considering all these values we can find out critical heat flux as 410.117 kilowatt per meter square also.

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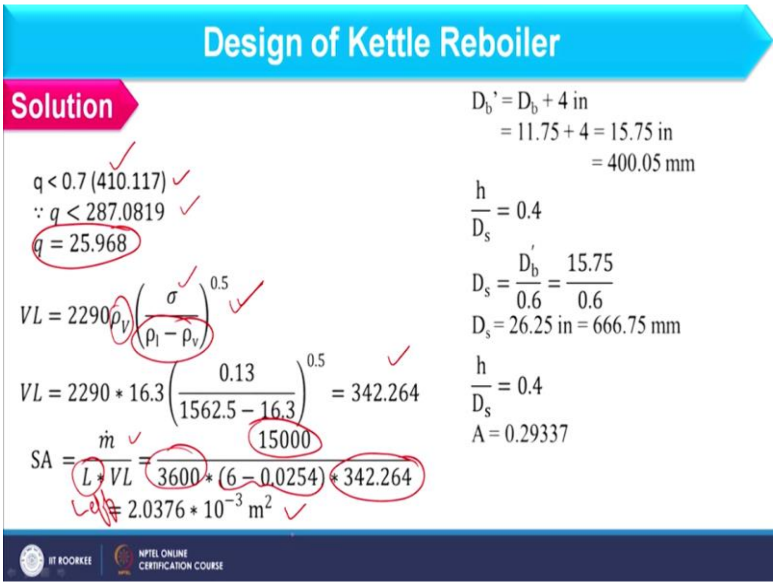


And what is the criteria for critical heat flux that the system heat flux should be less than 70% of critical heat flux. So, we should find out critical heat flux limit and that should be 0.7 into 410.117 so 287.0819 and system flux is this which is 25.968 kilowatt per meter square. So, you see the condition is satisfied here and next step is to find out the shell dia of kettle reboiler because here I am using special kind of shell.

And to design the shell diameter we have to first find out that how much vapour we are considering and how much segment area we want and to find out the segment area we also have to compute the vapour loading. So, first see the calculation of vapour loading. As far as the expression is concerned it is like this. And considering surface tension, densities of liquid and vapour and density of vapour over here we can find out vapour loading as 342.264 kg per second meter cube that is the unit of vapour unit VL.

So, once I am having the VL value we can find out the segment area as m dot / L into VL. So m dot you know already that is 15,000 kg per hour of chlorine vapour we are generating so that should be converted into per second also. And here we have this L is basically L effective and here you should also keep in mind that L is basically the length of tube bundle this is not the length of tube because for U tube length is 12 feet. But here we are considering only 6 meter because that is the length of the bundle.

So in SA you should consider L effective as length of the bundle not the length of the tube. So, in this case L effective should be 6 – 0.0254 and vapour loading we can consider to find out segment area which comes as 2.0376 into 10 is to the power – 3.

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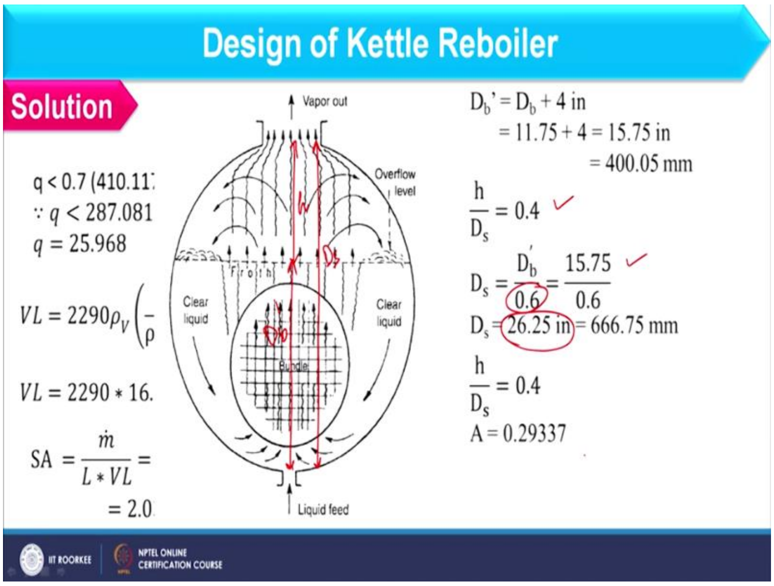


So, if I ask you that what is the segment area in kettle reboiler that we can understand with a schematic as shown here. If you see this is the bundle and this is basically the shell diameter and SA is the area of this section. Now, if you focus on this schematic SA can be computed after weir height and for now I only know the bundle diameter so how I can find out weir height.

Weir height can be obtained by adding 4 inches to bundle dia that is the thumb rule. So, this height we can find out and this we represent as D b dash. So D b dash you can find out as 11.75 + 4 inches so 15.75 inches you can convert that into mm. Now, to find out shell diameter we have to carry out iterative procedure. And for that purpose we initially assume that the height of segment section divided by the shell dia should be 40% or in other word we can say the height of the segment section is at least 40% of shell dia that is the initial guess.

So, if you consider height segment section so that we represent as h and this is nothing, but the D s. So h / D s should be 0.4. Now, if I ask you what should be D b dash / D s? Obviously the value will be 0.6 only because h + D b dash = D s. So, we can find out shell dia from this that is 15.75 divided by 0.6 so 26.25 inches is the shell dia. So, we have to find out revised segment area and for that purpose we have to find out segment area factor.

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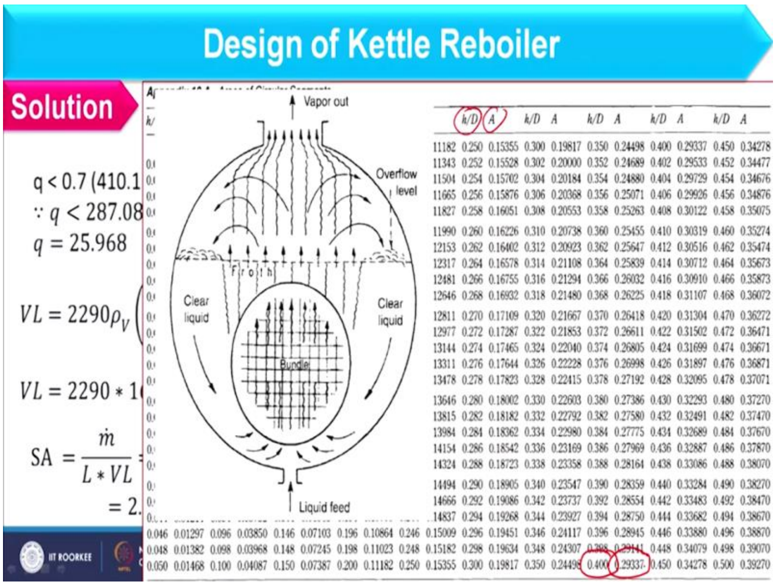


So, to find this we have to focus on this particular table and if you see this table here I am having h / D that is nothing but h / D s and A factor. So, if I focus on h / D as 0.4 A value should be 0.29337. So, this value you can note down over here.

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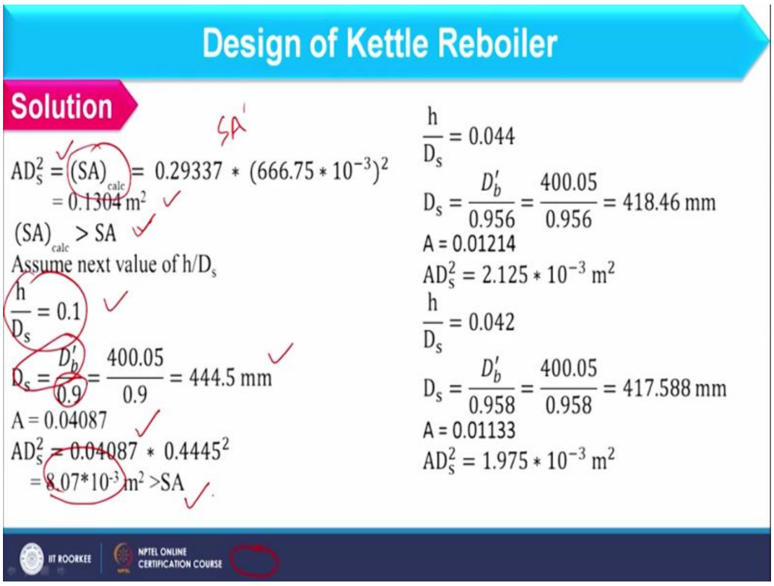


And further we can find out revised area as A into D s square. So, area we can obtain as 0.1304 that I am considering as SA calculated or you can simply consider that SA prime. So, in this case SA prime or SA calculated is very high in comparison to segment area. So, what we have to do further? We have to reduce the value of h? So, now we will consider slightly lesser ratio of h / D s.

So, further I am having value 0.1 and if h / D s is 0.1 D b dash / D s should be 0.9. So, considering this we can find out shell dia as 444.5 mm for this ratio h / D s as 0.1 we can find out segment area factor as 0.04087. So, you can see value over here SA calculated you can find as 8.07 into 10 is to the power – 3 and that is again more than SA. So, further we have to reduce h / D s ratio.

And we should carry out this iterative procedure till I am getting SA calculated should be equal to SA that will be the perfect design. Otherwise, we should obtain slightly larger value than SA. SA calculated will never be less than SA perfect design and for perfect design these two areas should be equal. So, iterative procedure you can see.

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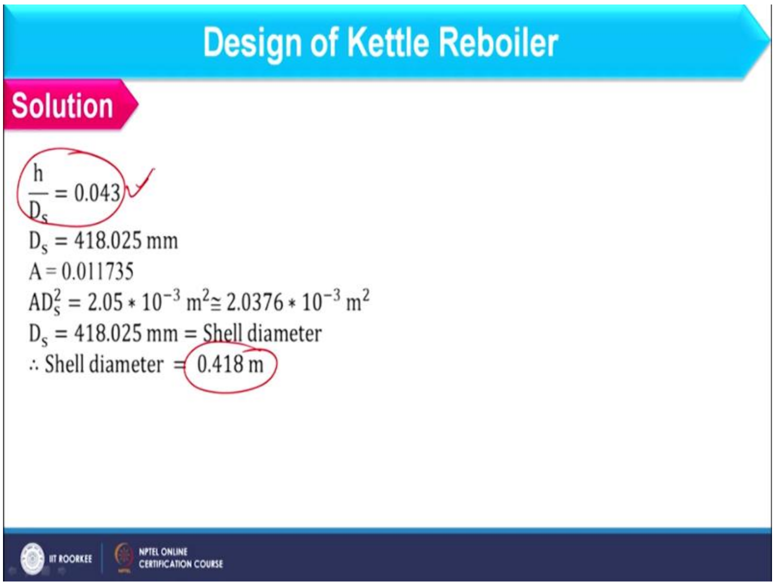


And we can obtain final diameter of shell as 0.418 and that is corresponding to h / D s value as 0.043. Now, if you recall the table 10 A where we have area sector factor. So, in that case only even values are available as far as h / D s is concerned so here we have to interpolate to find out the correct value for odd value of h / D s. So in that way you can design the kettle reboiler.

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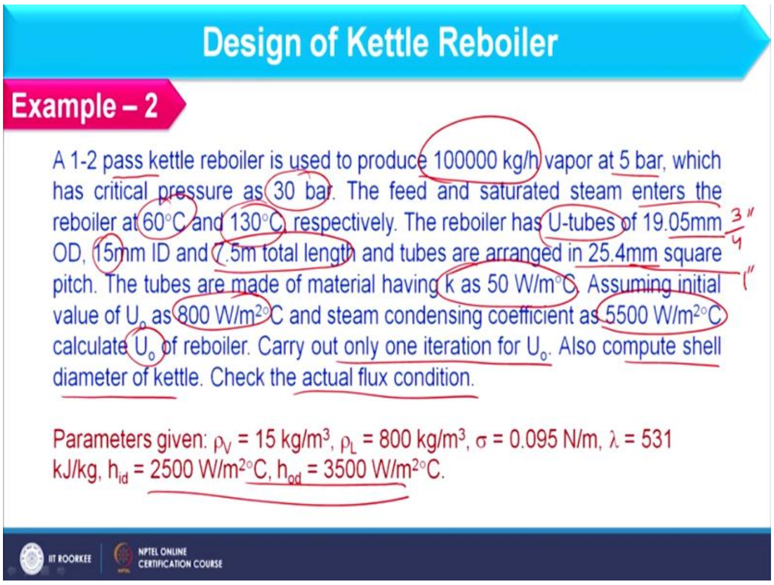


And here I am having second example which I will cover quickly. So, here you see 1-2 pass kettle reboiler is used to produce 1 lakh per hour of the vapour at 5 bar and critical pressure is 30 bar, feed and saturated steam enters the reboilers at 60 degree Celsius and 130 degree Celsius. So, in this case you see both are isothermal conditions. So, temperature difference should be difference of these two values.

So, mean temperature difference should be difference of these two values. So, for reboiler we are using U tubes with OD of the tube as 19.05 mm so that should be 3 / 4 inches, ID of the tube is 15 mm, total length of the tube is given as 7.5 meter and tubes are arranged in 12.5 mm square pitch. So, if you consider this pitch it is basically 1 inch and tubes are made with the material for k = 50 and for initial value of U 0 as 800 is given to us.

Condensing coefficient of steam is given as 5.5 kilowatt per meter square degree Celsius. We have to find out overall heat transfer coefficient for the reboiler and for that we have to perform only one, iteration and also compute shell diameter for the kettle and check the flux conditions.

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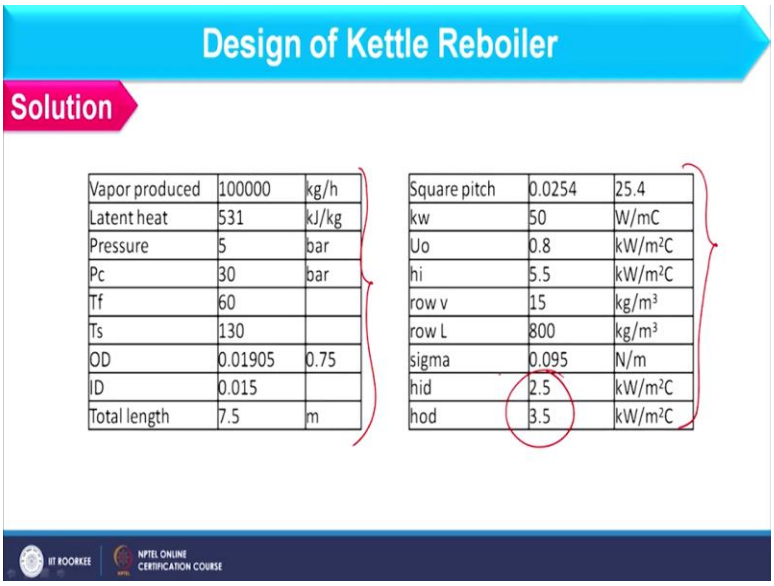


So just see the solution of this problem quickly and here we have the known values here as well as here and dirt factors are also given to us as you can focus on this line.

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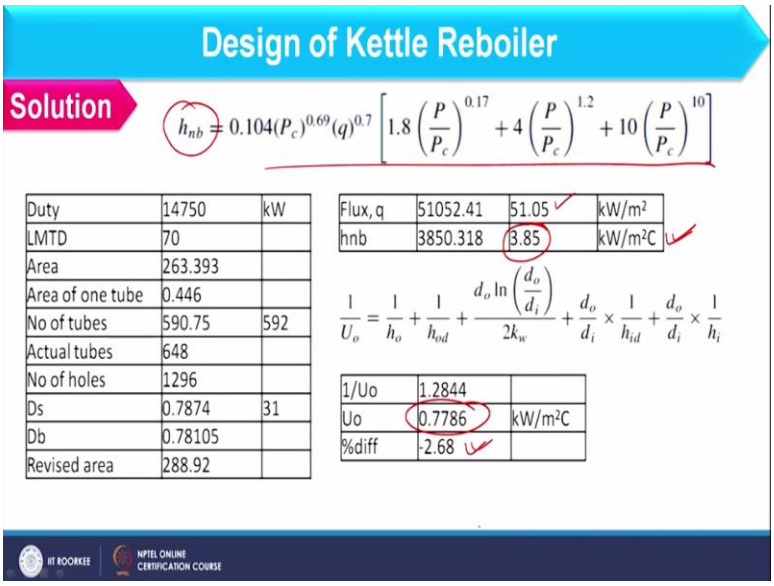


So, let us start the solution of this problem. Here, I have to find out heat duty that will be nothing but m lambda LMTD or we can say the mean temperature difference is 70 degree which is the difference of two temperatures only. Heat transfer area I can find out, area of one tube I can find out as we have discussed previously and number of tubes we can obtain as 592.

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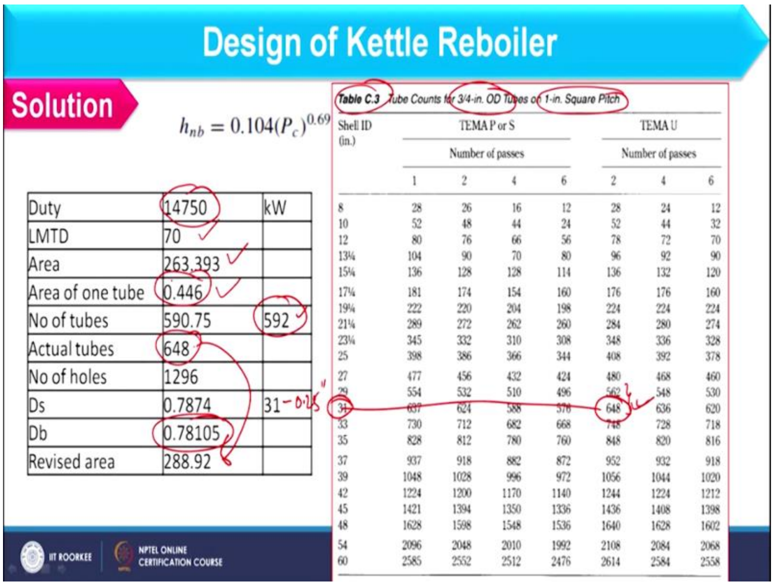


And actual tube count we can find from this table where if you see table C 3 there OD of the tube is 3 / 4 inch and 1 inch square pitch is given. So, this is as per the problem given to us. Now the number of tubes is 592 if you see 592 is not available next value is 648. So this would be the actual tube count and corresponding to this 31 is the shell dia and Db is basically 31 – 0.25 inches as we have discussed in previous example.

So, in that case because number of tube are changing now we have to find out revised area multiplying this number of tube with the area of one tube. So, in this way we can find out the revised area and we can find out the heat flux q depending upon the revised area and heat transfer coefficient. We can find out considering this expression and the value comes as 3.85 kilowatt per meter square degree Celsius.

Condensing side heat transfer coefficient dirt factor thermal conductivity of the material you know. So, we can simply calculate overall heat transfer coefficient and the value comes as 778.6 watt per meter square degree Celsius so we can have error around 2.5% so which is acceptable. Further, we have to check the critical heat flux condition.

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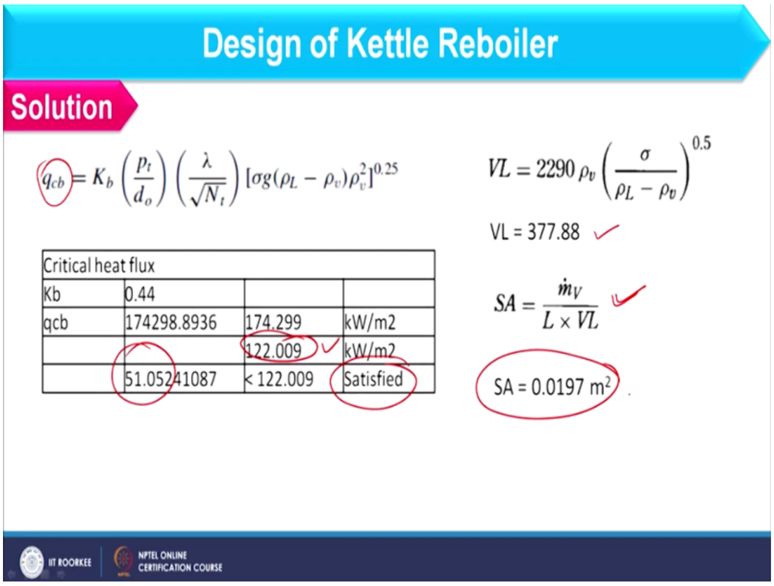


This is the expression which we have already discussed in the last example. So, I am simply giving the value of 70% of q cb and that comes as 122.009. System flux we have already calculated in the last slide and condition is satisfied in this problem. So, next we have to focus on shell diameter calculation and for that we should consider VL calculation and then SA.

So, VL you can obtain as 377.88 and segment area you can consider as 0.0197 meter square and how to use this expression that I have already explained in previous example.

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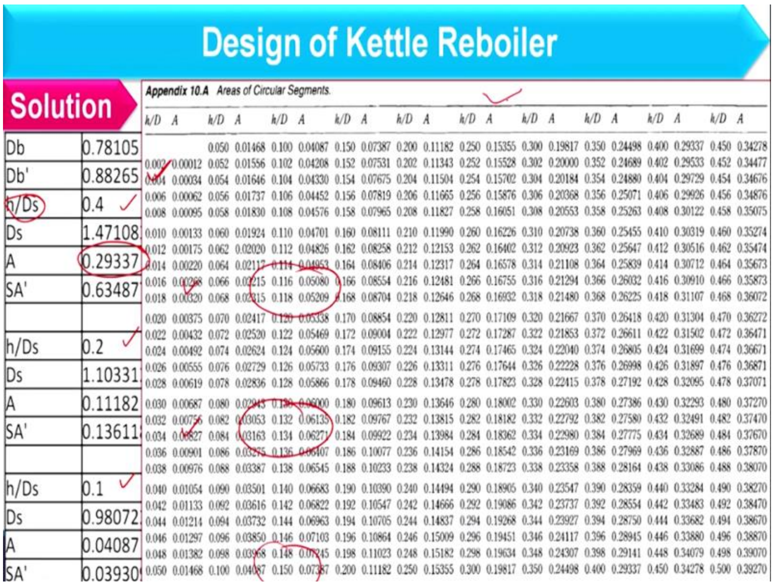


So, if you carry out the shell diameter calculation you have to find out Db dash and that should be 4 inches plus Db. So, Db dash you can obtain like this h / Ds initial guess as 0.4 factor A is like this as we have already seen in the last example and you can find out SA dash as 0.634 which is very high in comparison to whatever SA is required. So, we have to reduce h / Ds ratio.

So here I am having h / Ds as 0.2 SA dash we can obtain like this which is still very high and further we have to reduce h / Ds and further I am finding larger value of SA dash in comparison to SA and how to use this table that is appendix 10 A that I have already explained in the last example and I am not going into detail of that assuming that you know the use of it.

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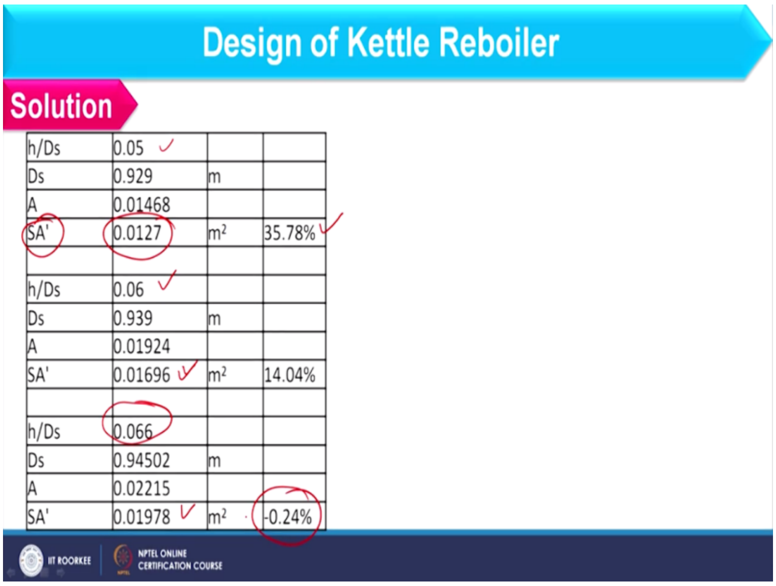


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|---|---|---|---|
| h/Ds | 0.05 | | |
| Ds | 0.929 | m | |
| A | 0.01468 | | |
| SA' | 0.0127 | m² | 35.78% |
| | | | |
| h/Ds | 0.06 | | |
| Ds | 0.939 | m | |
| A | 0.01924 | | |
| SA' | 0.01696 | m² | 14.04% |
| | | | |
| h/Ds | 0.066 | | |
| Ds | 0.94502 | m | |
| A | 0.02215 | | |
| SA' | 0.01978 | m² | -0.24% |

So, let us see further calculation h / Ds I am now considering as 0.05 SA dash you can obtain as 0.127 and the error you can see. Now the error becomes positive, so you have to increase SA dash value. To increase that we should increase h / Ds so now I am considering 0.06. So, SA dash you can obtain like this which is still less than the SA and further we have to increase h / Ds.

And finally we can obtain SA dash which is equal to 0.01978 which is slightly higher than SA, but comparable also. So, you can consider this value as final shell diameter. So, bundle diameter is 781 mm and shell diameter you can find as 945 mm. So, in this way you can design the kettle reboiler and here I am stopping this lecture. We will solve a few more examples in subsequent lectures. So that is all for now. Thank you.