Process Integration
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Module - 2
Fundamental Concepts
Lecture - 2
Fundamental Concepts Related to Heat Integration – Part 02

We have already discussed what is the F T factor? And how it takes into account the different flow patterns inside a shell and tube heat exchanger.

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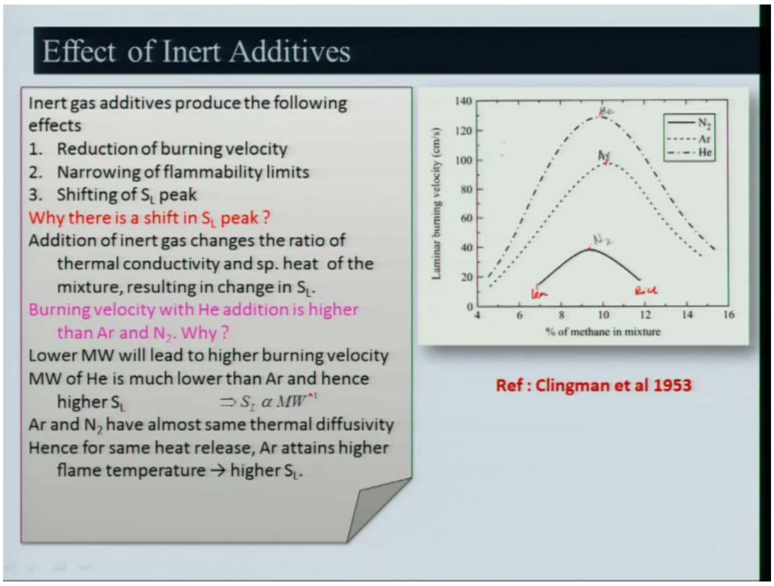

Now the F T factors can be expressed in different expressions like given here. The expression for F T for a 1-2 heat exchanger that is one shell, two-tube side heat exchanger is as follows for R is equal to 1, the F T factor is written in the screen and for R is equal to 1 that is another expression. So, we have two expressions R not equal to 1, and R equal to 1. Now, what are the salient features of this F T diagram. If you see this F T diagram, the y-axis is F T and the x-axis is P, and these F T plots are drawn for different values of R. It is R is 10.0, this is R is 2.0, this is R here R is 0.5. Now we see that for certain area, this F T factor is properly expressing the value of F T, but after that the slope becomes very steep.

So, from the diagram, it can be seen that with the decreasing F T, the slope of F T curve for a given value of R becomes very steep like in this range, very steep. In this range, it is very steep; in this range, it is very steep; in this range, it is steep; in this range, it is steep, and approaches to a certain value of p asymptotically. So, if this is a line, we see that this approaches to this line when F moves to the infinite values, so here we see that up to 0.75 this is a rough estimate we can measure the F T values properly, but after that the slope becomes very steep. So, this is the red area is called the infeasible area, and the green area is called the feasible area; that means, when designing a heat exchanger, we will always try to be in green area.

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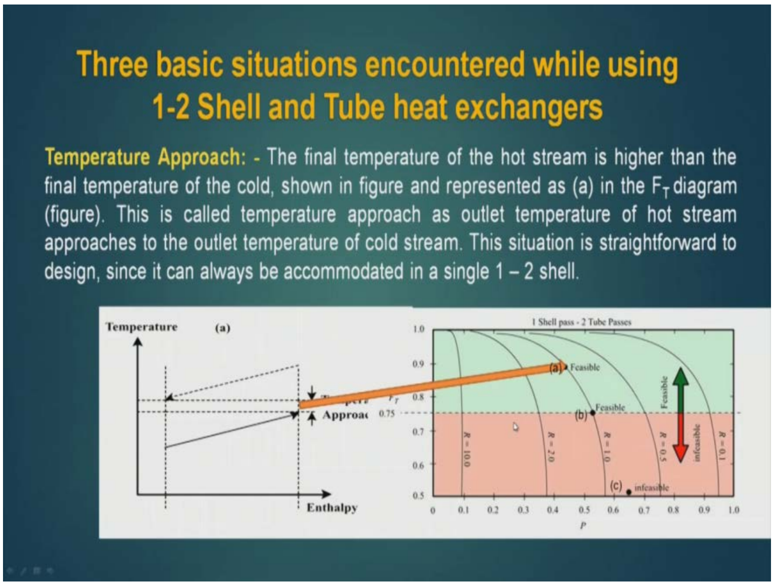

Three basic situations, which are encountered while using 1-2 shell and tube heat exchanger, and for that let us explain what is temperature approach? The final temperature of the hot stream is higher than the final temperature of the cold stream as shown here. This is the point is the final temperature of the cold stream and this point is the final temperature of the hot stream. In the F T diagram, if we want to represent this yet this is the scenario, in the F T diagram, we will have a F T somewhere here in the feasible region, this is called the temperature approach because this temperature is approaching this temperature. This is called temperature approach - as outlet temperature of the hot stream approaches to the outlet temperature of the cold stream. This situation is straight forward to design, since it can always be accommodated in a 1-2 shell and tube heat exchanges, and the F T value somewhere fall in this region.

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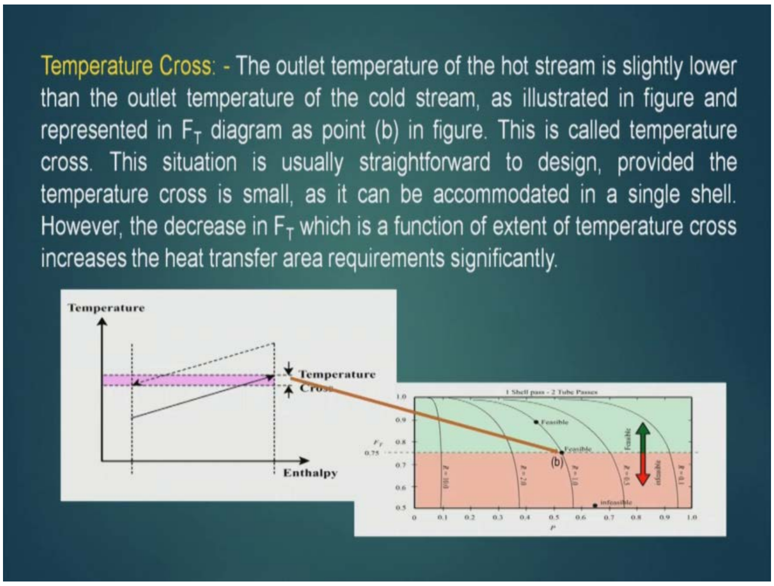

Now let see what is the temperature cross? The outlet temperature of the hot stream - this is the outlet temperature of the hot stream is slightly lower than the outlet temperature of the cold stream - this is the outlet temperature of the cold stream, so it is lower than the outlet temperature of the cold stream as illustrated in the figure. And if we want to relate this with the F T diagram then it gives you a F T value which is here; that means, it is very near to the infeasible region, but it is still in the feasible region, this is called the temperature cross. This situation is usually straightforward to design, provided with temperature crosses small, as it can be accommodated in a single shell. However, the decrease in F T which is a function of extent of temperature cross increases the heat transfer area requirements significantly.

Now, if this temperature cross, which is given by this band increases then what happens, F T drastically falls and we come into this unfeasible region. And then the designing becomes difficult and for that will show you that what are the techniques to account when temperature cross is more, where there is a large temperature cross like this, where the outlet temperature of cold stream is considerably higher than the outlet temperature of hot stream.

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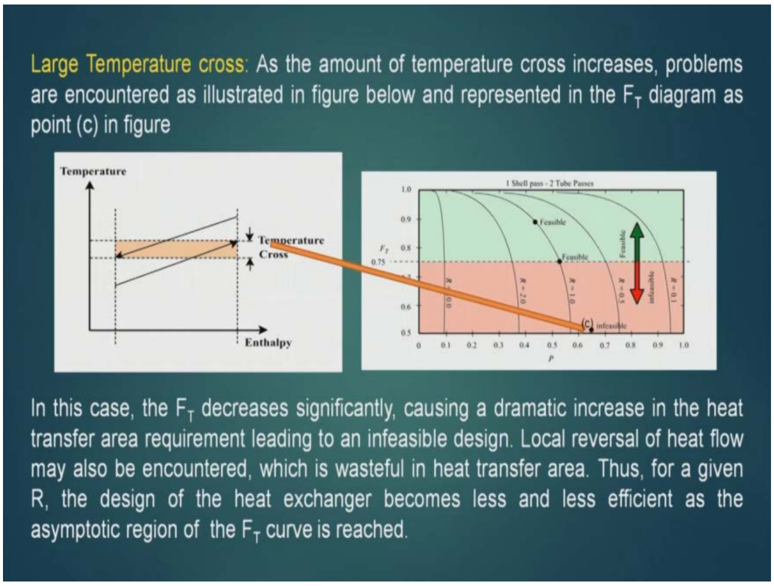

And if you relate this to the F T curve then we find that it falls somewhere here in the infeasible region. In this case, the F T decreases significantly, causing the dramatic increase in the heat transfer area requirement leading to an infeasible design. Local reversal of heat flow may also be encountered, which is wasteful in heat transfer area. Thus, for a given R the design of the heat exchanger becomes less and less efficient as a asymptotic region of the F T curve is reached. So, we will not like to design a heat exchanger in this asymptotical region, because this may lead to instability.

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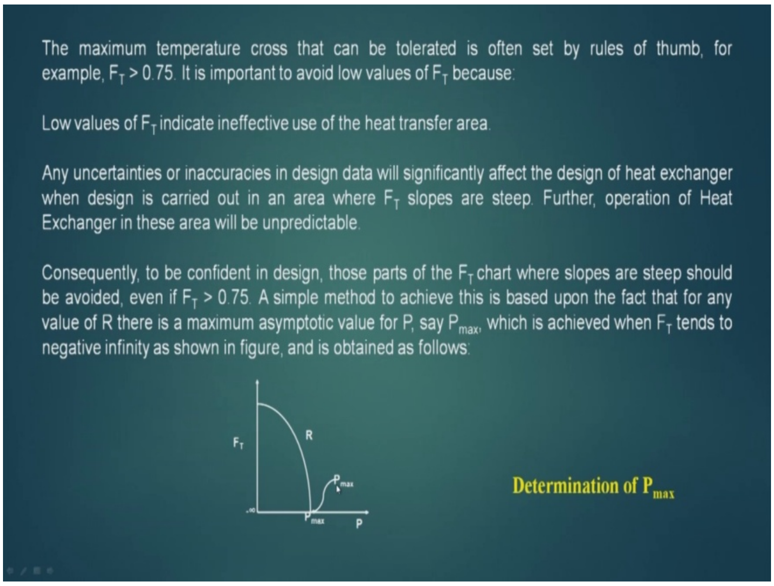

The maximum temperature cross that can be tolerated is often set by a thumb rule, for example, F T greater than 0.75. And we have seen that we have drawn this line to demarcate infeasible and feasible region, it is important to avoid low values of F T because low values of F T indicate inefficient use of heat transfer area. Any uncertainties inaccuracies designed data will significantly affect the design of the heat exchanger when design is carried out in the area where F T slopes are steep. Further, operation of heat exchanger in this area will be unpredictable.

Consequently, to be confident in design, those part of the F T chart where slope are steep should be avoided, even if F T is greater than 0.75. A simple method to achieve this is based upon the fact that for any value of R there is a maximum asymptotic value P, say P max, which is achieved when F T tends to negative infinity as shown in this figure, and is obtained as follows. Now when this F T curve we see when it reaches to minus infinite, this R asymptotically reaches to a P max value now we will see some derivation that how to compute this P max value and to find out a value of P, which will not put us in this region of design.

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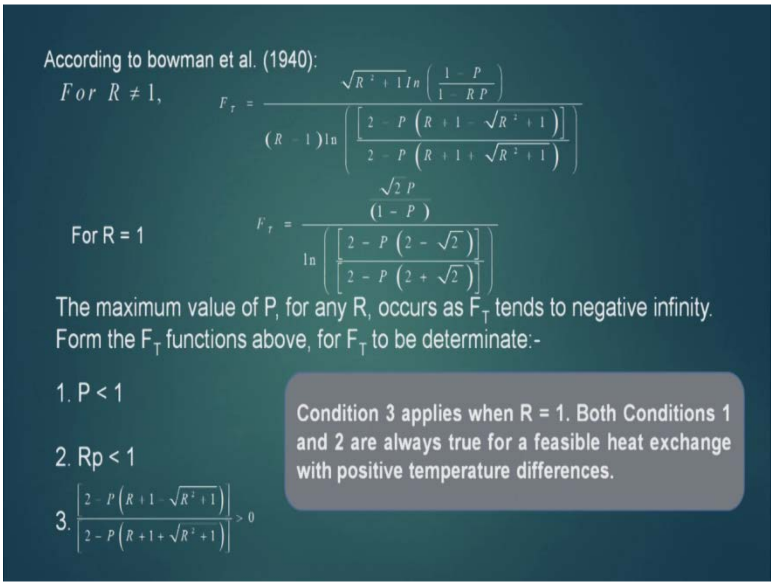

Now according to the bowman et al for R is not equal to one, this is the expression of the F T. And for the R is equal to one, this is the expression. The maximum value of P for any R occurs as F T tends to negative infinite that we have seen in the earlier figure, from the F T functions above for F T to be determinate the p should be less than one.

Because if p is less than one then the term inside the l n will not be negative and hence we would be able to compute the F T. For the R p multiplication should be less than one for this factor which is two minus p in brackets R plus one minus root over R square plus one divided by 2 minus P R plus 1 plus root over R square plus 1 should be greater than 0. So, these are the three conditions, and let us analyze one by one these conditions. The condition three applies when R is equal to 1. Both conditions one and two are always true for feasible heat exchange with positive temperature difference.

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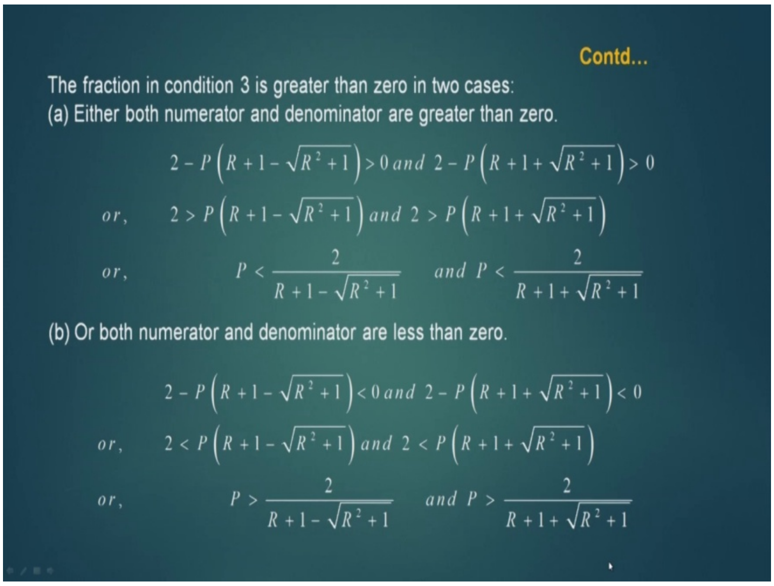

The fraction in the condition three is greater than zero in two cases. Either both the numerator and denominators are greater than zero. So, this is the condition 2 minus P and this in the bracket should be greater than zero, and this should be greater than zero. So, this gives rise to 2 should be greater than this value and 2 should be greater than this value, which gives rise to that P should be less than 2 by R plus one minus root over R square plus one, and P should be less than 2 over R plus one plus root over R square plus one.

Or there is a, b condition, both the numerator and denominator should be negative. So, they cancel it out and so, whatever we find inside the l n that is log will be positive. So, these are the conditions when both the numerator and denominators are negative. So, 2 minus P R plus 1 minus root over R square plus one should be less than zero and this should be less than zero. So, this gives rise to a condition that P should be greater than 2 divided by R plus 1 minus root over R square plus 1 and P should be greater than this.

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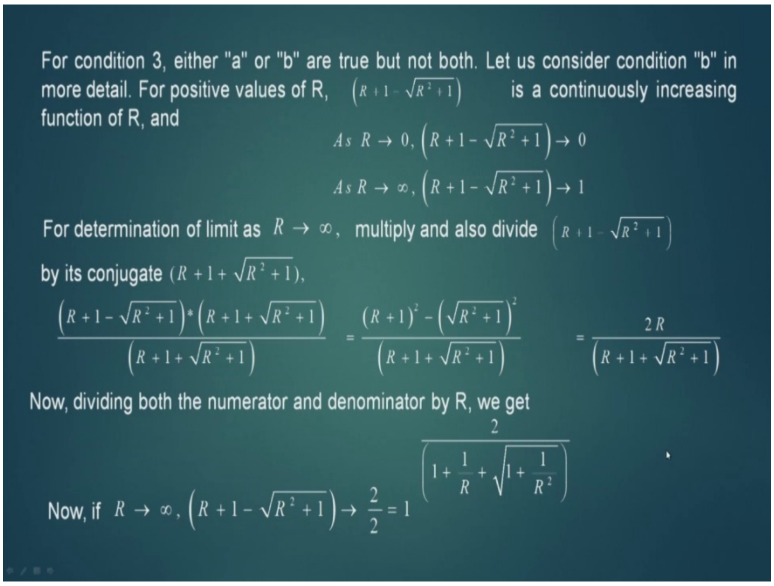

So, let us now closely examine these two conditions. For condition 3, either a or b are true, but not both. Let us consider the condition b in more detail. For positive value of R, R plus 1 minus root over R square plus 1 is a continuously increasing function of R and as R tends to 0, this value R plus 1 minus root over R square plus 1 will tend to zero. And as R tends to infinite, this tends to one; that means, if I move from zero to infinite, the maximum value which I will get for this factor will be one and minimum value zero. And if it is within this zero to infinite then the value will be less than one. For determination of the limit R tends to infinite, we have to process this a little bit. So, the processing is that multiply and also divide with its conjugate value with this which its conjugate value this. So, we multiplied by this and divide by this.

So, while doing the processing when we come to this 2 R divided by R plus 1 plus root over R square plus one. Now if you divide the numerator and denominator by R then we get a value like this 2 divided by 1 plus 1 by R root over 1 plus 1 by R square. Now this is a form which is suitable for putting R is equal to infinite. Now if we put R is equal to infinite here, then this becomes 2 by 2 which is equal to 1 and that is why we write here that as R tends to infinite then this factor tends to 1.

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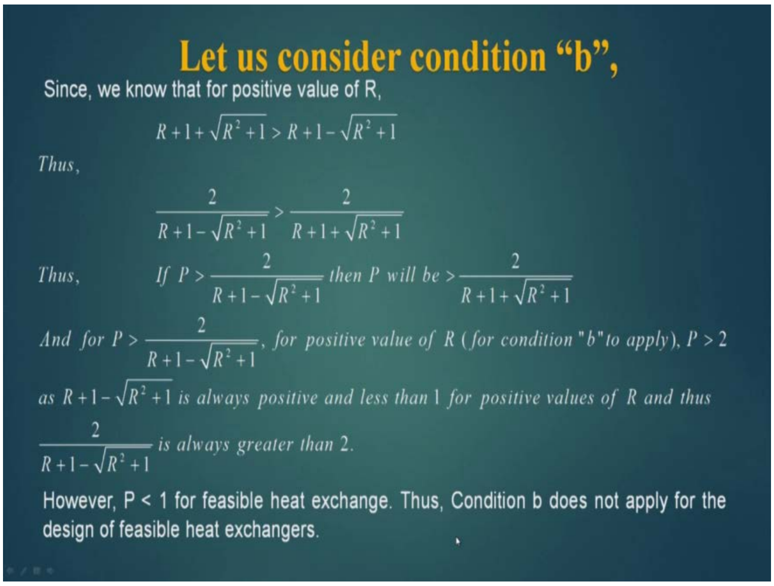

Now, let us consider the condition b. Since we know that for positive value of R, R plus 1 plus root over R square plus 1 is greater than this value. Thus 2 divided by this is greater than 2 divided by this, because this is a higher value and this is a lower value. So, when we divide by lower value this value increases. So, this is greater than 2 divided by R plus 1 plus root over R square plus 1. Thus p is greater than this value. Then p is automatically will be greater than this value, because this value R plus one minus root over R square is less than this. So, the total value is 2 divided by this R plus 1 minus root over R square plus 1 will be more, and this will be less.

So, P will be greater than this, so automatically P will be greater than this value. And for P to be greater than 2 divided by R plus 1 minus root over R square plus 1 for positive values of R, for condition b to apply then P becomes greater than 2. Now we have seen that in the earlier case, P has to be less than one. So, as R plus 1 root over R square plus 1 is always positive and less than 1; for positive values of R and thus this is always greater than 2. However, P is less than 1 for feasible heat exchanger design and what we are finding that P is becoming more than two, thus the condition b does not apply for the design of feasible heat exchangers. So, what conclusion we make that the condition b does not apply for the feasible design of heat exchanger a. So, the condition a is only left out. So, we will again chase check the condition a.

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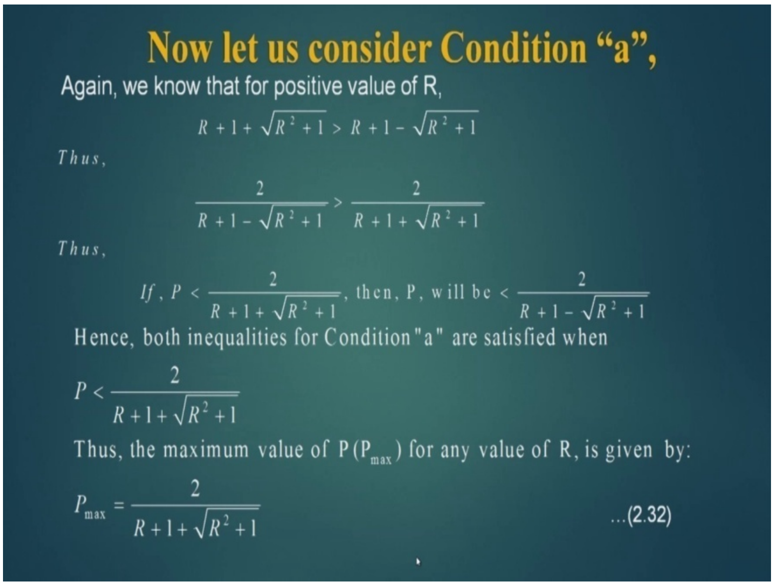

So, let us now consider the condition a. Again we know that positive value of R, this is greater than this; that means, R plus 1 plus root over R square plus 1 will be greater than R plus 1 minus root over R square plus 1. Thus if I take this form that is 2 divided by R plus 1 minus root over R square plus 1, so this will be greater than 2 divided by R plus 1 plus root over R square plus 1, because this value is less. So, when I divide it, this value will be more than this. Now if P is less than this value which is less out of these two then p will be automatically less than this value, because this value is more than this. So, if P is this value is greater than P then automatically this would be greater than p.

Hence both the inequalities for condition a are satisfied when P is less than 2 by R plus 1 by R square plus 1. And thus the maximum value of P max for any value of R is given by this, because this satisfies that it will be the P will be less than 1. And if I take this value, we have already proved that it will be more than 1, and hence the only condition that satisfies p max is this. So P max is equal to 2 divided by R plus 1 plus root over R square plus 1.

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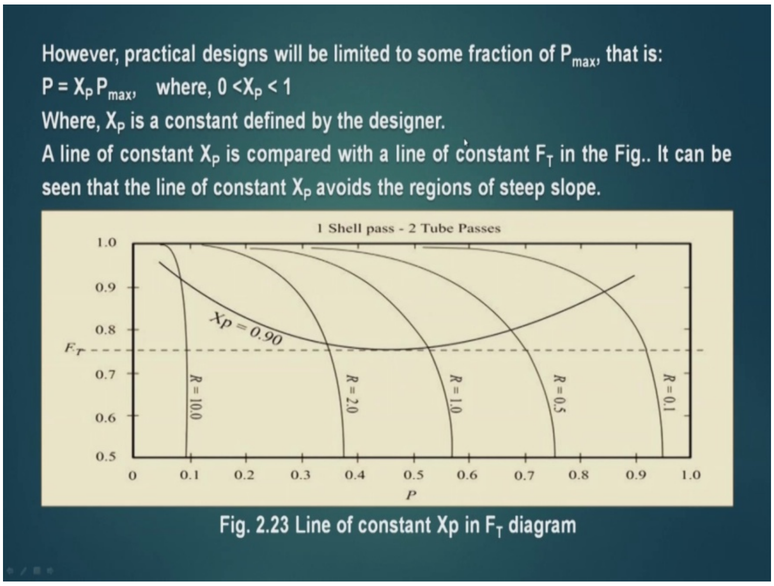

Fig. 2.23 Line of constant Xp in F_T diagram

However, practical designs will be limited to some fraction of P max. So, to do this what we tell that P is equal to X P into P max, but X P varies between 0 to 1. So, where X P is a constant defined by the designer. Now if you take X P is equal to 0.9, so this is the line of X P 0.9. So, we will see like this cutting this F T curves in those areas where the steepness is less; that means, we are almost in the feasible design zone of the heat exchanger, if I am considering x p is equal to 0.9. So, a line of constant X P is compared with the line of constant F T in the figure, it can be seen that the line of constant X P avoids the regions of steep slope.

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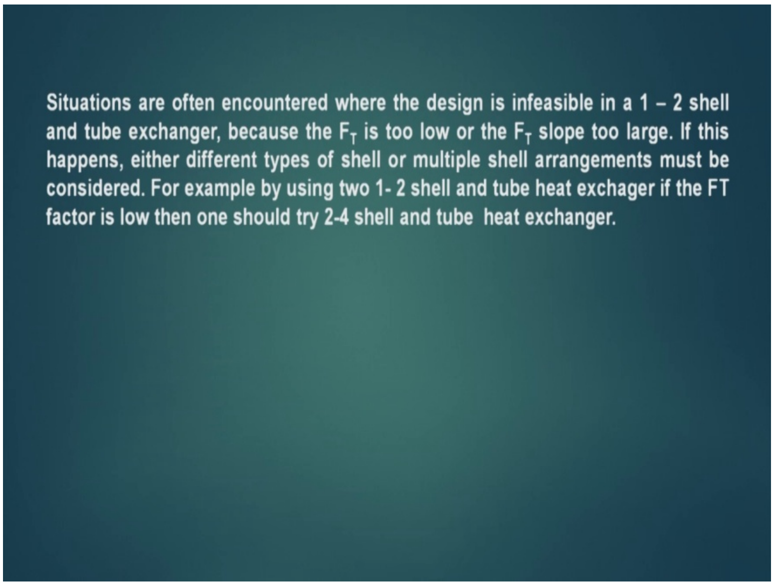

Now situations are often encountered when the design is infeasible in a 1-2 shell and heat exchanger, because the F T is too low, or the F T slopes are too high or too large or F T slope is steep. If this happens, either different types of shell or multi shell arrangement must be considered. For example, by using two 1-2 shell and tube heat exchanger the F T factor is low then one should go for 2-4 shell and tube heat exchangers. Or if in one heat exchanger, which is 1-2 shell and tube heat exchanger, the F T factor is low then I should go for two shell and tube heat exchangers one to type seven tube exchangers to improve the F T.

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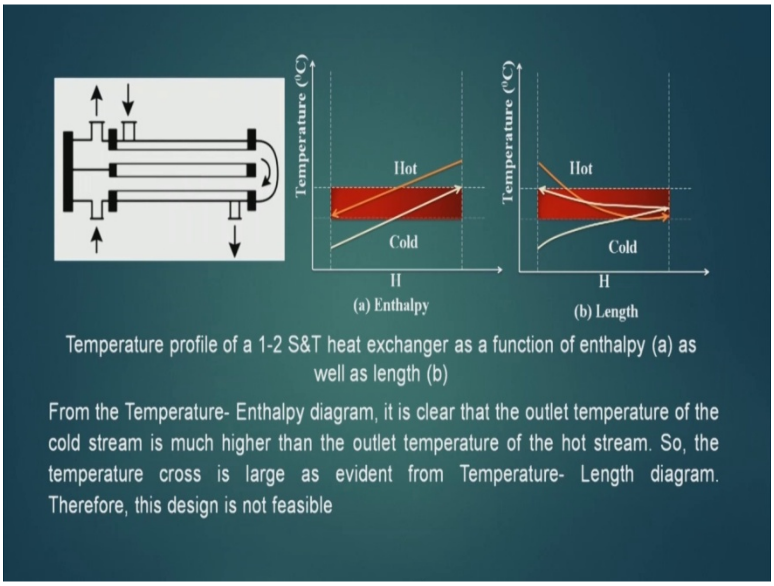

So, let us see this concept. Now here we see this is a one tube shell and tube heat exchanger. We are plotting two things that enthalpy h axis is enthalpy; h axis is also length, so here we also see a considerable temperature cross. And if we brought it in terms of length then here the cold stream temperature increases, and then further it increases in the second pass, this is the first pass, and this will be the second pass for liquid. So, from the temperature-enthalpy diagram, it is clear that the outlet temperature of the cold stream is much higher than the outlet temperature of the hot stream. So, the temperature cross is large as evident form temperature-length diagram. Therefore, this design is not feasible. So, if I get such a plot, then I can clearly tell the temperature cross is large and this design is not feasible. Why this design is not feasible, because it will require extremely large area and the heat transfer areas will not be used efficiently in the heat exchanger.

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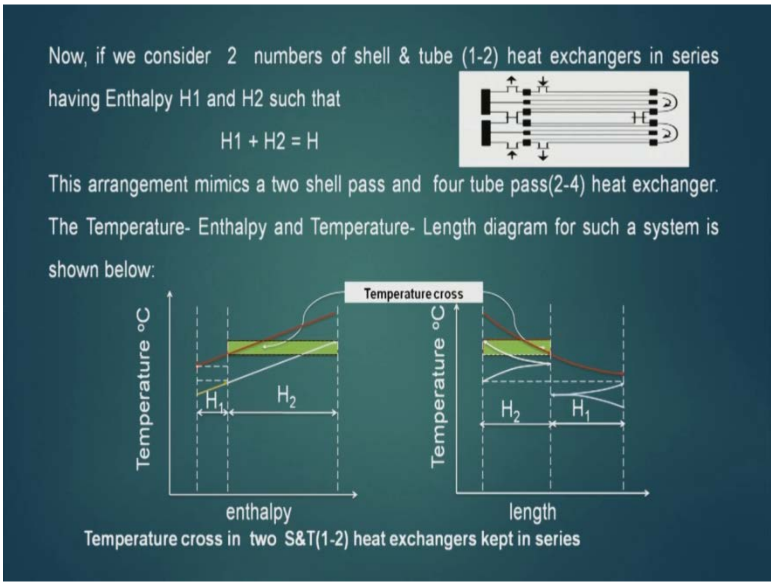

So, my aim will be to improve the F T factor. So, the improvement can be done by joining two one to seven tube heat exchangers in series. So, now, we consider two numbers of shell and tube heat exchangers in series having enthalpy H 1 and H 2 such that H 1 plus H 2 is H and this is H is our demanded H P enthalpy; that means, the load for heat exchangers. This arrangement mimics a two shell pass and four tube pass heat exchangers which is called 2-4 heat exchanger.

The temperature-enthalpy and temperature-length diagram for such a system is shown below. So, if I see here, here I find no temperature cross, but here I find certain temperature cross. Now if I analyze the shells here then I find that this temperature clot is not large small temperature cross which can be accommodated. And here this shell does not have the temperature cross. So, by increasing the number of shell passes, we can distribute the temperature cross or we can decrease the temperature cross, and hence the F T factor increases, and we move towards feasible design.

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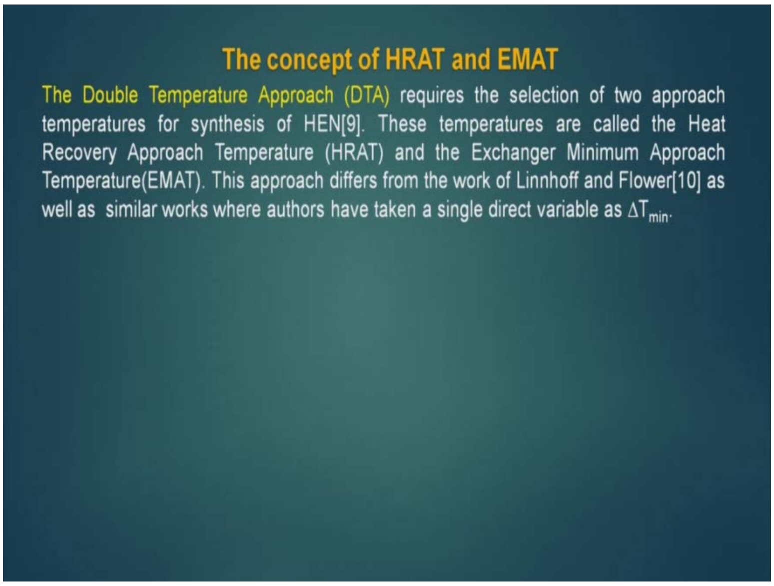

Now let us see a new concept, the concept of HRAT and EMAT, EMAT and HRAT. This concept is based on a double temperature approach for the design of heat exchanger network. The double temperature approach DTA requires the selection of two approach temperature for synthesis of HEN. These temperatures are called the heat recovery approach temperature – HRAT, and the exchanger minimum approach temperature – EMAT. This approach differs from the work of Linnhoff and Flower as well as similar works where authors have taken a single direct variable as delta T minimum. We have seen that in most of the cases of heat integration, a single variable is taken and that is delta T minimum. Here we see that two variables can be accommodated for this purposes, and let us see what is the definition of HRAT and EMAT?

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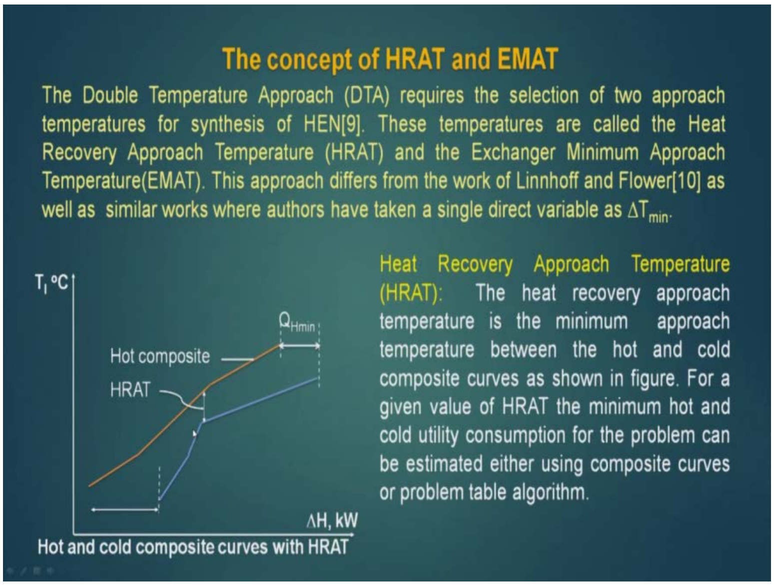

Now this was the hot composite curve, and this was the cold composite curve. And both composite curves come close closest at this point. So, this temperature drop delta T is called HRAT. So, heat recovery approach temperature - HRAT is the heat recovery approach temperature is minimum approach temperature between the hot and cold composite curves as shown in figures. For a given value of HRAT, the minimum hot and cold utility consumption for the problem can be estimated either using composite curves or problem table algorithm. So, we have seen that the out to define the HRAT, it is the minimum temperature difference between this hot composite curve and cold composite curve when they come closest to each other.

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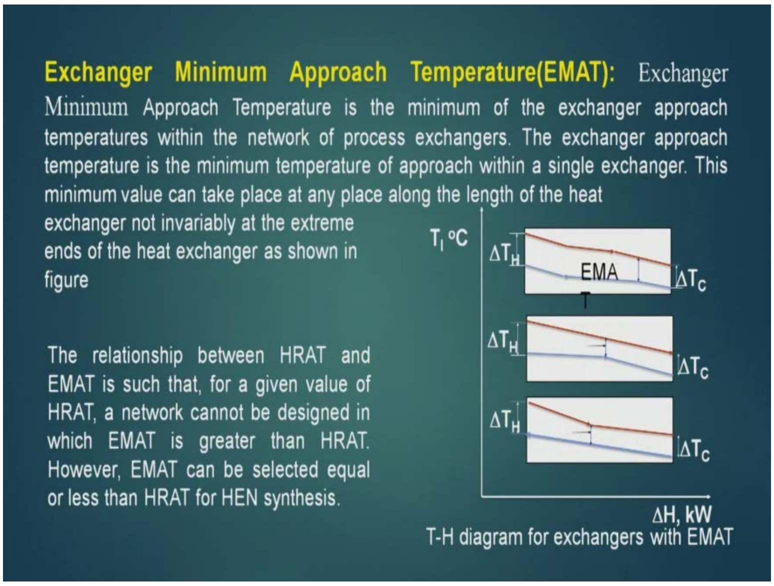

Now there is another temperature, which is called the exchanger minimum approach temperature - EMAT. Exchanger minimum approach temperature is the minimum of the exchanger approach temperatures within the network of process exchangers. So, if we examine all the heat exchangers available in the network, and try to find out their minimum exchange temperatures then exchanger minimum approach temperature is the minimum of the exchanger approach temperatures within the network of process exchangers. The exchanger approach temperature is the minimum temperature of a approach within a single exchanger. Now if we see the single exchanger here, this is the delta T at one end and this is delta T at the other end, we may find that the minimum temperature may be here, maybe here, may be here; that means, the minimum temperature delta T may be at the edges or inside the heat exchanger along the length.

So, if we compute this minimum delta T, which is called the exchanger approach temperatures, then changer minimum approach temperature will be minimum of all minimum approach temperatures of all the heat exchangers in the network. This minimum value can take place at any place along the length of the heat exchanger not invariably at the extreme ends of the heat exchanger as shown in the figure. The relationship, now let us see the relationship between HRAT and EMAT, why we are defining these two temperatures. The relationship between HRAT and EMAT is such that for a given value of HRAT, a network cannot be designed in which EMAT is greater than HRAT. So, this is the condition for the design of heat exchanger network. However, EMAT can be selected equal or less than HRAT for HEN synthesis.

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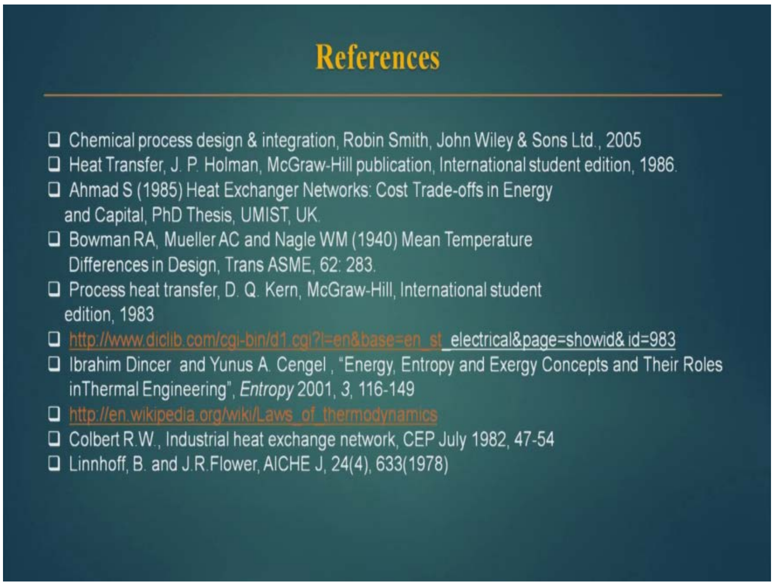

Now these are the references.

Thank you.