Cryogenic Engineering
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Module No. # 01
Lecture No. # 28
Cryocoolers Ideal Stirling cycle

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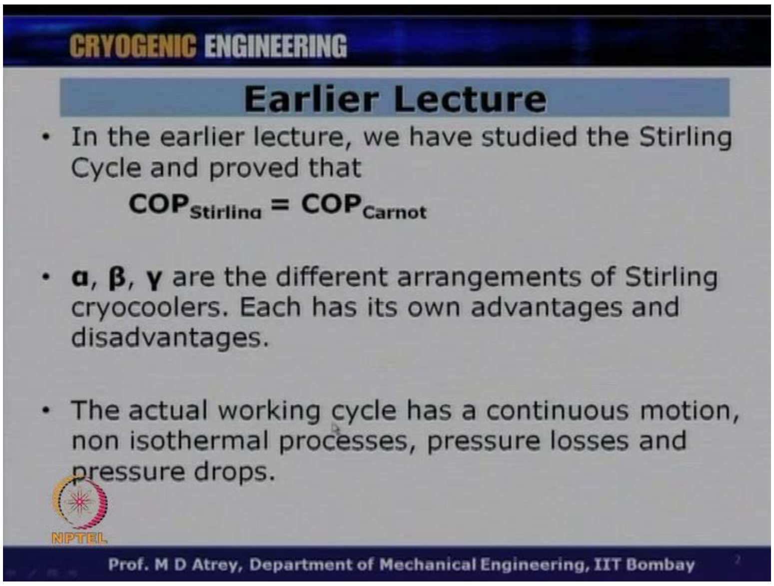

So, welcome to the twentieth lecture of cryogenic engineering under the NPTEL program. In the last lecture we were talking about stirling cycle cryocoolers. So, we have studied the stirling cycle in that and we proved that the COP of sterling cycle is equal to that of COP of carnot cycle. This COP is highest and it is as high as COP given by a carnot cycle working in the same temperature limits. We also found that alpha, beta, gamma are the different arrangements of stirling cryocoolers and each of them has its own advantages and disadvantages.

This classification of alpha, beta and gamma of different cryocoolers was based upon the position of or the arrangement of the drive of the piston and the displacer or a piston and a piston arrangements, that is used for a stirling cryocooler. We also found that the actual working cycle has a continuous motion of piston or displacer. While in ideal stirling cycle, it focuses most on the discontinuous motion of piston and displacer. While in actual case it is not easy to give the discontinuous motion and therefore, will have a continuous motion of piston and displacer, will have an non isothermal process. While the actual cycle demands, the ideal cycle demands isothermal processes. We have got in actual system, we will have pressure losses and pressure drops. So, in fact what we say from here, is the actual system will have more of losses. The actual system will try to go toward more practical system and therefore, the ideal system of isothermal processes cost and volume processes may not be assured in actual practice.

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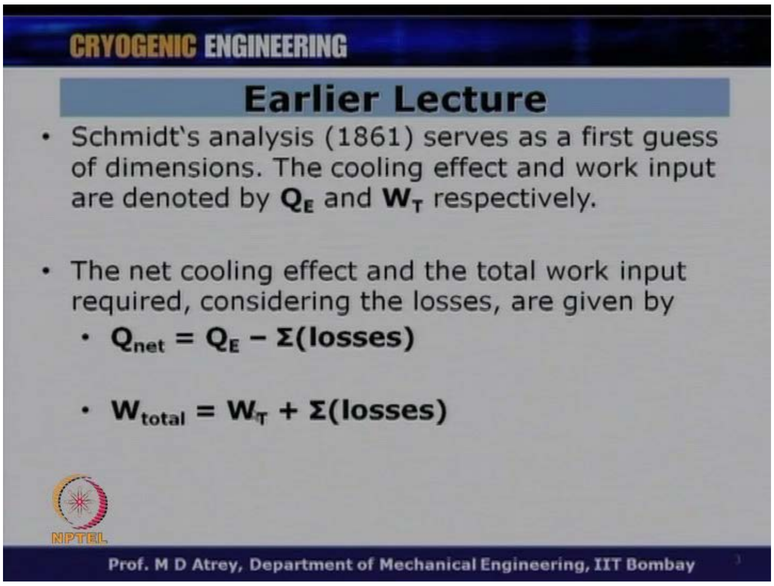

We studied Schmidt's analysis, which was given in 1861 and what we also observed what it serves as a first guess of dimensions; that means, if I want to design a cryocooler the first guess would be given by the Schmidt's analysis. We can talk about what is the diameter of the piston, what is the stroke of the piston or stroke of the displacer diameter of the displacer depending on whatever arrangement we choose to have. The cooling effect and the work input are denoted by Q E and W T respectively. And we are derived the expressions for Q E and W T for ideal Schmidt's cycle.

The only realistic assumption was in the Schmidt's analysis was that it have a continuous motion of piston and displacer, while in ideal stirling cycle as I earlier said the continuous motion of displacer and piston is not considered. What is considered is a discontinuous motion of piston and displacer. So, Schmidt's analysis was a step towards a realistic analysis taken in 1861.

We also studied that the net cooling effect and the total work input required will be considering losses, while Schmidt's analysis will not consider those losses Q E and W T are actually kind of ideal assumption still as far as Schmidt's analysis is concerned. So, if we consider the losses, the Q net that is the actual Q delivered, actual cooling power delivered will be Q E predicted by Schmidt's analysis minus various losses in a system. So, minus sigma losses.

Similarly, the work input W total is equal to W T predicted by the Schmidt's analysis plus various losses that is plus sigma losses. So, in order to relate my Q E given by Schmidt's losses to the actual case, actual Q net delivered, I have to calculate all these losses and then subtract those losses from Q E, that will give me the Q net delivered by a cryocooler. Similarly, I will have to add all those losses, which will cause me more work input to be done and this losses will be calculated and added to the W T calculated by Schmidt's analysis and this will give me W total for a practical system.

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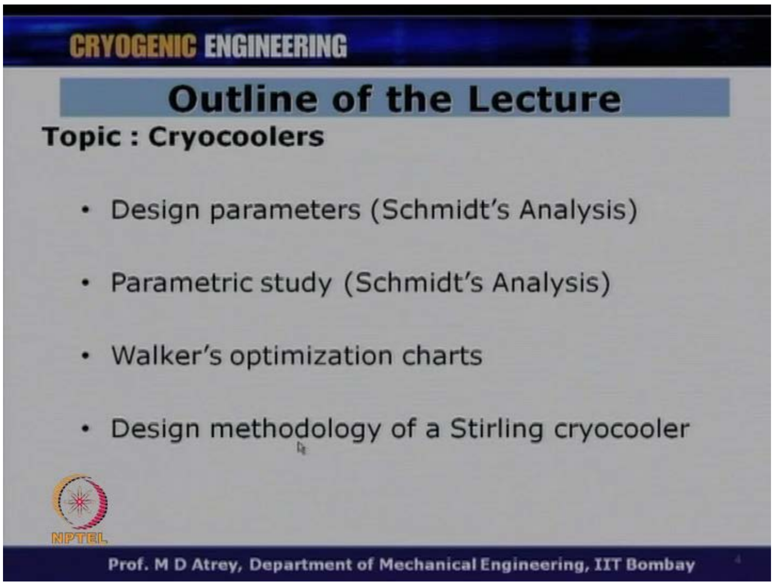

Outline of this lecture again extending from cryocoolers. Now, I will go to discuss, what are design parameters considering Schmidt's analysis, understand the effect of those design parameters and therefore, we will have parametric studies again based on Schmidt's analysis. Then we will have Walker's optimization chart and this is a very important optimum design specifications that could be opted using Schmidt's analysis. And from Schmidt's analysis, we will have Walker's optimization chart and here for the first time, we will derive those dimensions which will give an optimum combination of all these parameters.

And finally, using this Schmidt's analysis and Walker's design charts we will have a design methodology of a stirling cryocooler and this would give us a first guess of dimensions for any crycooler to be designed for a given cooling capacity. So, we will solve all this things and we will have a tutorial at the end. So, that the usage is known to you.

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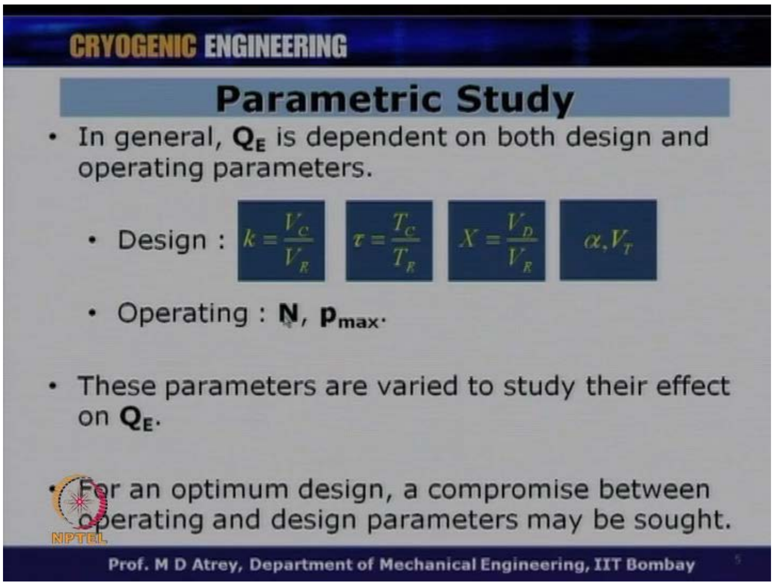

Let us have parametric studies, in general Q E is dependent on both design and operating parameters. So, all the parameters which affected design of a cryocoolers can be clubbed under two parameters, which is design parameters and operating parameters.

What are design parameters? The design parameters are the one, which cannot be changed. So, once the design is made, you cannot change those parameters. And therefore, they are mostly related to the design aspect or dimensional aspects. So, if I talk about the design parameters and if I talk about those non dimensionalized design parameters, we have got k which is equal to V C by V E the ratio of 2 volumes 2 swept volumes then tau is a T C by T E. This is basically what cold temperature; we have designed this cryocooler for. Once I have designed for a particular cold temperature I cannot change that parameter because the design will be carried out for that T C in mind.

Similarly, what is my dead volume ratio which is X dead volume ratio is nothing, but ratio of dead volume to the all the dead volume in the system to the swept volume in the expansion space for the cryocooler. And then alpha which is a phase angle between the expander and the piston motion, while V T is nothing, but V C plus V E that is total swept volume, this all could be clubbed as design parameter.

Similarly, we have got operating parameters, which can be changed later. So, once the design is carried out, I can still change the speed if I want to or I can still change the maximum pressure generated in a system by changing the charging pressure of the gas in the system. So, that it affects both p max and p minimum by a formula which we have derived earlier in Schmidt's analysis. So, these two parameters may be called as operating parameters because they can be changed by operator. They are not an inherent part taken in the design, in the sense they can be changed from outside.

However, these two parameters have to be considered in design analysis. So, the design is carried out for a particular N or particular p max, but these parameters can still be changed even after the design is made. This parameters are varied to study the effect on Q E. Now let us see, what is the effect of all these parameters on Q E? which is the cooling load that could be produced by the cryocooler.

For an optimum design a compromise between operating and design parameters may be sort. So, all these parameters may give a different variations of different parameters. So, what we have to go is an optimum combination of all these parameter. So, that I get maximum cooling effect or I get minimum power input or I get maximum COP or whatever design optimum design you want to carry it for that that can be optimized as a combination of all these parameters.

There are a 1, 2, 3, 4, 5, 6, 6 or 7 parameters which needs to be optimized, of which we can take few for granted; that means, they can be fixed and a design can be varied out for remaining 3 or 4 parameters.

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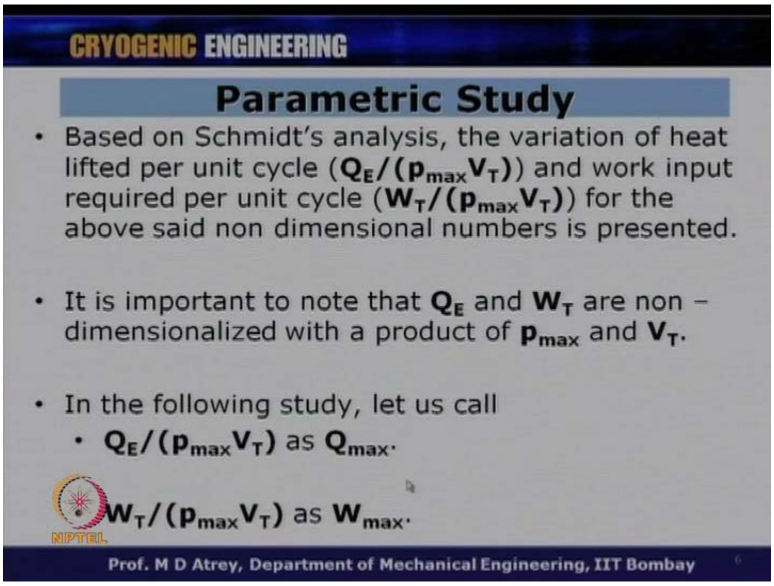

So, based on the Schmidt's analysis, the variation of heat lifted per unit cycle, which is Q E upon p max into V T, this the Q E here is heat lifted per unit cycle, p max is maximum pressure and V T is a total swept volume in the system.

So, if you see Q E upon p max by V T is basically p max into V T is basically a non dimensional parameter and work input required per unit cycle, which is W T divided by p max into V T, for the above said non dimensional number is presented. What does it mean? I will I would like to see what is Q E upon P max into V T? Similarly, what is W T into upon P max into V T? And we can see the variation of all the design and operating parameter as a function. So, that what is this non dimensional parameter would be, how does it behave?

So, Q E upon p max into V T becomes a non dimensional parameter. Similarly, W T upon p max into V T becomes a non dimensional parameter. So, this parameter basically talks about the cooling effect generated per cycle, while this parameter talks about a work input required per cycle. It is important to note that Q E and W T are non dimensionalized with a product of p max into p max and volume p max into V T.

In the following study, let us call Q E upon p max into V T as Q max. It is just a simplicity to address this parameters as. So, we have got a Q max, which is nothing, but Q E upon pmax into V T and we have W max which is nothing, but W T upon P max into V T. So, I would like to study now, what are the variation of Q max and W max as a function of different design parameters. So, let us study the effect of Q max and W max and vary those parameters and understand, how Q max and W max vary because these are the most important parameters related to the design of a cryocooler.

What is the cooling effect I get from this cryocooler? What is the power input to this cryocooler? In fact, this divided by this will become the COP of the system, if you understand. Because p max into V T is common to both the cases. So, here the most important parameter, I would like to see as a function of different parameters. So, let us take the first parameter as a temperature at the expansion space, that is the coldest temperature T E for which the entire cryocooler has been designed. This is the T E at which Q E is obtained. So, cooling effect is obtained at a particular temperature T E.

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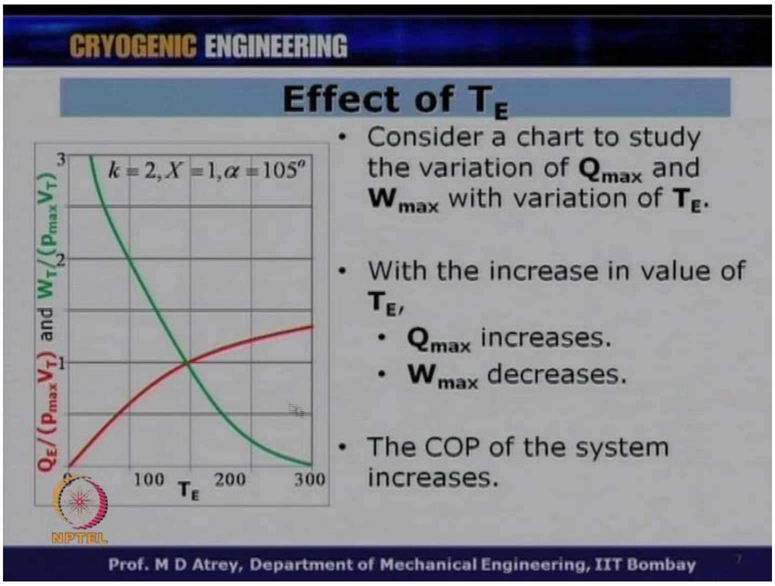

So, let us study the effect of this parameter and this is my y axis and this is my x axis and on x axis you can see, I have put T E given in kelvin, over here while on the y axis I can show both the parameters as Q max and W max. So, the red curve will show a relationship between Q max to T E and the green curve will show the relationship of the W max to T E. And these curves are plotted for given parameters as k is equal to 2, X is equal to 1 and alpha is equal to 105 degrees. So, these 3 parameters are kept constant and only T E E is varied, in order to study the effect of variation of T E on Q max and W max.

So, this is what variation you can see. So, consider a chart to study the variation of Q max and W max with variation of T E. Now what do you see? As you go on increase the value of T E; that means, as the cold end temperature increases, it is basically coming to room temperature 300 kelvin is nothing, but room temperature. And you can very well understand that as the colder end temperature increases, the cooling effect increases; that means, the Q max value given by this red curve will increase. This is absolutely clear that as you increase the lower end temperature, the value of T E the cooling effect will increase, while at the same time the power input required will go on decreasing.

So, if my cooler end temperature or the expansion space temperature increases, the cooling effect increases and the W max or the power input will decrease. Thereby, increasing the COP of the machine, I think this effect is very very clear with the knowledge of refrigeration for example, you have that as the cold end temperature increases, refrigeration effect will increase. At the same time power input will decrease.

So, with the increase in the value of T, let us summarize here. Q max increases, which is in by this red curve and W max decreases, which is in by this green curve. As a result of which, the COP of the system increases and this is what is obvious from the system.

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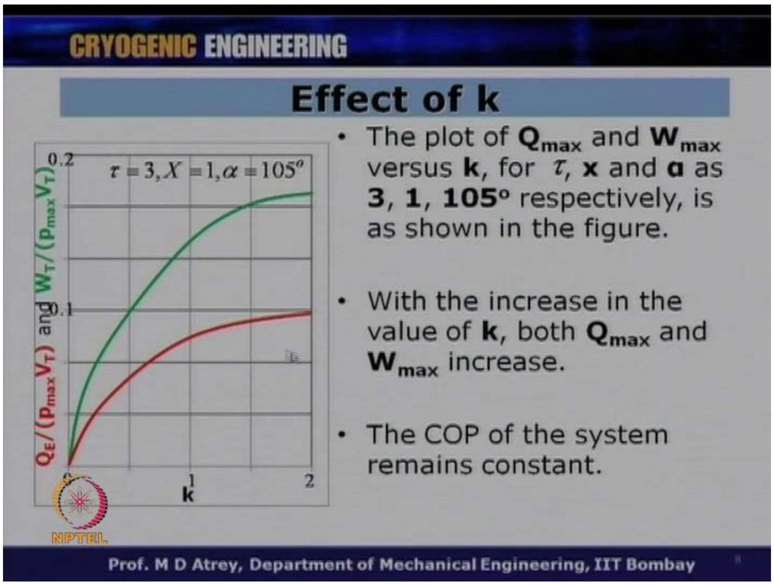

The next effect is effect of k, which is the ratio of swept volumes that is V C by V E. Again this curve is plotted for both the parameters Q max and W max and here now we have kept temperatures tau is equal to 3; that means, my both the temperatures are fixed

T C and T E are fixed, the data volume ratio is taken as 1, while alpha is still taken as 105 degrees, which is nothing, but the phase angle between the expansion and compression volume variations.

On x axis what has been plotted is k value, the plot of Q max and W max versus k, for tau, X alpha as 3, 1 and 105 degrees respectively, is as shown in this figure. So, what do you see from this figure? It means that as the swept volume ratio is increased; that means, as V C by V E gets increase, the cooling effect Q max will start increasing. Because the flow rate will increase, as my V C by V E increases, I am getting more and more volume of gas getting compressed over here. And similarly, because I am compressing more and more gas, my power input system will also increase thereby, increase W max.

So, both as a value of k increases, the Q max will increase and W max also will increase, but can I go on increasing this forever. No, I cannot, at a particular point I will the curve will get flattened, over there at the particular point the curve will get flattened over there. So, with the increase in the value of k, both Q max and W max increase, the COP of the system remains constant because by Schmidt's analysis the COP of the ideal stirling cycle depends only on the value of tau, while we have kept the value of tau to be constant. So, even if I go on increasing the value of k, W max to Q max ratio will always remain constant at whatever k value we are talking about.

So, for a given value of X, if I go on increasing the value of k, which is very important for a given value of tau and X, if I go on increasing the value of k and Q max and W max will go on increasing and the curve will get flattened over there. Because the X value also is limited in that sense, the ratio is limited to one in this particular case. The COP of the system remains constant because we have seen that the COP of the system depends only on the value of tau, while increase of K will not affect the COP, but it will increase the Q max as well as W T or W max.

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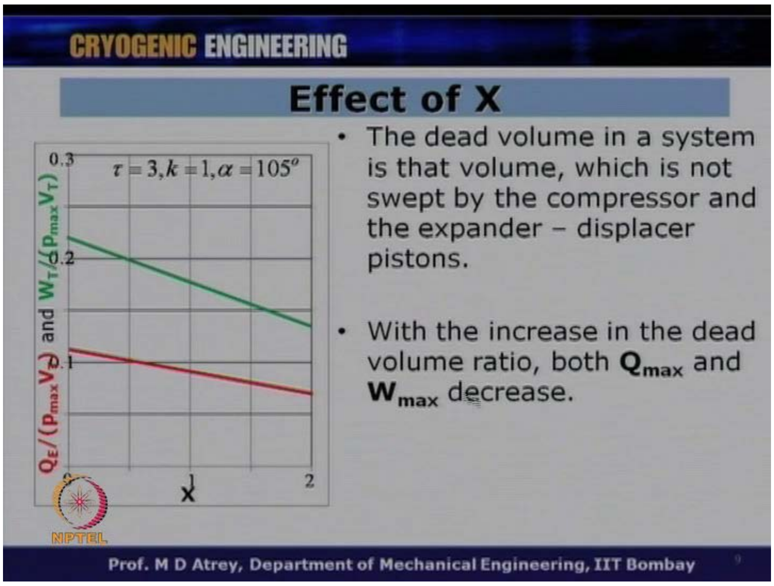

The next parameters to be studied is the effect of X or the dead volume ratio. So, again as you say the dead volume in a system is that volume, which is not swept by compressor and the expander displacer or expander piston; that means, the whatever volume is there which is not traverse by pistons or displacer is what we call as dead volume. For example, all the heat exchanger volume will be a dead volume because it is not travelled by the compressor piston or the expander displacer.

So, here when I want to study about effect of X on Q max and W max, I have kept now tau k and alpha as fixed, k has been taken equal to 1; that means, V C by V E is equal to 1. So, what do you see from this curves? What do you see from this curve is as we increase the value of X; that means, as we go on increasing the value of dead volume in a system for a given expansion volume because X is nothing, but V D upon V E. So, if I go on increasing the value of X, we can see that the Q max decreases at the same time W max also decreases.

So, with the increase in the dead volume ratio, both Q max and W max decrease; that means, additional of dead volume addition of dead volume is actually detrimental from the performance point of view or from the cooling effect point of view. At the same time the work input has also reduced. So, again the COP of the system, what you can see from here is going to be remaining constant because COP depends only on the value of tau and this is as far as ideal stirling cycle is considering actual system the things will change.

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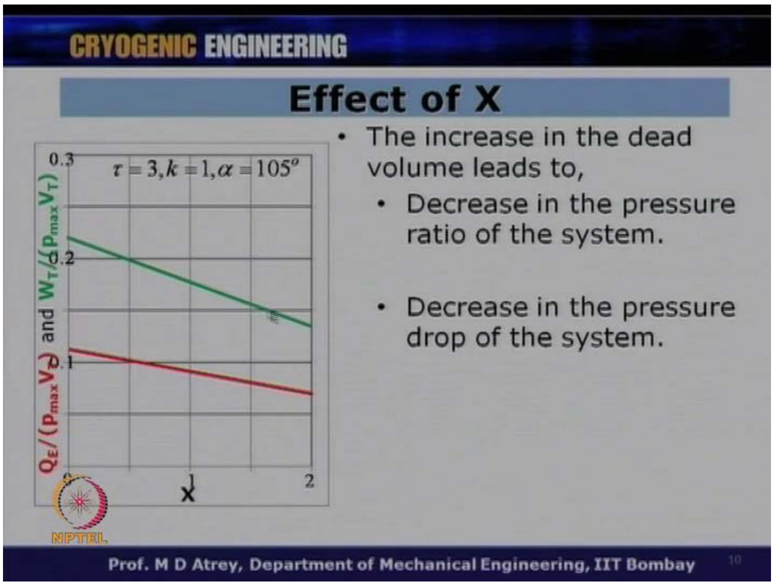

What is happening basically? Why in the with the increase of X, my Q E decreases, Q max decrease, as well as my W max increases. So, increase in the dead volume leads to decrease in the pressure ratio of the system. So, as I have got more and more volume now, which is not a swept volume, which is a dead volume. My pressure ratio ratio p max to p minimum will decrease and the moment your p max to p minimum will decrease the the ratio decreases, it will result in lowering of Q max or cooling effect. And therefore, increase in X will result in decrease in the value of Q Q max.

Also there will be decrease in pressure of in a system, but this is not considered, pressure drop losses are not considered in a Schmidt's analysis, but in actual system pressure drop losses in system will decrease in this with the result of increase in the value of dead volume ratio. So, what is most important is the pressure ratio in the system decreases and this is what leads to decrease in cooling effect, as well as decrease in W max or the power input to the system.

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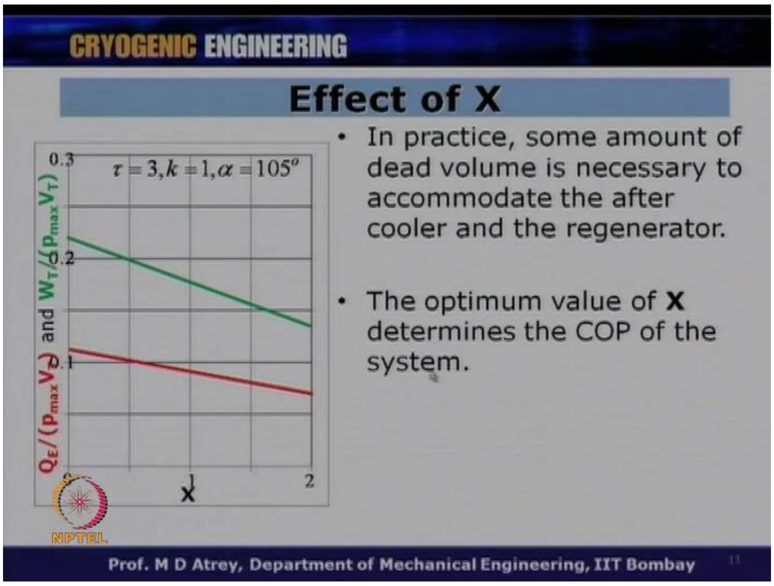

It increase the value of X, your p max will come down. And as a result of which the W max will decrease, as well as Q max will decrease. However, what does it mean, that I should keep value of X to be very small as as small as possible. This is what one would expect, but that is not a practical solution. Because in practice, some amount of dead volume is always necessary to accommodate the after cooler and the regenerator. These are heat exchangers and heat exchanger volumes are nothing, but dead volumes, but there has to be some optimum value of X, which will accommodate the dead volume generated because of the presence of after cooler and the regenerator. And this is most important, this is very very important.

So, some amount of dead volume is always important, is very very important, which will sacrifice some amount of Q max basically, while W max will get get lowered. So, we have to have some amount of X, which possibly able to X is equal to 8. I cannot have X is equal to 0, for actual design. So, I have to have some value of X or 1.2, 0.8 or something like that. So, that my regenerator volume and after cooler volume is taken care of.

So, effect of X basically one would like to keep X as small as possible, but some amount of X or some amount of dead volume is going to be always existent in a cryocooler. The optimum value of X will determine then the COP of a system. In a actual case, in actual system, the actual volume of COP will be determined by the value of X. There exists a phase angle. Now, we see effect of phase angle on Q max and W max, this phase angle is nothing, but the angle by which the expansion space volume variation lead the compression space volume variation, which is what we had seen earlier.

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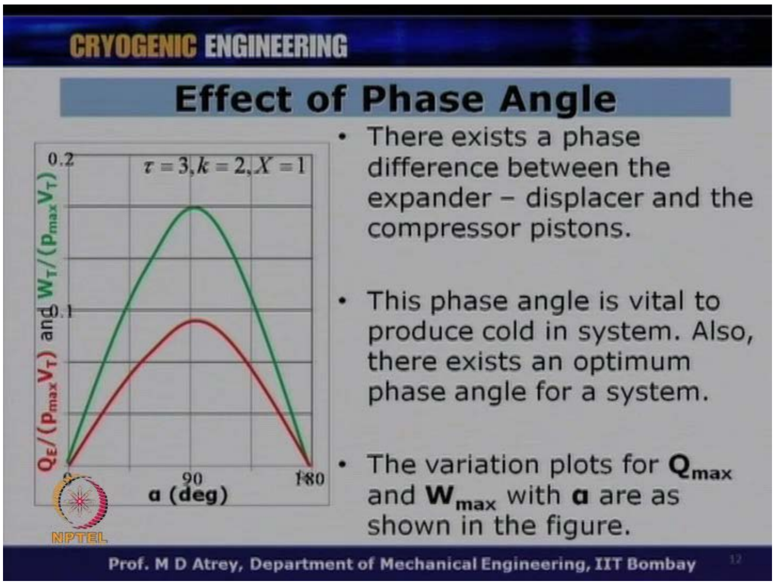

So, x axis is plotted with alpha in degrees, while these values are taken as tau is equal to 3, k is equal to 2 and X is equal to 1. So, there exists a phase (( )) phase difference between the expander displacer and the compressor piston, this could be expander piston, also if it is a working as a piston and not as a displacer. This phase angle is vital to produce cold in the system; also there exists an optimum phase angle for a system.

For example if the phase angle is 0, you will not get any cooling effect. This is very important, there has to be some phase angle and this phase angle has to be an optimum phase angle basically. So, if I just plot Q max and W max variation against alpha, what we can see that? Both the both these curve go through maximum in the travel during this alpha, the variation plots of Q max and W max with alpha are as shown in this figure.

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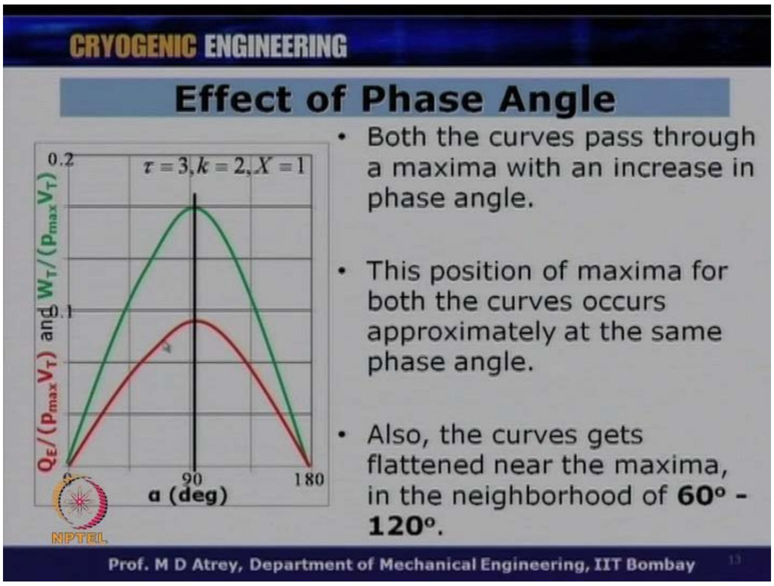

And what we see, both the curve pass through a maximum with an increase in the phase angle. The position of maxima for both the curves occur approximately at the same phase angle. So, what you can see that, this is going to be maximum somewhere around 90, very close to 90 and W max is maximum for that phase angle and Q max is maximum for that particular phase angle. And also what you can see that, also the curve gets flattened near the maxima, in the neighborhood 60 to 120 degree.

That means, this increase is very very high and you can see that if I have alpha is equal to 60 to kind of 120. The change in this maximum and this value is not that drastic; that means, I can have an alpha ranging from 60 to 120, if I have to sacrifice this alpha for some mechanical limitation. If I cannot have alpha is equal to 90 to touch this peak. I can as well have alpha between this 60 to 120, where I say that, I do not sacrifice so much on Q max and W max. So, that is why I say that, the sensitivity of W max and Q max is not that high in this region, while if you go beyond that it is very high. In this case, in this part below 60 and after 120, the variations in Q max and W max is quite drastic for the variations in alpha. And therefore, my alpha should, I should see that alpha remains between 60 and 120 as far as possible.

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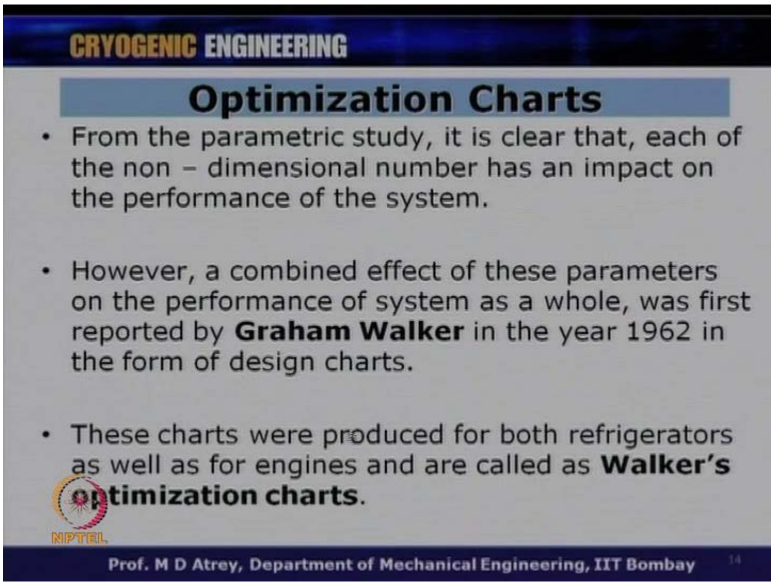

Now, you have seen that, there are so many charts which exist. So many parameters which exist and the variation of Q max and W max is different for these variations of the parameters. From the parametric study, it is clear that each of the non dimensional parameter has an impact on the performance of the system. However, a combine effect of this parameters on the performance of the system as a whole was first reported by Graham Walker in the year 1962, in the form of design charts.

So, Walker was the person, who first studied all the effect of this parameters and he came up with some design charts. And these charts were produced for both refrigerators as well as for stirling engines and they are called as Walker's design optimization chart or Walker's optimization chart. So, he was the one who extended Schmidt's analysis and got all these parameters optimized and converted to optimization into some kind of design optimization chart and they are called as Walker's optimization chart.

See if I got so much of variations of k, X, alpha etcetera, I can refer to Walker's optimization chart and get those parameters for a cryocooler to be designed for a particular cooling effect at a given T E or a given cooling temperature. So, let us see what are these optimization chart refer to.

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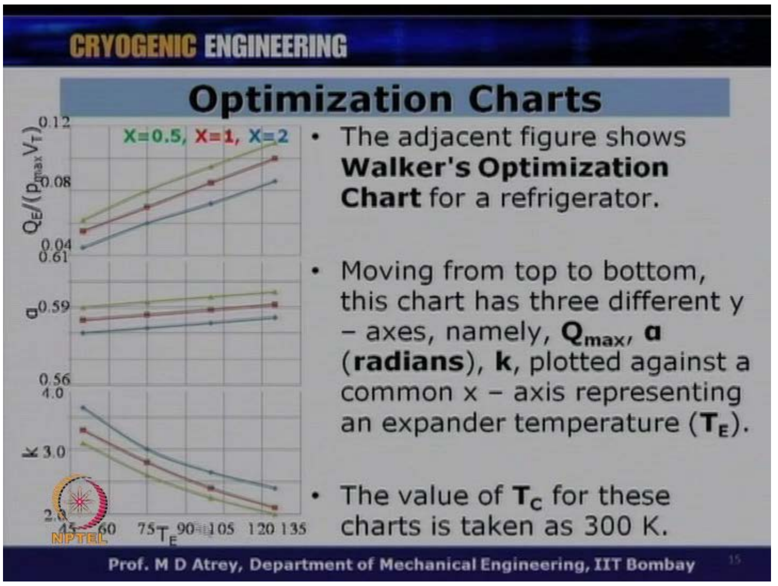

So, these are the optimization chart Walker has given. So, what you can see for, from here is the adjacent figure shows Walker's optimization chart for a refrigerator.

Moving from top to bottom, this chart has 3 different axes named Q max. So, you can see that, there are 3 charts; 1, 2 and 3 and what you see on the left axis is, we have got a Q max which is nothing, but Q E upon p max into V T. We have got alpha, the alpha is been given in radians. As you see here, there are 3 different axes, namely Q max alpha in radians and K which is volume variation ratio V C by V E and this all things have been plotted across a common T E temperature; that means, cooling expansion space temperature T E.

So, if I know that, I have to design a cryocooler at a particular T. Say, let us say, let us say, nitrogen temperature, which is T is equal to 77 kelvin or oxygen temperature, which is 90 kelvin or whatever temperature, you have got in mind. I should have that T E over here and if a draw a vertical from here, I can get variations of Q max alpha and k as against for different X parameter, that is a dead volume ratio. So what parameters do you see here? X, k and alpha and also for which a value of Q max is obtained against the temperature of my interest.

So, Walker charts basically gives a parameters k, X and alpha, for different cold end temperatures and against that what you obtain is basically the value of Q max and this is what Walker's chart gives us. The value of T C for all this charts is assumed to be at 300 kelvin; that means, T C is 300 and if I want to have tau, it is 300 divided by the value of T E which I consider.

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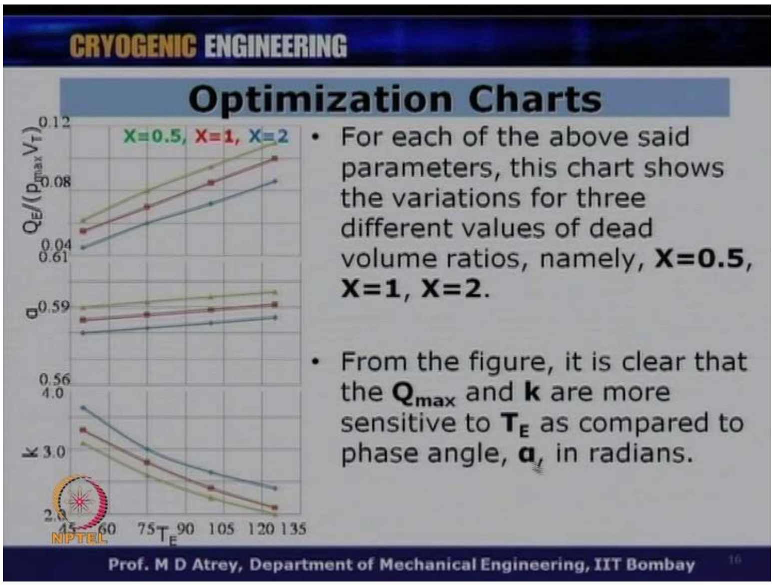

So, for each of the above said parameter, this chart shows the variation of 3 different values of dead volume ratios, which is X is equal to 0.5,1 and 2. What you see X equal to 0.5, which is this green line, X is equal to 1, which is this red line and X equal to 2, which is basically the blue line.

And this 3 variations are shown over here, if I have got any variation between this X 0.7 for example, one can interpolate between this 2 lines or if I got a 1.2 or 1.5, I can interpolate between this 2 line linearly and get variation of Q max alpha or k. From this figure what you see is Q max and k are more sensitive to T E, as compared to phase angle alpha. It is clear that, the alpha variations are these graphs are quite flatter these graphs are quite flatter over there. So, whatever the variation T E happens there is not a drastic change of value of alpha basically, is not it?

While Q max changes drastically, as well as the k value changes drastically and that is what one can see from this figure that alpha variation, which is given in radiance is not very very sensitive to T E, while Q max and k is quite sensitive. So, with this background of Schmidt's analysis and Walker's optimization design chart, now let us go to the design of a cryocooler. Let us see, how we use this analysis and this charts for carrying out a first simple, first guess design of a cryocooler to attain a particular temperature T E and to get a cooling capacity of Q E at that particular temperature.

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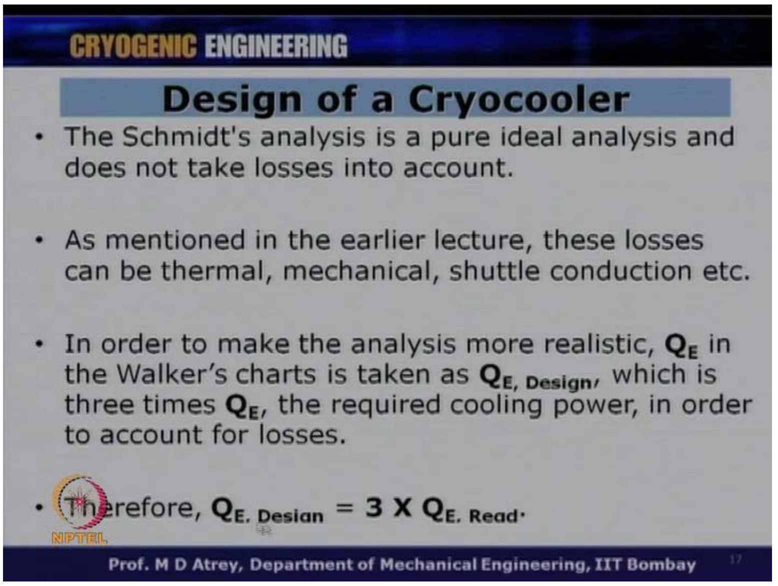

The Schmidt's analysis is a pure ideal analysis and does not take losses into account. We have seen that, the only parameter Schmidt's considers is basically the continuous motion of piston and displacer, as against the discontinuation motion demanded by ideal stirling cycle. So, from the first realistic deviation from ideal stirling cycle, which was taken into account by Schmidt's. However, he had not taken any losses into account.

As mentioned in the earlier lecture, these losses can be thermal losses, mechanical losses, shuttle condition. We have got a heat exchanger effectiveness, re genetic effectiveness, we have got a pressure drop across the system and all these losses have to be first calculated properly and they have to be encountered, they have to be understood and the net cooling effect for which the cryocooler has to be designed, has to be taken into account; that means, I require some Q E, while I will design Q E for an higher value taking into a consideration all these losses that are going to add up to my cooling effect.

As a result of which, in order to make the analysis more realistic Q E in the Walker's charts, if I want to design my cryocooler based on Walker's charts, whatever Q E has been considered there, I will replace that by a parameter called as Q E design, I will not take that as a required Q E, but I will replace that Q E as Q E design, for which the cryocooler is designed, which is normally, I will say 3 to 4 times Q E. In this case I say 3 times Q E; that means, I will understand that of this three times Q E, only one Q E is designed, I mean one Q E is designed.

While one third of this Q E is lost as losses, the required cooling for in order to account for these losses; that means, I will design this cryocooler for 3 times the value of Q E. What is required by me is only Q E, but I will go for 3 times Q E and which I will refer to as Q E design. I will use this Q E design value for referring to Walker's charts. So, can I say therefore, that Q E design is going to be my 3 times Q E required, if I want to design a cryocooler for 100 watts, I will now design it for 300 watt assuming that out of this 300 watts, 200 watts are losses and only 100 watts are going to be delivered to the cryocooler to the user basically.

Therefore, I will have Q E design taken up as earlier what I have taken as Q E, when I refer to Walker's charts, this is an important consideration design Q E value.

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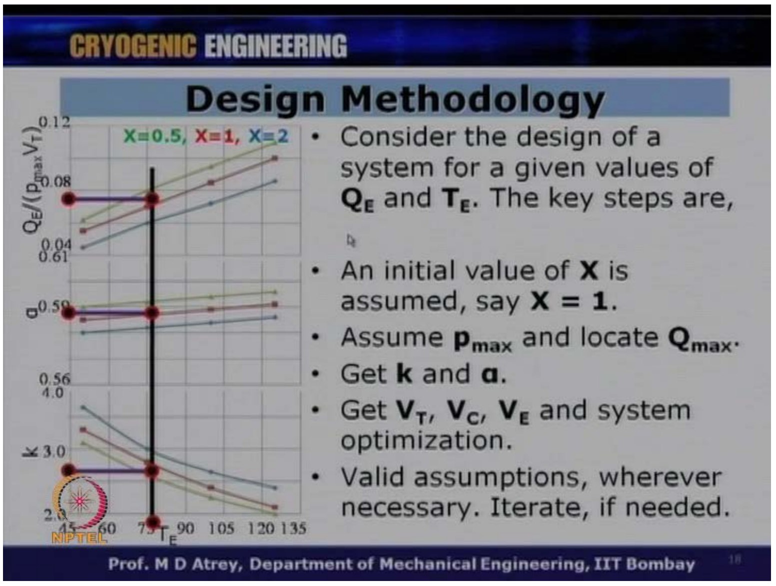

So, the design methodology if I want to understand; what I will do? I will know the value of Q E, that is cooling effect required and at what temperature T E. The key steps therefore, will be an initial value of X may be assumed. So, what I do first is basically draw a vertical from T E is equal to 77 kelvin and up to this parameter.

And assume that, X is equal to 1 for example to begin with, X may be equal to 1.1, 1.2 or 2, 0.7 or 0.8, I can determine that later, but in the beginning if I assume that X is equal to

1, from here I will understand; what is my Q max value? So, I can get a Q max value from over from from this may be 0.07 or something from this chart and I will have some assumption, I will have some knowledge from mechanical point of view, what is my maximum pressure allowed is?

So, once I know maximum pressure, I will know this maximum pressure, I will know this Q max, I can therefore, know what my total volume that is V T. So, I can know V T now, at the same time from other curves, I will know what my K is? What my alpha is? Once I know this thing, what I know now? I know my V T value, I know the alpha value, I know the K value. And therefore, with this knowledge, I can compete my swept volume, that is the V C and V E. I can get my V C and V E therefore, V T from this and I can therefore, come to the first guess of my swept volume V C and V E, which will give me; what is the diameter of the piston? What is the stroke of the piston? I can decide; what is the ratio of the stroke and stroke the piston diameter could be? Accordingly now, once I get the first guess of all this things, I can go back, I can see; what is corresponding to V C ,V E, my dead volume is; is that okay? Are this dimensions okay? If not I will again go back and go for X is equal to 1.2 or something like that and do this iteration.

So, some with valid assumptions wherever necessary, I will understand; what are my dimensions I am going to get? Are they okay? If they are not, I can change the value of X now and go back to the top end again and iterate using this optimization chart. The very simple first order guess, I will get, in order to get the value of the particular Q E at particular T E.

Now, as I said earlier, I will take this value of Q E, in this particular argument over here as 3 times Q E required. So, my I will take design Q E now, for getting the first guess dimension of a cryocooler. I will not take required Q E, but I will take 3 times required. I can take 4 times required Q E, depending on how conservative you want your analysis or you want your design to be. I think that this this design procedure can be well understood by taking a tutorial and therefore, I will, you can get a actual number feel and therefore, I will go for a simple tutorial.

And this tutorial is aiming to design an alpha type stirling nitrogen liquefier. This is a nitrogen liquefier, using the Schmidt's analysis and using the Walker's chart. Therefore, the working gas is helium and the capacity of the plant is 10 liter per hour of liquid nitrogen. So, I am using helium as the working fluid and the cooling effect should be such that, it will cater to 10 liters per hour liquefaction of nitrogen. The maximum allowable straight in pressure that is p max is given to be as 40 power and the speed of the primer will be 1440 rpm, these are mostly standard values.

Therefore, I got a limitation on maximum pressure that could be generated over here. now first and foremost most important thing is calculate my Q E required, how much cooling effect will I required in order to get 10 liters per per hour of liquefaction of nitrogen gas. So, what I go to? I go back to my basics and understand from temperature entropy diagram; what is my enthalpy requirement? What is my cooling effect requirement, in order to get 10 liters per hour of liquid nitrogen?

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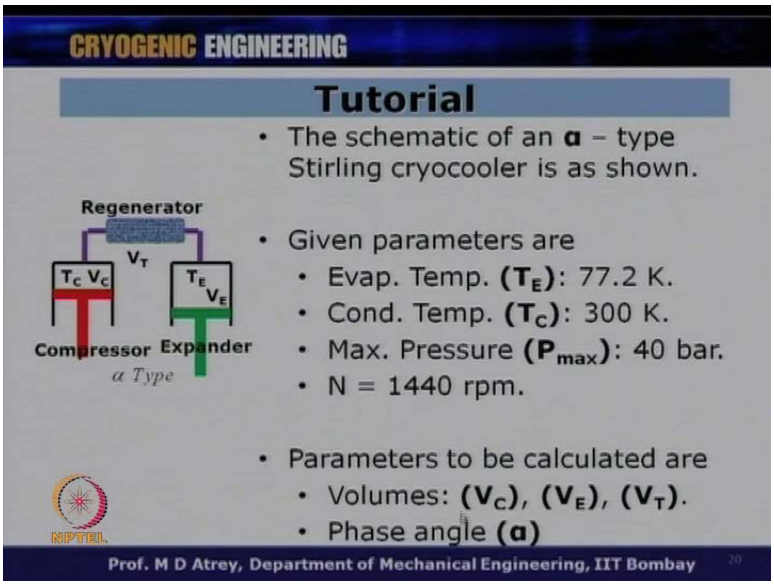

So, this is my alpha type cryocooler, which has got a compressor piston and a expansion piston also connected through a regenerator. The schematic of an alpha type stirling cryocooler is as shown, the given parameters in the problem are evaporation temperature equal to T E, which is going to be produced in expansion space over here at 77.2 kelvin. The compressor temperature is T C, which is 300 kelvin. The maximum pressure in the system is going to be p max, which is 40 bar.

N is equal to 1440 rpm, these are basically my operating parameters. The parameters to be calculated are; what are these volumes? V C, V E and V C plus V E is nothing, but V T. So, what is my total volume in a system, especially, I am going to basically get the the diameter and the stroke of compressor piston and a expander piston also in this case. And also I will get a phase angle, which is basically the volume variations the phase angle between the compressor and expansions volume variations.

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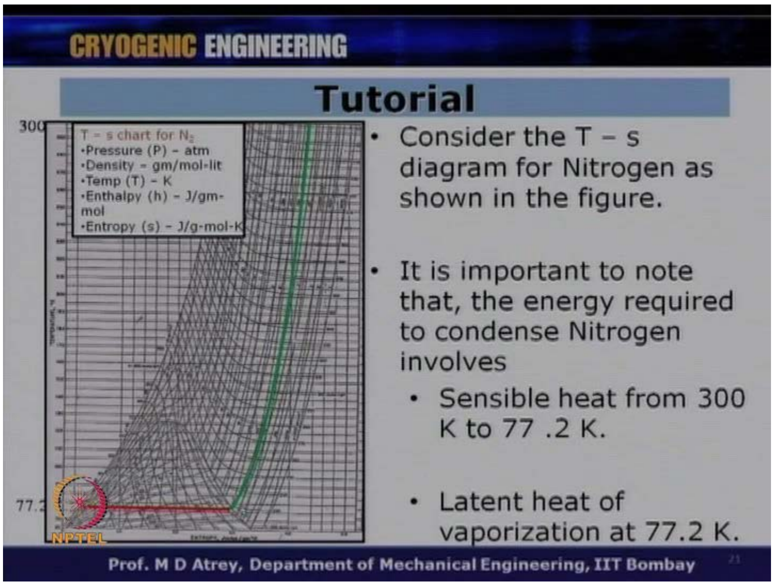

So, first thing I will go the temperature entropy diagram of nitrogen, in order to calculate the cooling effect required or Q E required in this case. So, consider T - s diagram of nitrogen as shown in this figure, it is important to note that, the energy required to condense nitrogen involves sensible heat from 300K to 77K. I have to now decrease the heat or decrease the gas temperature from 300 kelvin, which is my this point at one bar come down to 77 kelvin over here, which is my sensible cooling and then I have to cool the gas the latent part and therefore, latent heat of vaporization at 77.2 kelvin.

So, how much energy do I require, in order to get from 300 kelvin at 1 bar to 77.2 kelvin at 1 bar and then take out the latent part of heat. So, that I get liquid nitrogen at 1 bar, at 77.2 kelvin, this is the minimum heat, I have to remove from nitrogen gas in order to reach to saturated liquid region at 77.2 kelvin and what is most important is, in order to get 10 liter per hour of liquid nitrogen; what is my mass flow rate?

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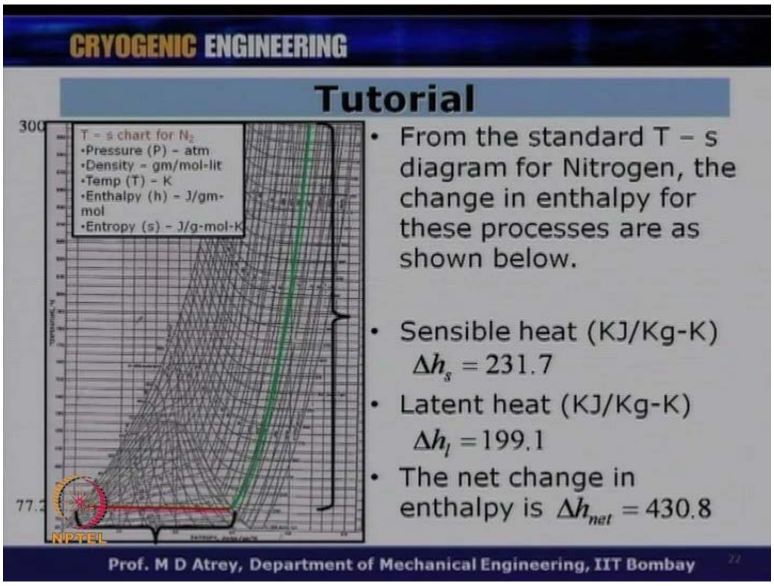

So, first let us calculate the cooling effect required and then we will see how much is the mass flow rate? So, from the standard T - s diagram for nitrogen the change in enthalpy of this processes are the sensible heat from 300 to 77 kelvin, which is 237.7. So, h at 300 kelvin and h at 77 kelvin, this is my difference delta h s 231.7 plus the latent heat, which is going to be 199.1 kilo joule per Kg Kelvin. I will add this the net change in the enthalpy therefore, is 430.8 kilo joule per Kg kelvin. This is my enthalpy change from 300 kelvin 1 bar to 77 kelvin 1 bar at saturated liquid condition

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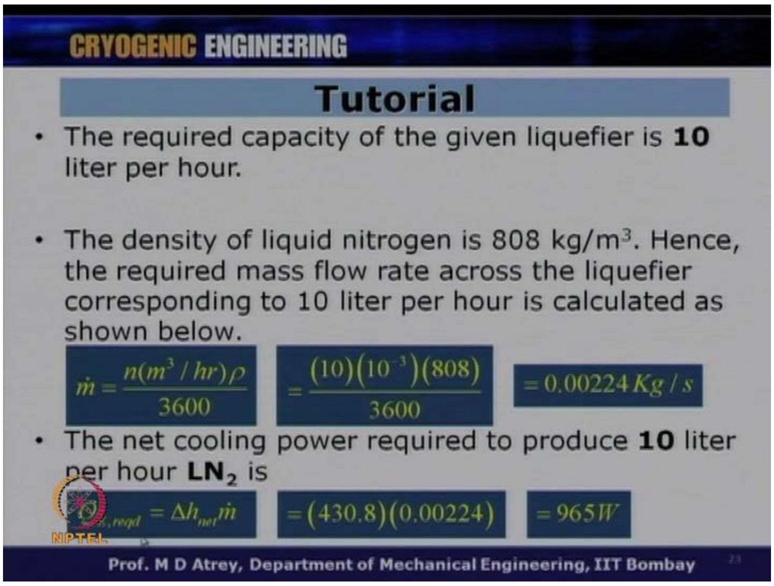

The required capacity of the given liquefier is 10 liter per hour, the density of liquid nitrogen is 808 Kg per meter cube. Hence, the required mass flow rate across the liquefier corresponding to 10 liter per hour is calculated as mass flow rate is going to be given by; what is my n value? That is meter cube per hour into density divided by 360. So, convert my 10 liter requirement into meter cube, which is going to be 10 into 10 to the power minus 3 into density of liquid nitrogen 808 at 1 bar divided by 3600, which is giving me 0.00224 Kg per second, this K g per second.

So, the net cooling effect required to produce 10 liter of liquid nitrogen per hour is Q E required is going to be delta h, we just calculated per Kg earlier, multiplied by how much Kg per second my flow rate will be, which is going to be this, which will amount to 965 watts. So, my Q E required to get 10 liters of liquid nitrogen at 1 bar is equal to 965 watts, this is my Q E required.

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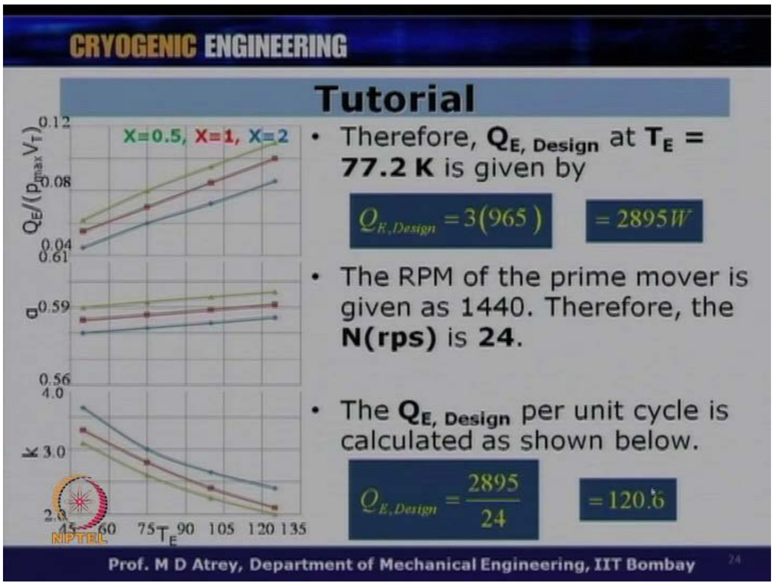

Therefore, Q E design at 77 kelvin is going to be 3 times this value. So, Q E design is going to be 3 times 965, which is nothing, but 2895 watt.

What does it mean? I am going to design a cryocooler now, for 2895 watt assuming that so many watts will be lost as losses, in order to deliver 965 watts as cooling power at 77 kelvin. So, my net loss assume will be 2895 minus 965, this is the loss and what is delivered is 965 watts, which are responsible to produce ten liters of liquid nitrogen at 77.2 kelvin.

Now, in order to design this cryocooler, I will now refer to the Walker's charts over here, which will give me Q max, alpha and k, which is what we just saw at different temperatures. So, first thing I will do basically is to locate the line of T E is equal to 77.2 kelvin. Also what is known to me is the rpm of the system is 1440 and therefore, rps or how many hertz are there, which is 24 hertz 1440 divided by 60, this is my in order to calculate how much Q E design per unit cycle will be?

So, Q E design per unit cycle is therefore, will be equal to 2895 divided by 24, which is equal to 120.6 and this is Q E design is used to calculate my Q max now. So, this is my Q E design per unit cycle.

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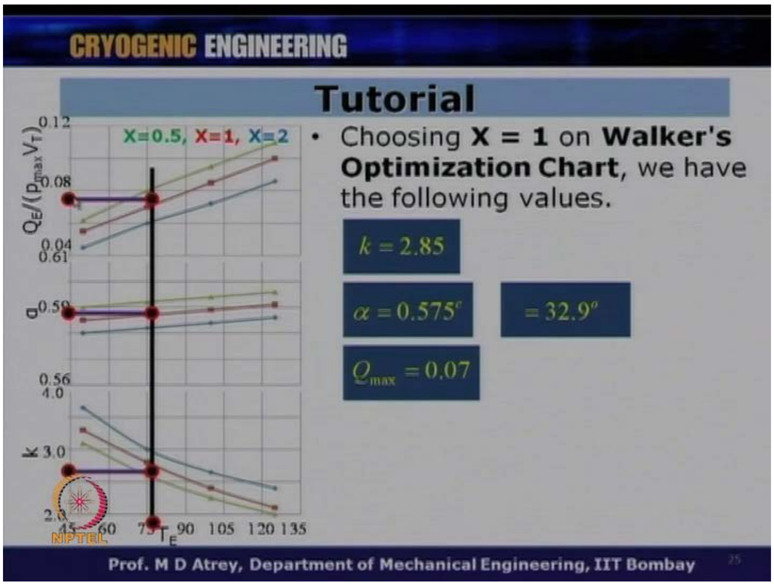

So, let us go to the Optimization chart and let us draw a vertical line from 77.2 kelvin, at which cooling effect is going to be produced and the first iteration we can assume that X is equal to 1 from Walker's chart and we can see that for X is equal to 1, I will get different values.

So, I get k is equal to 2.85 from here, I get alpha is equal to 0.575 radians, which is equal to 32.9 degree. So, this is not a very happy; I mean as a as we just saw that it should be between 60 to 120, but this is our first iteration and we are getting value of alpha to be 32.9. If you want I can increase my value of or decrease my value of X. So that, I will land up in whatever alpha I normally would like to have. And the corresponding the value of Q max is going to be 0.07, which is located from this curve and all these values have been taken at X is equal to 1 and T E is equal to 77.2 kelvin

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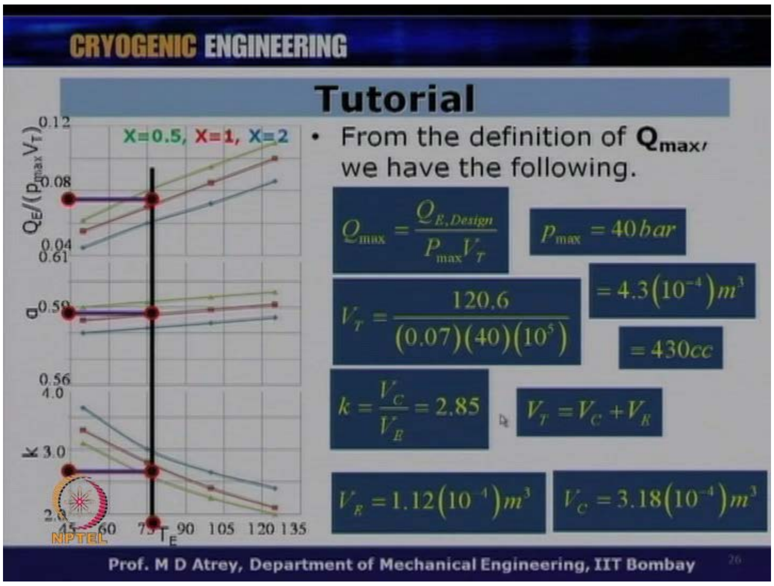

From the definition of Q max now, I get Q max is equal to Q E design upon p max by V T and we have already calculate my Q Q E design, we already know what my p max should be? Because the problem defines that p max should not be more than 40 bar and I know Q max, which means I will get the value of V T from this particular expression, p max is equal to 40 bar. And therefore, V T equal to Q E design, which is 120.6 divided by Q max, which is 0.07 into 40 bar to be converted into 40 to the power into 10 to the power of 5, in order to get millimeter if I want to have or a meter, go over here. From here I get V T to be equal to 4.3 into 10 to the power minus 4 meter cube; that means, I have got a total swept volume V C plus V E, compression space volume plus expansion space volume as this particular quantity, which is nothing, but 430cc.

Now, I know k again here, which is 2.85 from this particular expression, from this particular graph V C by V E equal to 2.5, what I know V C plus V E equal to 430cc. And therefore, I can calculate the two volumes and this is nothing, but V E is equal to 112 into 10 to the power minus 4 meter cube, which is nothing, but 112cc 112cc and again I have got V C, which is 3.18 10 to the power minus 4 meter cube, which is nothing, but 300 and 18cc.

That means, I know now compression space volume, expansion space volume in meter cubes and I can now calculate work should be correspond in diameter and the stroke of the piston and displacer for the unit for which we are designing this a cryocooler.

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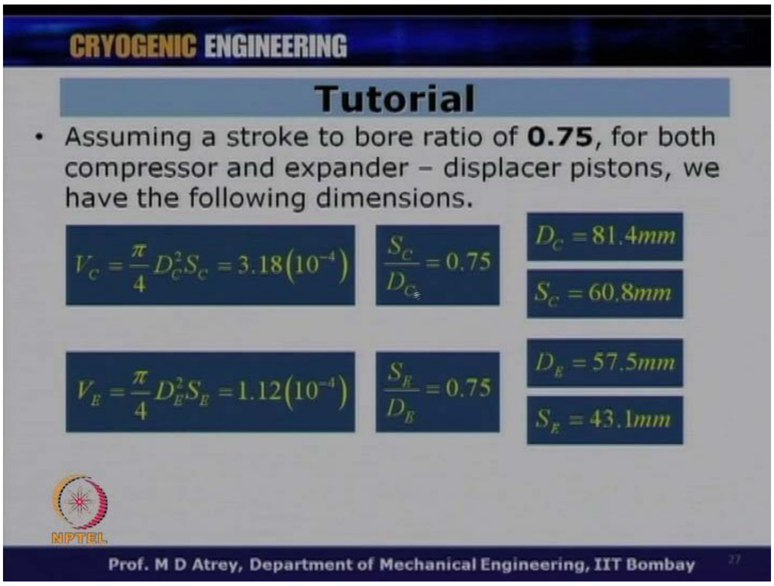

Assuming now, stroke to bore ratio of 0.75 for both compressor and expander pistons we have the following. We have got a V C equal to pi by 4 into D C square into stroke of the piston and therefore, we know what my V C is, which will give me the value of S C by D C has been assumed to be 0.6, 0.75 correspondingly are can calculate my diameter of the piston to be equal to 81.4 millimeter and the stroke of the piston to be 60.8 millimeter. Similarly, I know value of V E, which is pi by 4 into D E square into S E. In fact, expander piston that is what I should call it here because it is not a displacer in this case. S E upon D E 0.75, which is an assumption. I get D E as points diameter of the piston for the expansion side is 57.5 and the stroke is 43.1 millimeter. These are my first guess dimension, if I am not very happy about this, I can go back to my (( )) chart; for example, this dimension can come very large depending on for which capacity you are deriving this cooler and if you find it impractical to have such fabrication or such space allocation, I can as well go back change my value of X for example, or you can also change your p max required in that case. For example, if p max required is going to be smaller quantity, all these values are going to be very large. If I allow my maximum pressure to be higher side then my dimensions might come down on the lower side and this is where you have to do iterative exercise.

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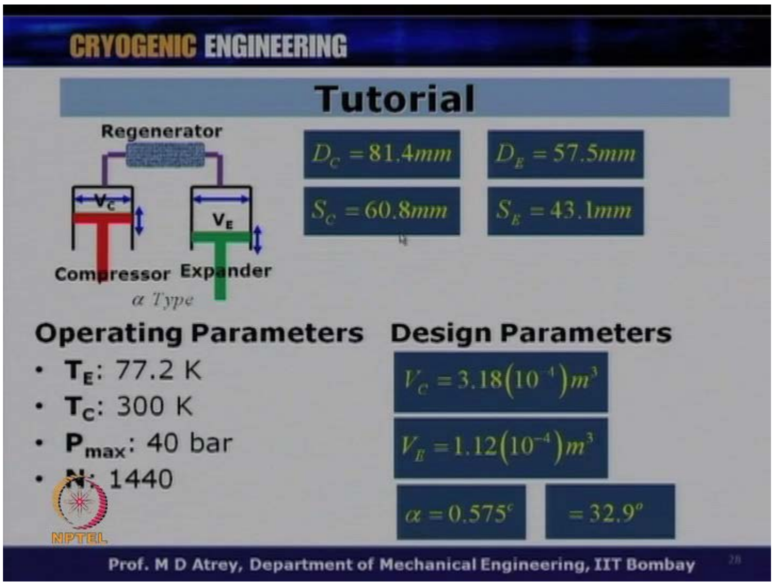

So, this tutorial gives me for this compressor expander arrangement, D C to equal to 81.4 as given over here, S C or the stroke to be 60.8 millimeter as given over here. Similarly, diameter of the expander will give you 57.5 and stroke is given as 43.1 millimeter. So, my operating parameters and design parameters are given as the operating parameters are T E is equal to 77.2 kelvin, T C is 300 kelvin, p max is 40 bar and N is equal to 1440 revolutions per minute. Similarly, for design parameters, I have got V C, V E and alpha as 0.75 radians, which is equal to 32.9 degrees.

So, these are my first guess, I am not going to iterating over here. What the point I want to come across? I want to give as, if this dimensions you find are on a very higher side for example, this is for a 10 liter per hour, but tomorrow if I want to you have to design for 15 liter per hour and I say that the maximum pressure should not exceed 30 bar. In that case, these dimensions can come very large and in that case you may find that one compressor piston is not enough and you may have to go for 2 cylinder system or you may have to go for 4 cylinder system depending on capacity you are talking about.

For example, a 50 liter per hour cryocooler may have 4 cylinders. That means, each cylinder will give around 12.5 liters per hour. Accordingly, decision has to be taken to determine; what my diameters? And what my strokes should be? What my maximum pressure should be? What my X value should be? And this will determine the diameters and the strokes of the piston and a displacer or the expander and the compressor respectively.

So, here you have to take a call how many iteration would you like to do? Is p max is equal to 40 bar is enough? If not can it be higher, if it is on higher side this dimensions can still be reduced. Because comparatively for a given max by V C or V E will get reduced for higher pressures and therefore, this can be considered on a lower side. It also depends on how much area is available for your cryocooler, if the space available is going to be smaller and smaller then you might allow it to go for higher pressures in that case.

However, parameters which are not being considered over here is the mechanical design. It should stand the mechanical design that mean diameter the thickness is etcetera, should be able to stand all the stresses generated because of this higher pressure. What we are doing, going to do, is only a first guess based on the thermal design the thermal aspects of the system.

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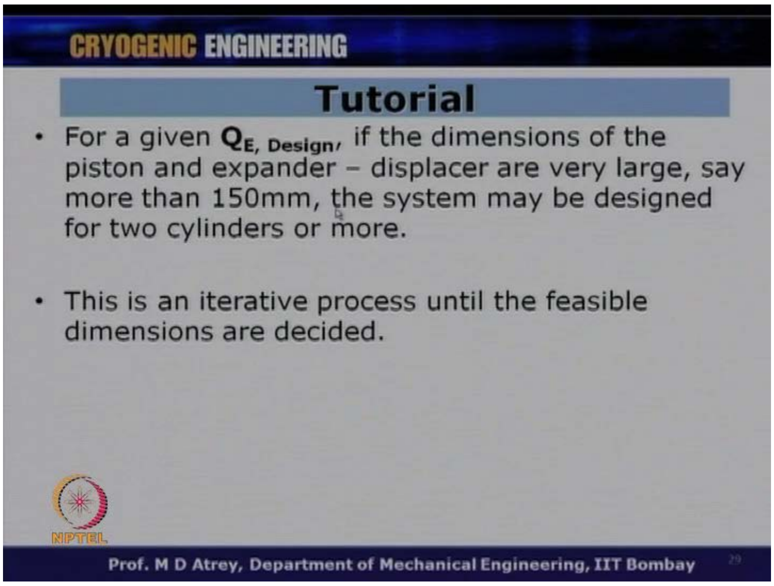

So, what we see for a given Q E design, if the dimensions of the piston and displacer are going to be very very large, say more than 150 millimeter, the system may be designed for 2 cylinder in that case, this what I just said earlier.

So, this is an iterative process, until the feasible dimensions are decided. So, you can play with operating parameters like maximum pressures, cooling effect requirement, the factor of which we have taken is 3 times Q required. It could be 4 times Q E required, it could be 2.5 times Q E required, again the dead volume ratio as I said X is been taken as 1, you can reduce this to X is equal to 0.8, this also will make an impact on overall design of the system. So, this has to be done therefore, in a iterative manner. What we have just shown is 1 iteration, what we have just shown you, how do we calculate this parameters or dimensions for a design of a cryocooler of 10 liter capacity. You should try different version of 5 liter, 8 liter, 14 liters and so on.

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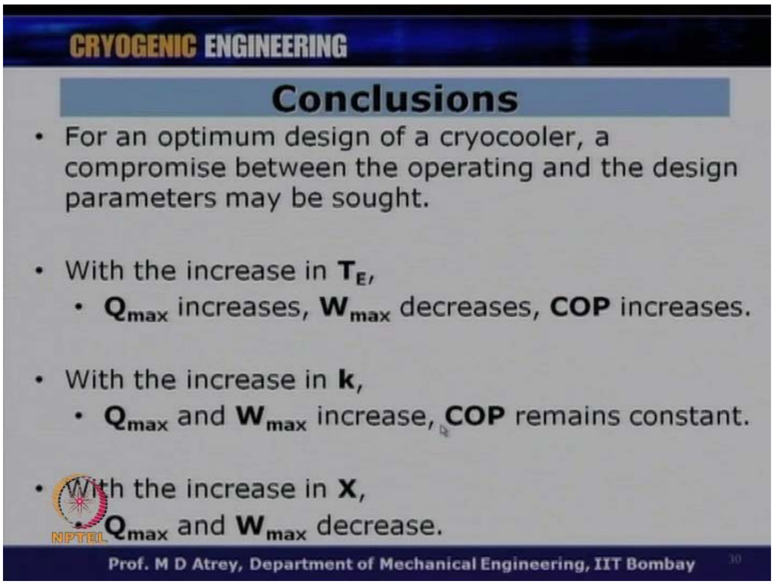

So, the conclusions that are drawn from these lectures are for an optimum design of cryocooler a compromised between the operating and the design parameters may be sought. As I said that, can I increase the maximum pressure? The design parameters will be different in that case.

Can I increase the dead volume; the design parameters will be different in that case. Also, we we saw that with the increase in the value of T E the Q max increases, W max decreases and COP therefore, increases. With the increase in the (( )) ratio of k, we found that Q max and W max increases, COP will remain constant because COP is a parameter, which depends only on the tau as well as ideal stirling cycle is considered with the increase in the value of X Q max and W max decrease in both the cases.

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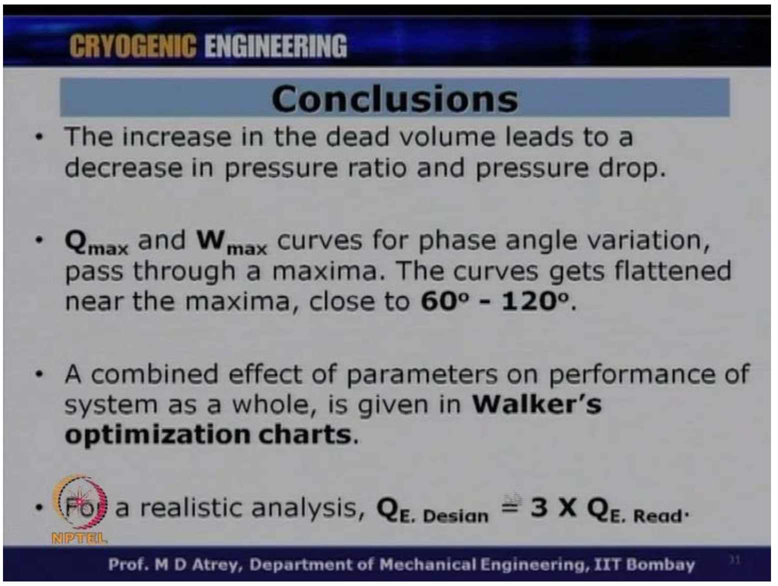

The increase in the dead volume leads to decrease in pressure ratio and pressure drop. Q max and W max curve for phase angle variation pass through a maxima, the curve gets flattened near the maxima close to 60 to 120 degrees. So, as far as possible, you may would like to have a value of alpha between 60 to 120 degrees if allowed. A combined effect of parameters on the performance of system as a whole is given by Walker's design chart. So, this is the first level optimization chart, which combines various operating and design parameters. And therefore, can be used for first guess dimensions. For a realistic analysis, we have taken Q E design equal to 3 times Q E required. This is where 3 is basically acting like a factor of 50, it can be taken as 2.5 or 3 or four or whatever design conservative design, one would like to design for.

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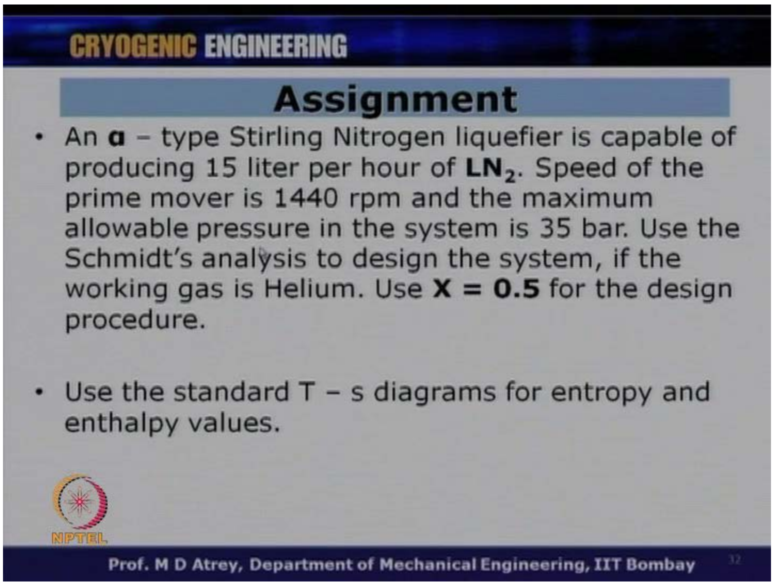

And lastly, we have given an assignment for a 15 liter design of a nitrogen liquefier for a 15 liter system, the steps have been given. You can have X is equal to 0.5 for the design procedure and go ahead for design calculations. Thank you very much.

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