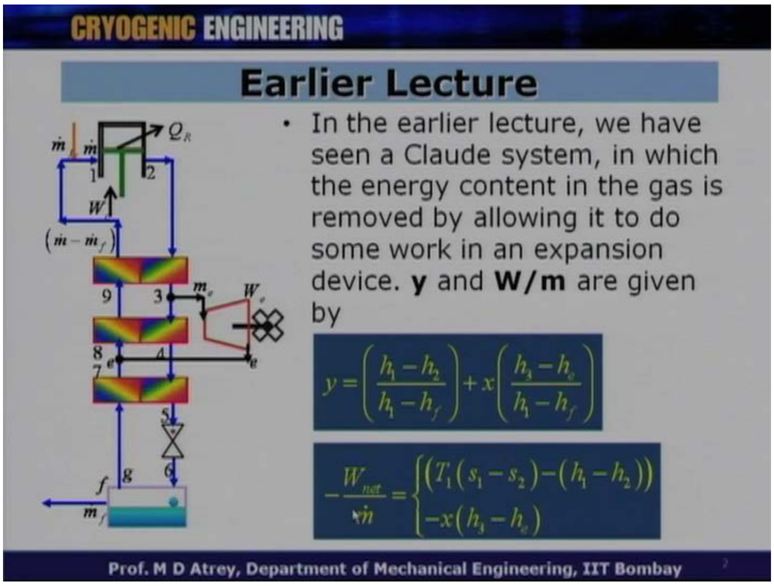
Cryogenic Engineering
Prof. M. D. Atrey
Department of Mechanical Engineering
Indian Institute of Technology, Bombay

Lecture No. # 16
Gas Liquefaction and Refrigeration Systems

Welcome to the sixteenth lecture of cryogenic engineering under the NPTEL program from IIT Bombay. Before, I go further in this lecture, I just want to do take you ahead from where we left during the last lecture; and that is the Claude cycle.

(Refer Slide Time: 00:34)



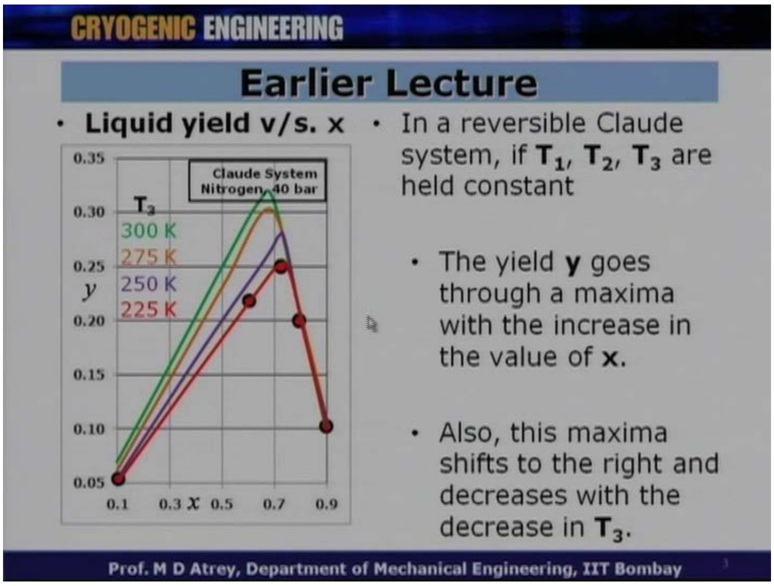
We were talking about Claude cycle, and in the earlier lecture we have seen a Claude system, in which the energy content in the gas is removed by allowing it to do some work in an expansion device. And we talked about having y as yield and W by m as the work per unit mass of gas which is compressed, and they are given by this formula.

Just to give a recap of the cycle, we have got a compressor, we have got a three heat exchangers 1, 2 and 3, and we got a expander over here from where you get a work output. The gas gets compressed, it gets precooled, and the part of the gas amount into m dot e is taken off. It gets expanded, low temperature form point 3 and meets the return stream at point e. The remaining gas - that is m minus m e goes ahead; it gets expanded in an isenthalpic pattern from 5 to 6, and what you get here is liquid. The return gas which is m minus m f minus m e goes back, when it goes back and gets warmed up to back to point 7. The cold stream comes from here after expansion, joins the point at e; and the gas then gets at the point 8 as the result of this mixture, then this gas gets warmed up to point 1 where the makeup gas comes, and the cycle repeats.

This we have talked about in great details in the earlier lecture. The yield given by the Claude cycle depends on this formula, which is h 1 minus h 2 upon h 1 minus h f. Which is the parameter comes best on this point 1 and 2; addition to this is coming, because of the x fraction which is nothing, but m e upon m dot which is diverted to the expansion device. And therefore, x into delta h or x 3 minus h e which happens across the expansion device is an additional yield, what you get in the Claude cycle.

Now, as you get work output, as you get work done by the expansion device, the W net by m dot that is work of compression per mass of gas which is compressed, is given by this formula. This is a standard formula minus x into delta h, basically this is nothing but the work done by the system, because of which net work input becomes less. This is what we had done last time.

(Refer Slide Time: 02:55)

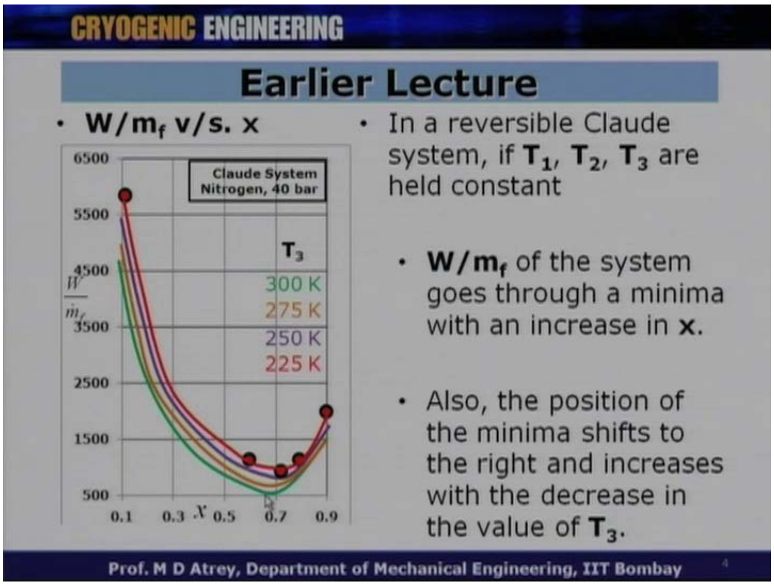


And we also studied the parametric effect of variation of x and its effect on the value of y. And this we studied for different T 3 values; that means, the temperature from where the gas expands. So, what we have studied was, in a reversible Claude cycle, if T 1 and T 2, and T 3 are held constant. 1 is an ambient pressure, ambient temperature, point T 2 is an isothermal compression, and T 3 is nothing but the point or temperature from where the gas expands. We had seen from this curve that the yield y, which is plotted on the y axis and on the x axis what we have plotted, is x which is nothing but the fraction of the gas, which is diverted to the expansion device.

The yield y goes through a maximum with the increase in the value of x; this is obvious from this particular figure. At the same time, what you can see is, this maxima shift to right and the maximum value decreases with the decrease in the value of T 3, which we can see from different T 3 values as 300 K, 275, 250 and 225 K, what you can see form here is, as the value of T 3 decreases from T 300 to 225, the maximum value of y also decreases from let say about 0.32 to around 0.25, as the temperature or the T 3 point decreases.

At the same time, what you see is, the optimum value of x, which in this case is just below 0.7 increases marginally, as you go on reducing the value of T 3, and it goes beyond the value of 0.7. So, one can see that the maxima shift to the right and the maximum value decreases with the decrease in the value of T 3. This is just to recap, what exactly we did during the last lecture.

(Refer Slide Time: 04:42)



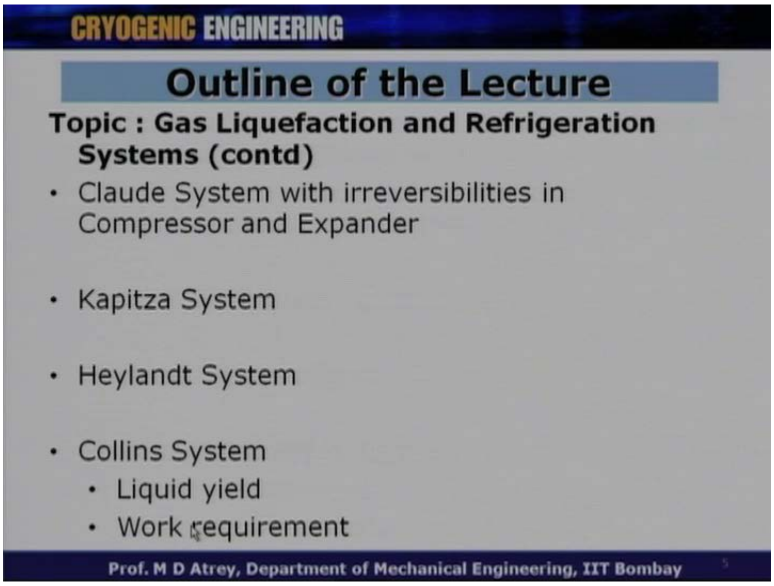
Similarly, what we can see from this curve is? How is the variation of W by m f that is work compression per unit mass of gas liquefied, how it changes as a function of x. So, again we can see that in a reversible Claude system, if T 1, T 2, T 3 are held constant. The W by m f value of the system goes through a minima with an increase in the value of

x. This is what you can see for every temperature T 3, we have got a minima; that means, the work done per unit mass of gas liquefied is going to be minimum and we would normally aim at this particular point and this point essentially matches with the value where, the y becomes maximum.

So, at this point your work input is minimum and yield is maximum. Also, what you can see from here is? As the value of T 3 decreases in this direction. For example, this green curve is for 300 Kelvin value of T 3 and as you go up what you can see the value of T 3 is decreasing, what you learn from this curve is?

The position of the minima shifts to the right. So, you can see that the minima again was at a value of x, which is just less than 0.7 and it shift it to right, as we went on reducing the value of T 3 from 300 to 225 Kelvin. At the same time, if the value increases W by m f increases with the decrease in the value of T 3. So, as you go on reducing the value of T 3, the W by m f or the net work increased here as shown in this particular figure. This we had seen during the last lecture.

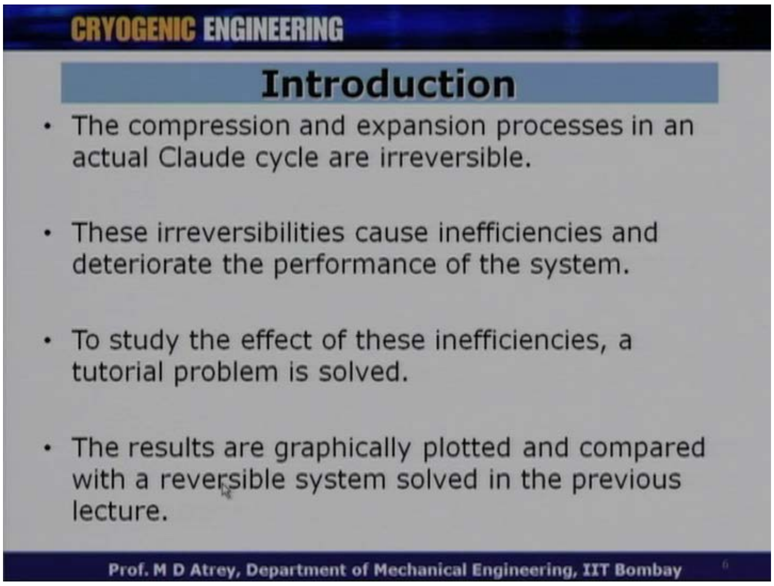
(Refer Slide Time: 06:15)



The current lecture would aim at same topic, but what we want to do is? Now, study the Claude system with irreversibilities in compressor and expander. So, what we had done was? We had assumed 100 percent compression process, 100 percent expansion process basically and what we can see? Now, the different efficiencies associated with these 2 devices.

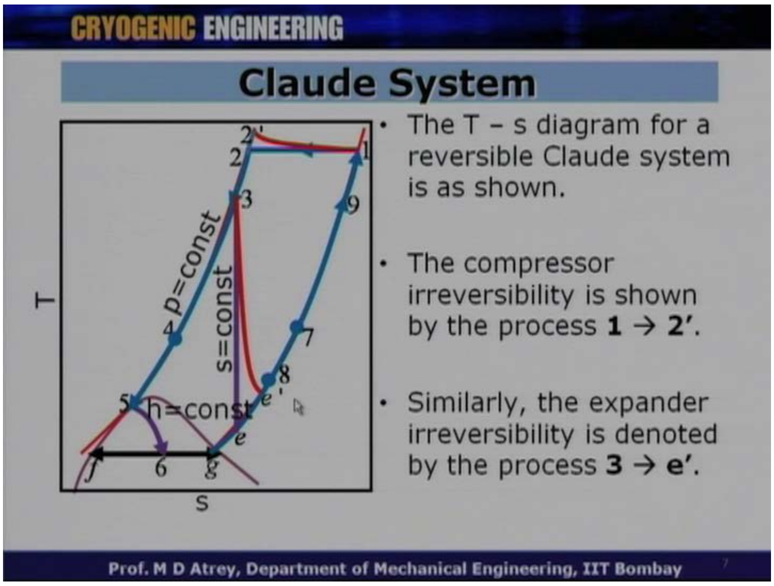
Then we will also study the Kapitza system, the Heylandt system and the Collins System which are actually in a way some kind of modification of the Claude system and that is why club them together in the lecture regarding Claude cycle. So, first let us see how Claude system behaves for different irreversibilities. Under Collins cycle, we will see the value of y and again work requirement.

(Refer Slide Time: 06:58)



As you know, the compression and expansion process in an actual Claude Cycle are irreversible. In actual cycle, all the processes are actually irreversible also, the heat exchange process also is going to be irreversible during this lecture, I am going to talk only about the compression and expansion process. These irreversibilities cause inefficiencies in a system and it deteriorates the performance of the system, this is obvious. To study the effect of these inefficiencies or irreversibilities a tutorial problem is taken up here. The results are graphically plotted and compared with the reversible systems. So, let us see the effect graphically as to what exactly happens, if these inefficiencies are taken into account.

(Refer Slide Time: 07:36)

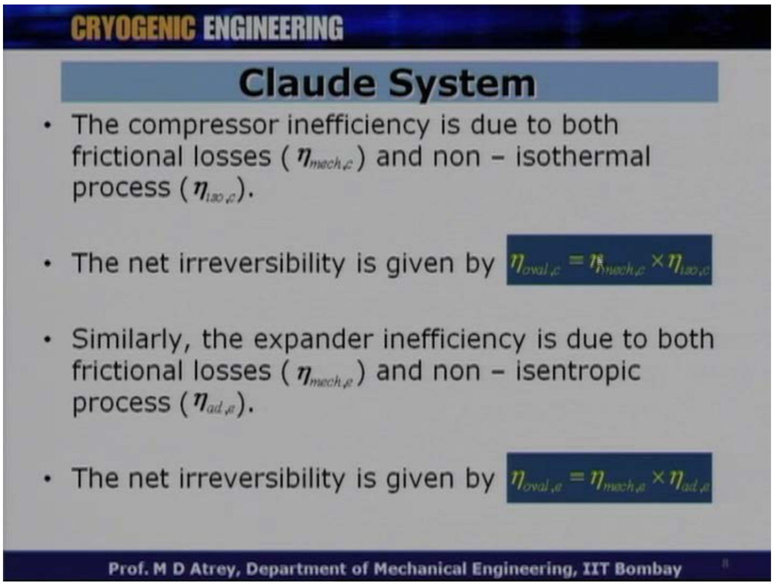


So, this is the Claude Cycle you can see here, the gas is expanded from 3 to e and 1, 2 is a compression process; 2, 3 is an heat exchange process; 3 to 4, 4 to 5 also are heat exchange process; 5 to 6 is isenthalpic process and this is the return stream. The return gas, the expanded gas joints the return stream at point e. This is what we show on T - s diagram.

Now, here what you see is a 1 to 2 is a isothermal compression process, which is given by 1 to 2. But in actual system this will not be 1 to 2 process, it will it will have it is own inefficiencies and therefore, 1 to 2 process would behave like 1 to 2 dash process. So, actual work done will be more than what is ideally assumed 1 to 2 process.

Similarly, the expansion process which happens from 3 to e, when it is 100 percent isentropic or adiabatic. In actual case, it will be 3 to e dash depending on the inefficiencies involved and therefore, the process of 3 e will become 3 e dash and these are the inefficiencies of compressor and expander, which we would like to take into account and solve in a tutorial problem.

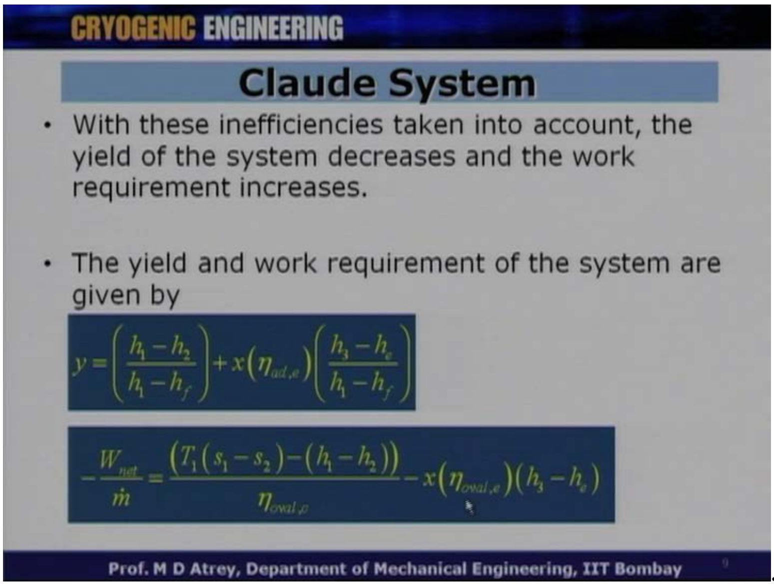
(Refer Slide Time: 08:48)



The compressor inefficiency is due to both frictional losses calling as mechanical efficiency of compressor that is eta mechanical and the non isothermal process that it is eta isothermal compressor. So, basically these are two efficiencies eta mechanical and eta isothermal and the net irreversibility is given by eta overall which is nothing, but eta mechanical into eta isothermal that it is clear in most of the thermo dynamic course, this is stopped.

Similarly, the expander inefficiency is due to both frictional losses, which is eta mechanical expander again and non isentropic nature of the process, which is given by eta adiabatic or the expander process. So, again we will have overall efficiency for the expander which is nothing, but eta mechanical into eta adiabatic for expander. So, we have two efficiencies for one for compressor and one for expander and these have to be taken into account in order to get actual work input and in order to get actual yield from this system.

(Refer Slide Time: 09:48)



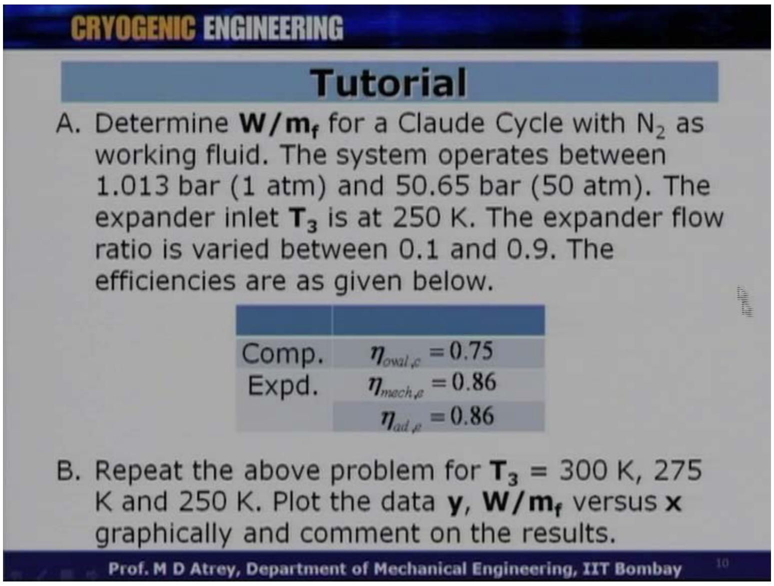
So, with these inefficiencies taken into account, the yield of the system decreases and the work requirement increases, this is clear that, because of the irreversibilities in a system. The yield that is y value will decrease while, the work input will increase. The mathematical formula for this yield and work requirement, they are given by this.

So, our formula becomes now y is equal to h 1 minus h 2 upon h 1 minus h f plus x time eta adiabatic, because actual enthalpy drop will not be now h 3 minus h e, but it will be eta adiabatic into h 3 minus h e. So, these values have been replaced by multiplying the parameter x by efficiency of the expander everything else remains the same and the work input, the net work input now, will increase depending on what is the overall efficiency of the compressor?

So, instead of having the work input as T 1 into s 1 minus s 2 minus h 1 minus h 2 for a normal process will have T 1 into s 1 minus s 2 minus h 1 minus h 2 divided by the overall compressor efficiency. Also, from where we subtract the work done by the system and this work done by the system also will reduce depending on the overall efficiency of the expander. So, the formula is going to change in this manner.

Now, in order to understand the effect quantitatively, what I am going to do is basically solve it tutorial and therefore, we can have some quantitative field of as to exactly what happens to this values and how much corresponding work input increases and how much correspondingly, the y or the yield decreases. So, let us a tutorial which takes into account all the inefficiencies involved in a claude system.

(Refer Slide Time: 11:34)

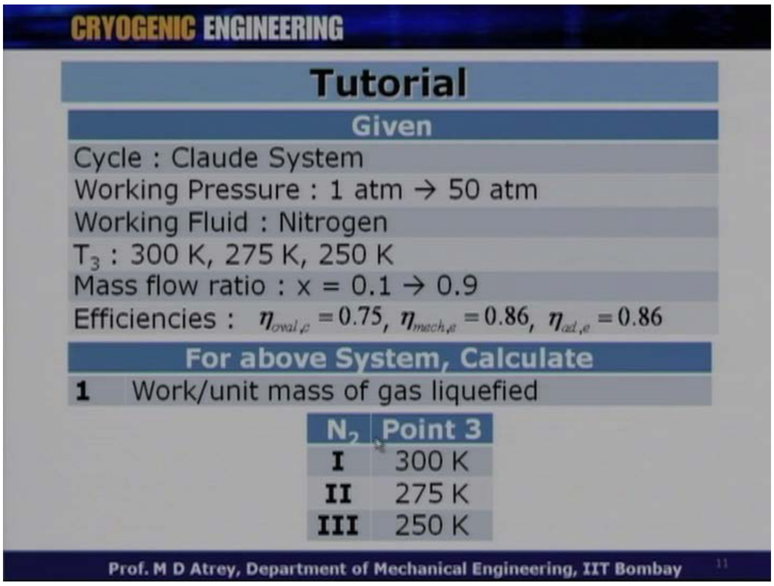


So, now the problem definition is determined W by m f for a Claude Cycle with Nitrogen as working fluid. The system operates between 1 atmosphere and 50 atmosphere, the expander inlet assume to be T 3 which is 250 Kelvin. The Expander flow ratio is varied from 0.1 to 0.9 that is the value of x, the efficiencies are given as below. The Compressor efficiency that is overall efficiency of the compressor is 75 percent or 0.75 and the expander has mechanical efficiency of 0.86 and adiabatic efficiency of 0.86.

So, overall efficiency of expander will be 0.86 into 0.86. Also, we would like to understand the effect of this inefficiency on the value of T 3. So, Repeat the above problem with T 3 is equal to 300, 275, 250 Kelvin. Plot the data y and W by m f versus x graphically and comment on the result.

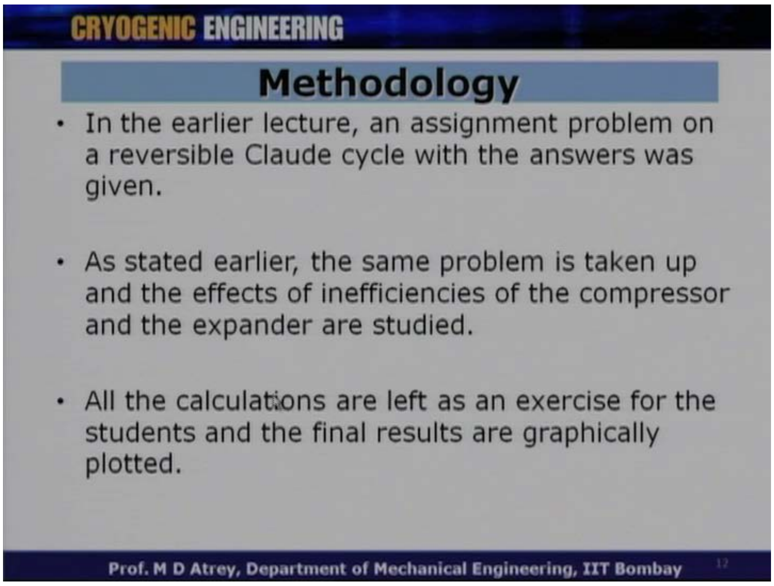
So, you can realize that this problem essentially is similar to what we have done in the tutorial; we conducted during the last lecture. What I am going to do now is? Basically add on the inefficiencies in the Claude cycle, and see how do they affect the values which we got assuming that all the efficiencies were 100 percent.

(Refer Slide Time: 12:47)



So, that given data is the Claude system, 1 atmosphere to 50 atmosphere, working pressure for Nitrogen fluid, T 3 value 300, 275, 250, the Mass flow ratio that is goes to the expander 0.1 to 0.9, efficiencies are govern over here. What we have to do is? Work per unit mass of gas liquefied to be found out for these 3 temperatures of the value of T 3 all right.

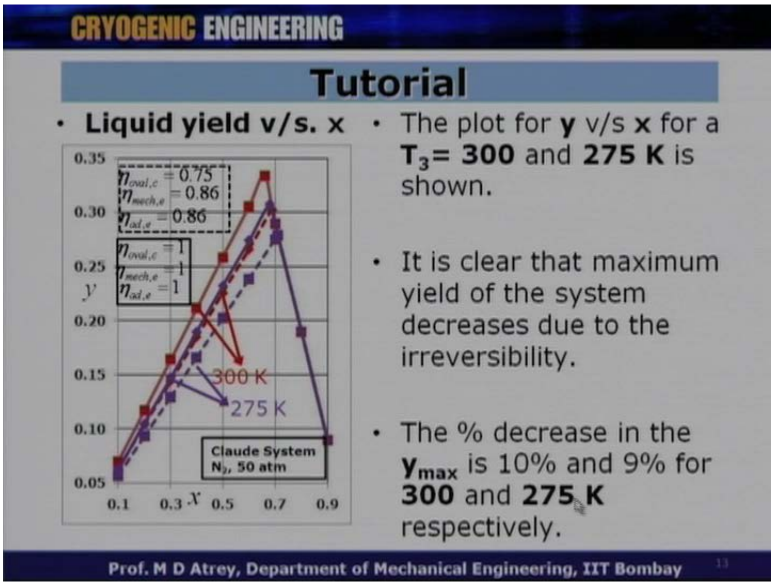
(Refer Slide Time: 13:09)



So, methodology which we are going to follow here is, I am not going to go into the details of the solution of this problem, but I would come to the result straight away by following this methodology, because we have solved this problem in detail, in the last lecture.

So, in the earlier lecture, an assignment problem on a reversible Claude Cycle with the answers was given. As stated earlier, the same problem is taken up and effects of inefficiencies of the compressor and the expanders are studied here. All the calculations detailed calculations are left for you as an exercise for the students and the final results are graphically plotted. So, what I expected you to do is to carry out all this calculation by yourself and check your answers with the graphical plotting which we have done.

(Refer Slide Time: 13:55)

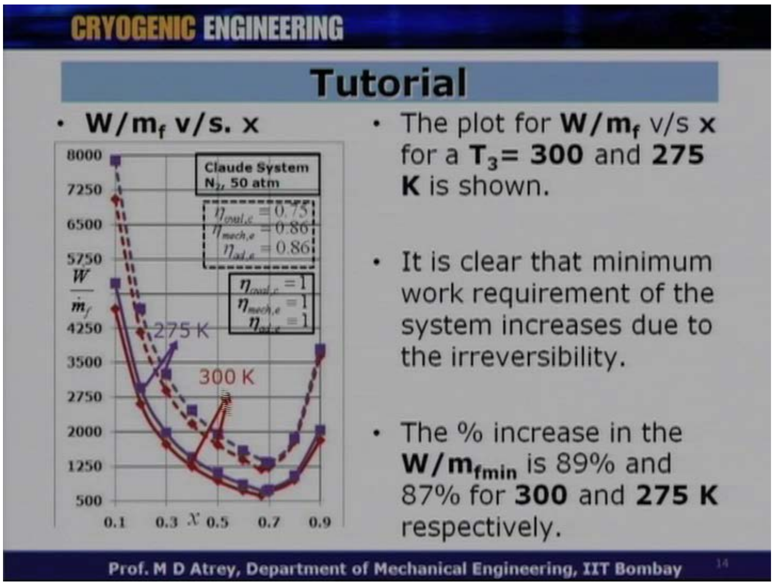


So, these are the results actually. So, what do the results tell you? These results are now variation of y versus x for a system, the continuous lies line basically shows 100 percent efficiency, which are given over here. While the dotted line gives for the inefficiency system for which the efficiencies are given over here and these two plots are done for 300 K and 275 Kelvin for 1 to 50 atmosphere.

So, what you can see from here? The y again goes through maximum when y is plotted versus x and what you can see here is? As the system become inefficient, the y value reduces from this point to this point. This is a dotted line while the violate line is for 275 Kelvin value of T 3 and here also the y reduces form this value and it comes down to this value, which is around 0.27. So, the reduction of y value and for both the cases for 300 Kelvin as well as for 275 Kelvin all right.

So, the plot for y versus x for T 3 is equal to 300 Kelvin and 275 Kelvin is shown over here. It is clear that maximum yield of the system decreases due to irreversibility. So, because of the inefficient system, which is dotted line showed here. In this plot, the y value decrease from this point to this point and therefore, what we can see here is? Decrease due to the irreversibility or the inefficiencies in a system. Also, what you can see? The percentage decrease in the y max is around 10 percent and 9 percent for T 3 value of 300 to 275 Kelvin; that means, as you went on reducing the temperature of T 3, the percentage decrease is less. So, for a high T 3 value, the percentage decreases higher for an inefficient system.

(Refer Slide Time: 15:55)



I hope this is clear to you, same thing we can study with plotting W by m f versus x. Again, you can see that the continuous lines are made for the efficient system as shown in this table here. While, the dotted lines show the inefficient system, the values for inefficiencies are given in this rectangle as value appoints 0.75, 0.86 and 0.86.

So, again you can see that the value of W by m f or the work done per unit mass of gas liquefied gets lifted up; that means, the values increase, as the system become inefficient and here you can see that the increase in the value is tremendous. If you see the values on the y axis you can see that this increase is tremendous and therefore, the figure of merit also is going to be changing substantially all right.

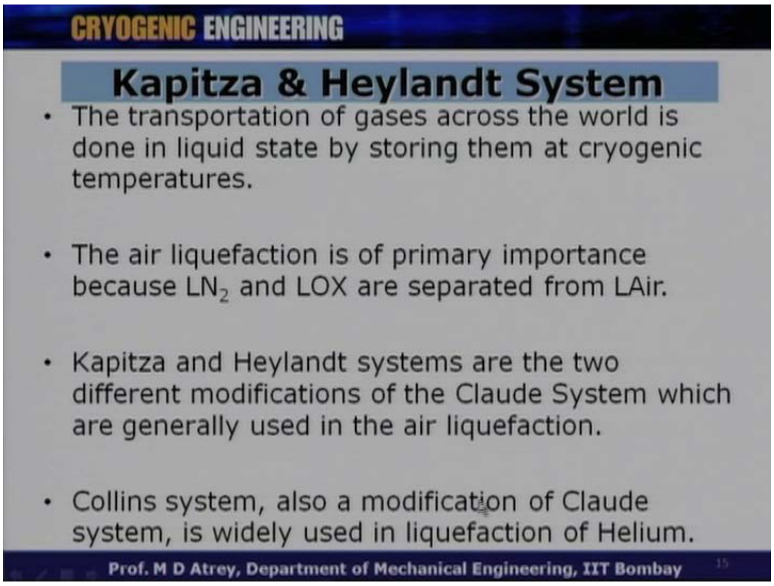
So, the plot shows for 300 Kelvin and 275 Kelvin values of T 3. It is clear that a minimum work requirement of the system increases due to the irreversibility. So, here one can see that the minimum work input has increased dramatically, this was close to around 500 here while, it has gone about 1250 over here. So, one can see that the increase has been almost of the order of 90 to 100 percent. The percentage increase in the value of W by m f minimum is 89 percent and 87 percent for 300 and 275 Kelvin respectively.

Again, the increase is more for higher value of T 3 that is 300 Kelvin as compared to that the increase is little is marginally less for 275 Kelvin. But the point to be noted here, as soon as the inefficiencies came into picture, the work input the net work input increase substantially mind well that we have not included the inefficiencies of the heat exchanger. As soon as that inefficiencies also come into picture will have lot of problems with this curve and increase in the work input or decrease in the y value, the yield value will be substantial.

So, these were basically an indicative exercise to let you know, what is the effect of inefficiencies of a system? In relation with compressor and expander only on the work input to the system as well as on the yield value. So, one has to really understand the importance of this devices the expanders and the compressors and the effect of their efficiencies on the yield and the W by m f values.

This makes this clear that how the inefficient system increases the work input or decreases the value of y. This actually concludes, the Claude Cycle from here, I would like to now take you to the next cycle, which are basically nothing, but the modified Claude Cycle.

(Refer Slide Time: 18:54)



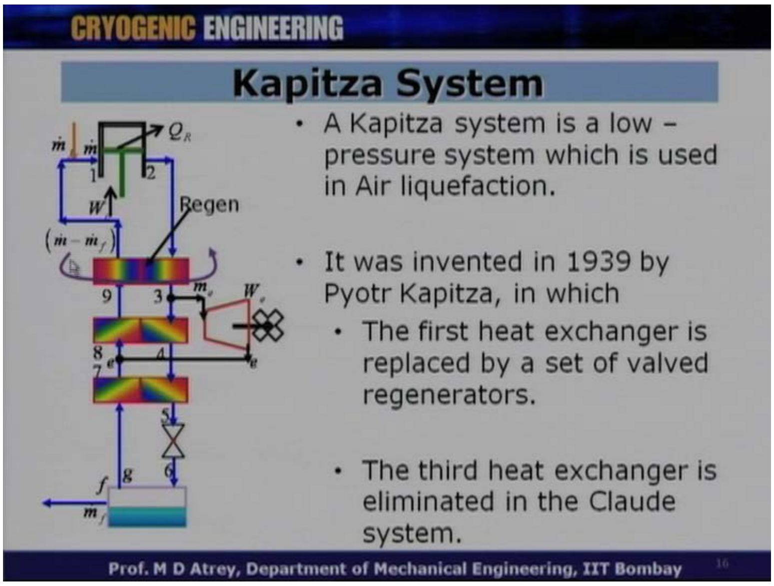
And they are now named after the people who invented those cycles as usual; they are called Kapitza cycle and Heylandt cycle. Why do these cycles are required? Because now, we are moving towards more practical cycles, they are the cycles which normally exist and they are being used in actual liquefaction of gases. So, you know that the transportation of gases across the world is done in liquid sate by storing them at cryogenic temperature. This is what we have talked about? Also, we talked about the air liquefaction is of primary importance, because Nitrogen and Oxygen or liquid Nitrogen and liquid Oxygen are separated from liquid air.

So, air liquefaction industry is a very big industry, because from this air liquefaction only by cryogenic distillation, what you get is? A liquid Nitrogen and liquid Oxygen operators had higher purity. So, therefore, air liquefaction plant utilize, this cycles and air therefore, this cycles are of very high importance in cryogenic engineering.

Kapitza and Heylandt systems are the two different modifications of the Claude system which are generally used in the air liquefaction. These are two very commonly utilized cycles or systems and which are nothing, but modification of the Claude system, we will see how this modifications are brought about? And finally, we will talk about the Collin system which is nothing, but the modification of Claude Cycle again, but it is for now liquefaction of Helium.

Till now, we are talking about around 80 Kelvin region that is Oxygen, Nitrogen, air etcetera. But then comes the next cycle which is the Collin cycle, which is now we are talking about Helium temperature that is 4.2 Kelvin. So, for a very low temperature gases Collin cycle comes into picture. Now, we will talk about the Kapitza and Heylandt cycles.

(Refer Slide Time: 20:31)



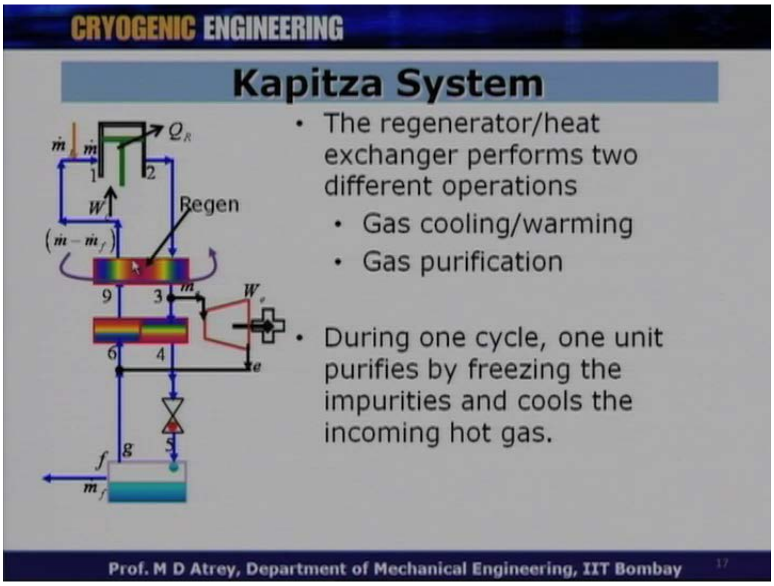
So, this is like basically we are talking about the Kapitza system. A Kapitza system is a low pressure system which is used in air liquefaction. This is not a Kapitza right now; this is as you know is a standard Claude Cycle. What I want to show now here? What are the modifications are done in a standard Claude Cycle, in order to gate from Claude to Kapitza system. So, a Kapitza system is a low pressure system which is used for air liquefaction.

It was invented in 1939 by pyotr Kapitza, in which the first heat exchanger is replaced by a set of valved regenerators. So, this heat exchanger which is the first heat exchanger now is being replaced by another heat exchanger called as regenerative heat exchanger, the regenerator all right.

So, you can see that this first system is off and a second heat exchanger comes into place and this heat exchanger is called as regenerator and please see that there is an arrow, I am showing here means that this is a kind of a rotary heat exchanger, which rotates like this. We will talk about the regenerator and this rotary business in the coming slides, but what other changes happen from the Claude Cycle? When you go from Claude Cycle to Kapitza cycle, is third heat exchanger is eliminated in the Claude Cycle and therefore, I will just remove that and the cycle gets reduce to now only 2 heat exchangers and one expansion device all right.

So, it is became a very simple now to understand that I got the first heat exchanger removed and replaced by something called as regenerator and I got sign, which tells be that this rotates. And then the third heat exchanger has been removed and therefore, in effect a Kapitza cycle or a Kapitza system has only 2 heat exchangers and one expansion device.

(Refer Slide Time: 22:22)



The regenerator or the heat exchanger performs two different operations. This regenerator, the first regenerator performs two operations. It cools the gas, when it goes from 0.2 to 0.3 and also, it wants the gas when it goes from 9 to point 1. This is what a heat exchanger expected to do? In addition to that what it does is? It purifies the gas.

A practical problem which comes in the actual cycle is the gas, which gets compressed comes with contamination. The contaminates could be moisture or other gases and the gas which goes beyond this heat exchanger has to be devolved of this all the contaminates like c o 2 or moisture or thing like that.

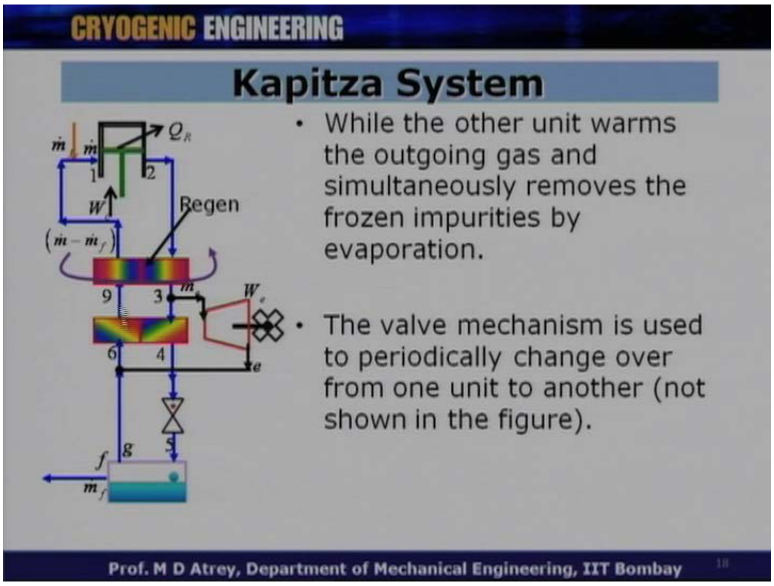
In order to remove, those contaminants this first cycle is made kind of a rotary cycle and in addition to cooling and warming the gas it purifies this gas also. How does it do? How does it purify the gas? During one cycle, one unit purifies by phasing the impurities and cools the incoming hot gas.

So, when the gases goes here and let us say, this is impure gas. This impure gas let us say this whole heat exchanger is divided into two part and this high pressure gas goes through one part to begin with, because of the cool gas which goes back, the impurities get frozen over here. And once the impurities get frozen, it will not allow the gas to go through it, because it blocks. And thereby, what we do now here? The whole heat exchanger rotates and this block heat exchanger comes, this side while this part will come on this side.

When these block heat exchangers with impurities come on this side, these are counter blow. Because of warm gas this basically evaporates the impurities, which had blocked the regenerator or this part. Thereby, releasing all the impurities and therefore, the gas can get warm, at the same time once this part of the heat exchanger gets devolve of the impurities. This can come on this side and therefore, the heat exchanger basically the rotates it freezes down the impurities while the other side removes the impurities and therefore, the improved part will come on this side, the present part will go on this side and this continues.

In the rotary manner, this heat exchanger one side will get blocked and then this block cell will go in other side where the counter blow gets into picture, which evaporates all the frozen impurities and this has to be achieved with lot of wall mechanisms. So, during one cycle one unit purifies by freezing the impurities and cools the incoming hot gas.

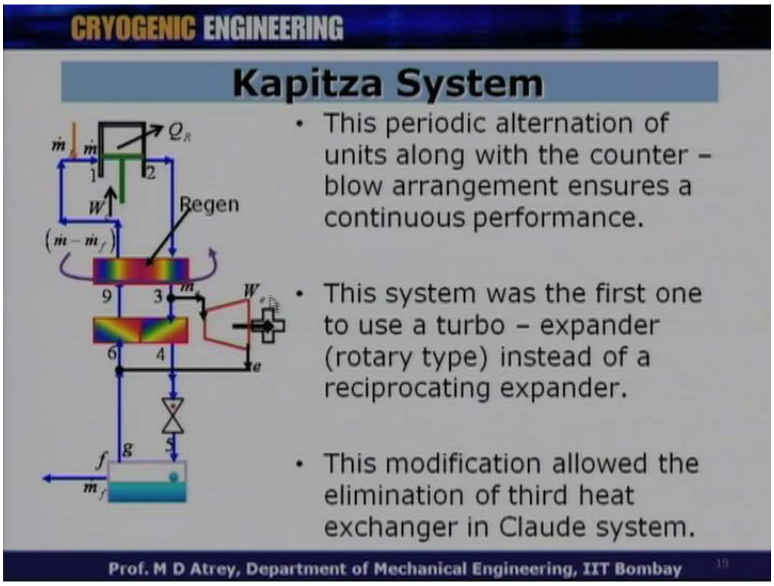
(Refer Slide Time: 24:54)



While the other unit warms the outgoing gas and simultaneously removes the frozen impurities by evaporation. So, two actions are happening simultaneously, one side is freezing down the impurities; the other one is removing the impurities.

The valve mechanism is used to periodically change over from one unit to another. These valves are not shown in the picture, but you have to see that the valves open at correct time and for correct amount of time the high pressure gas passes through it and for the correct amount type, the low pressure gas removes these frozen impurities. This is the most important thing.

(Refer Slide Time: 25:29)

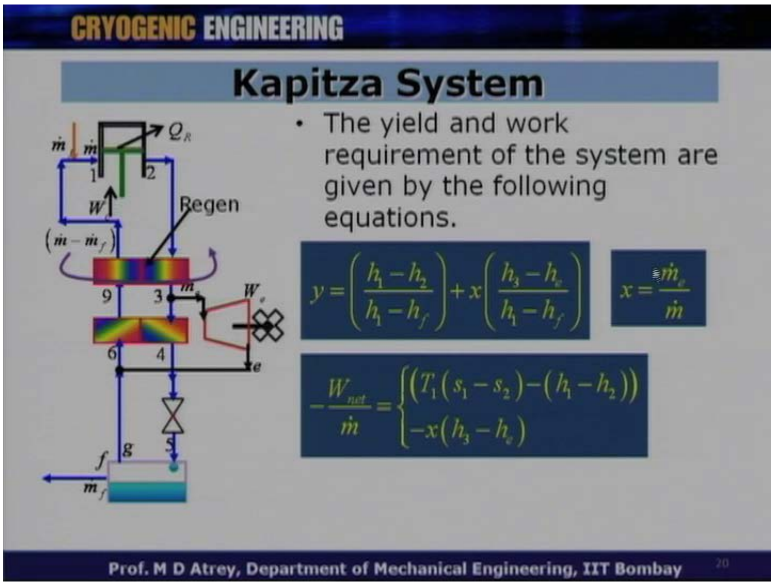


This periodic alternation of units along with the counter blow arrangement ensures a continuous performance. In addition to these changes, what was introduced by Kapitza is a use of turbo expander? Till now, what expander we are talking about was of a reciprocating type Kapitza where the first one, who introduce a turbo - expander instead of a reciprocating expanders.

So, the mechanical engineering development, in terms of having a high speed turbine came into existence in a liquefaction cycle and now, it can take higher flow rates. But you have to worry about turbine runs at a very high frequency; it has to have all the correct bearings shafts and all the mechanisms which come with the rotary expander that has to be taken into account. So, all those turbo expander machinery comes into picture and Kapitza introduce for the first time in the Kapitza system all right.

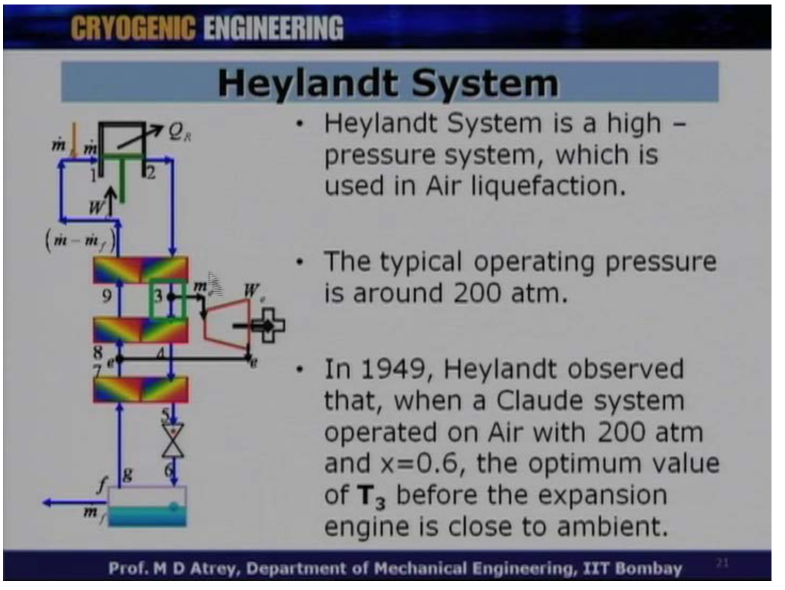
So, the modifications we have plenty as compared to Claude Cycle, the rotary expander came into picture. The first heat exchanger was changed to regenerative valve kind of heat exchanger and the third heat exchanger was removed and these are basically, the changes that happened when we modify Claude Cycle for Kapitza cycle. This modification allowed the elimination of third heat exchanger in Claude Cycle. Basically now, the turbo expander could handle more and more flow rates and therefore, it allowed to removal of this last heat exchanger all right.

(Refer Slide Time: 26:56)



The yield and the work requirement of the system are given by the following equations. If you see that nothing has changed much from mathematical perspective and therefore, the equation actually remains the same. So, the equation for yield y is given by h 1 minus h 2 upon h 1 minus h f plus x time h 3 minus h e divided by h 1 minus h f. So, equation is similar to what we had earlier? And W net also is a same formula; this is the work of compression on compressor over here. While this is nothing, but the work done by the expander which is nothing, but x into the enthalpy drop across the expander. So, work decreases by this amount and here x nothing, but the mass flow fraction that is driven to the turbo expander and this is what the Kapitza system is for air liquefaction.

(Refer Slide Time: 27:42)

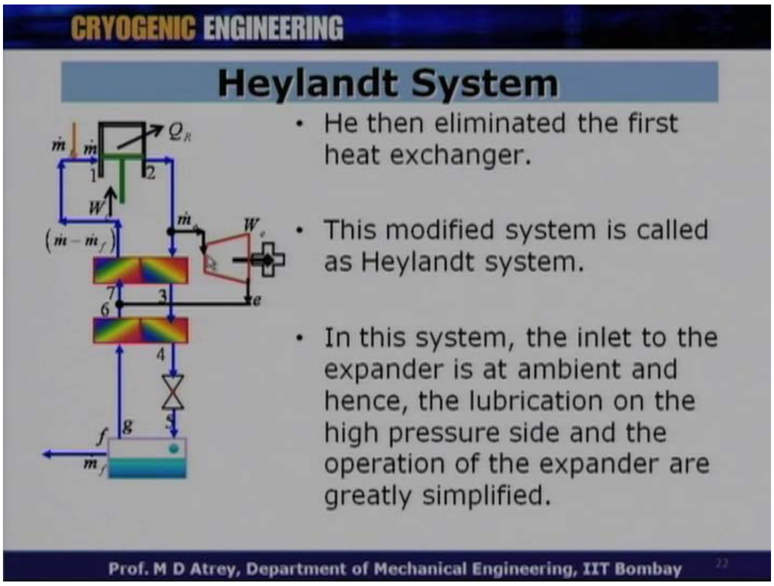


Now, let us study what modification happened to the Claude Cycle, when we went from Claude Cycle to Heylandt cycle. So, Heylandt cycle is basically higher pressure system which is used in air liquefaction. The typical operating pressure for Heylandt cycle around 200 atmosphere. In 1949, Heylandt observed that when a Claude Cycle is operated with air with 200 atmosphere and x is equal to 0.6, x is nothing, but m e upon m dot.

The optimum value of T 3 before the expansion engine is closed to ambient and this was a basic reason how Heylandt got idea? He found out that if you had a pressure as highest 200 atmosphere and the value of x is equal to 0.6; that means, 60 percent gas is diverted to the expander. Then the yield is maximum, when point T 3 or the temperature at 0.3 is at ambient; that means, here at this point as we have seen in our tutorial when the value of T 3 is at ambient temperature, the yield is maximum.

This gave him an idea that what is the need of first heat exchanger? Why not have the gas expander first without going into the heat exchanger and this is what basically (( )) Heylandt come up with this Heylandt system.

(Refer Slide Time: 28:56)



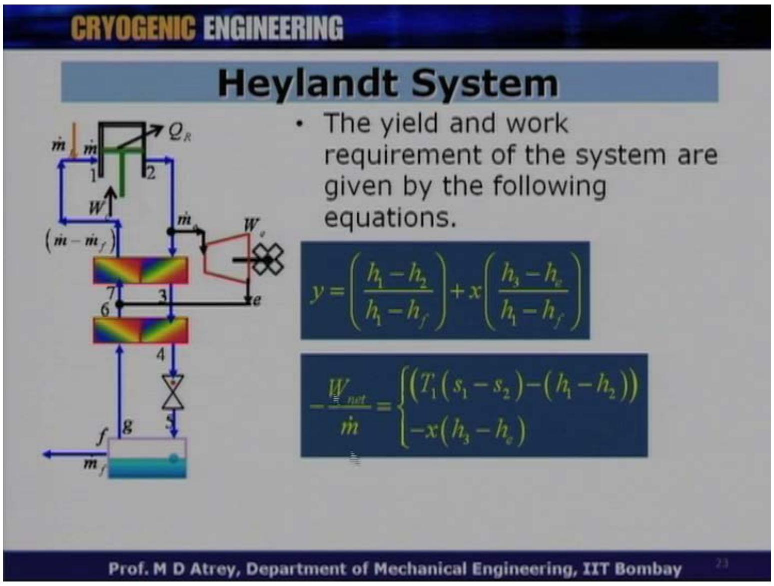
So, what Heylandt did was? He eliminated the first heat exchanger and therefore, the system become like this. What is it mean? That means, the expansion started happening; that means, m dot e is drawn from this cycle are right at ambient temperature and the gas is taken at right at the ambient temperature that is 300 Kelvin and expanded and joints the return stream at this point.

If you remember in Kapitza system, we had removed the last heat exchanger, but in Heylant system now we can see the first heat exchanger is removed and that is only difference. In addition to other differences like the regenerative heat exchanger introduce on the top plus the turbo expander as Kapitza had introduced. Basic difference however, the Heylandt removed first heat exchanger and Kapitza removed the last heat exchanger.

This modified system is called the Heylandt system. In this system, the inlet to expander is at ambient. Now, these solve lot of practical problems and what are the practical problems? The lubrication on the higher high pressure side of the turbo expander or any expander is now at ambient temperature. So, the approach one can easily approach to the high pressure side of the expander and the lubrication at least at the higher pressure side can be taken care of and the operation of the expander are greatly simplified.

So, lubrication problem and also the operation of the expander got very much simplified in a Heylandt cycle and this is what I say that the Claude system modified from practical perspective in Kapitza and Heylandt.

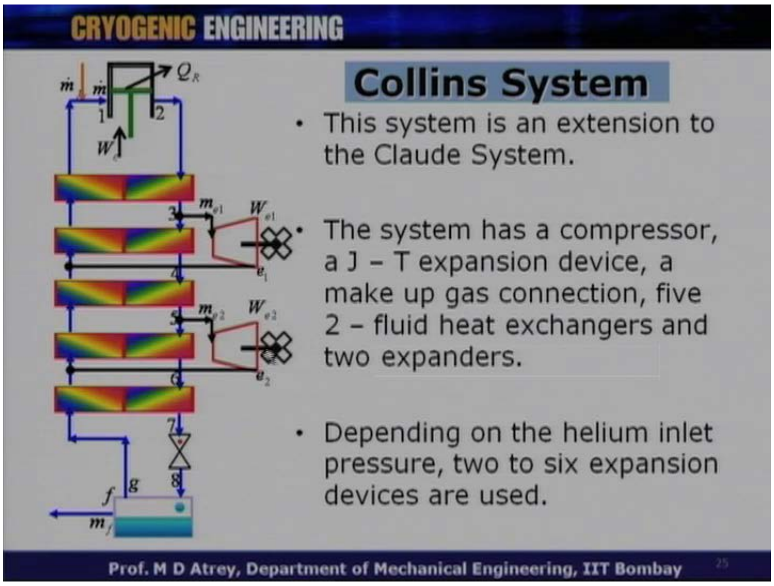
(Refer Slide Time: 30:26)



So, the yield and the work requirement of the system are given by following equations. Again actually, they remain the same; the formula mathematical formula remains the same as for Claude and Kapitza, y value is given by this equation and W net by m dot value also is given by this equation. And essentially, these points have that the expression for y and W net by m dot are essentially same for Claude system, Kapitza system and Heylant system.

But the cycle has changed in terms of all the changes, we have just talked about and these are the three important cycles for mostly used for air Liquefaction or for around 80 k operation. So, with this background of the Claude Cycle, Kapitza cycle and Heylant cycle. Now, I will talk about the low temperature cycle and the most important cycle called as Collin system or Collin cycle.

(Refer Slide Time: 31:23)



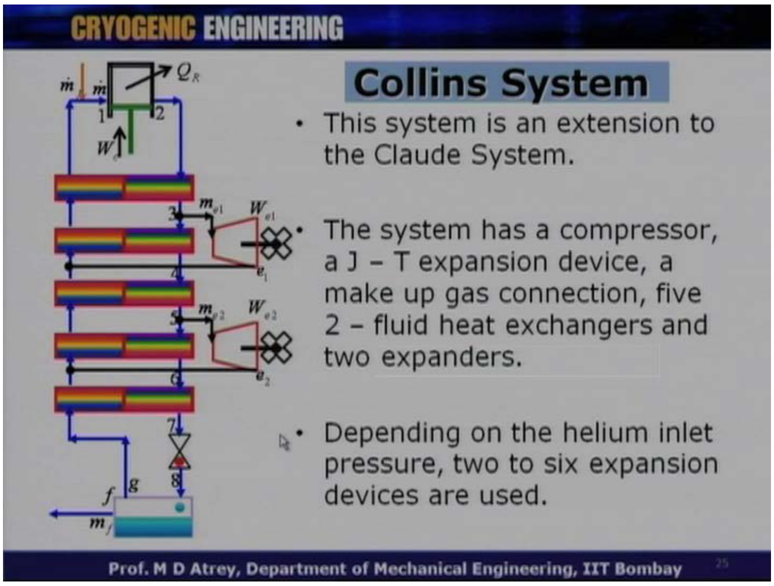
How does this cycle look? This looks more complicated and now as I said the basic objective of this cycle is to reach lower and lower temperature. And the Collin cycle is a very important cycle, which is used for Helium refraction or for those gases which have got very low temperature boiling point.

So, you can see how complicated it looks? It looks a very big cycle over here, what does it comprise of? And now, I am talking about reduction of temperature from 300 Kelvin to let us see 4.2 Kelvin, if I am talking about Helium as the working fluid. So, as soon as you see that the delta T span is from 300 Kelvin to 4.2 Kelvin. Essentially, it would have more heat exchangers, because we would like to have conservation of this cold. At the same time, because the inversion temperature of Helium is 45 Kelvin, I have to somehow come down much below 45 Kelvin and therefore, I need expansion devices to produce more and more cold.

So, one device may not be enough, as it was in Claude cycle, but now I mean in two devices or more than two devices. So, that the temperature before, the J - T expansion let us say at 0.7 here is much less than 45 Kelvin for Helium as a working fluid. So, a Collin system basically comprises of heat exchangers and expanders. It was invented in the year 1946 by Samuel C Collins at MIT, USA. Samuel Collins is a very well known in cryogenic engineering and there is actually an award given on Collins name conferences that are yield every alternate year. Collins award is a very prestigious award for doing some applied research work in the field of cryogenic engineering he was from MIT, USA.

This system is considered as one of the biggest milestones in Cryogenic Engineering and lot of variations or modifications happened over a period of time. If it was the first system or first practical system that came into existence for Helium Liquefaction.

(Refer Slide Time: 33:29)



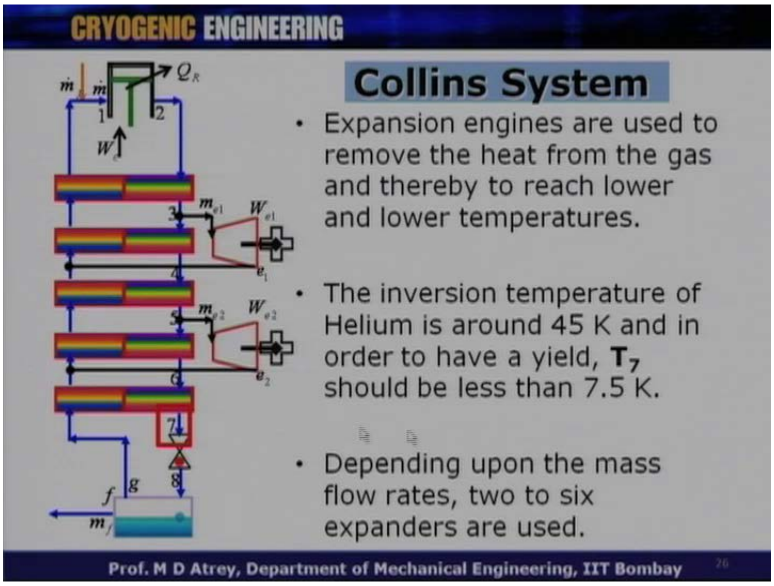
So, this system basically as you can see is an extension of Claude Cycle or modification of Claude cycle. The system has a compressor, which is what you see over here? A J - T expansion device which is what you see here. So, every system will have compressor J - T expansion and heat exchangers. It also has a makeup gas connection which is coming at this point. There are five 2 - fluid heat exchangers, you can see 1, 2, 3, 4, 5 and there are all 2 - fluid heat exchanger and not 3. As we had seen in couple of systems studied earlier and also it has 2 expanders. This could be turbo expanders; this could be reciprocating expanders also all right.

So, what we can see from here is? The gas gets compressed from 1 to 2, it gets precooled from 2 to 3 and some part of the gas amount into m e 1 is taken off from the main circuit and is expanded from m e 1 to e 1 and join the return stream at this point. The remaining gas is m minus m e 1 goes ahead and again at point 5 m e 2 gas is taken off again, it is expanded over here and it joins the return stream.

So, these basically two expanders produce cold and join the return stream. The remaining gas which is nothing, but m minus m e 1 minus m e 2 comes at point 7 gets expanded out of which m dot f goes out. The gas which comes at point g is going to be m minus m e 1 minus m e 2 minus m f. So, this gas is going to come over here and at appropriate points, the gas after expansion m e 2 and m e 1 join and the return stream will ultimately have m minus m f at this point, m f is a makeup gas and cycle continues and this is a way, this cycle operates.

Depending on the Helium inlet pressure, we can have 2 to 6 expansion devices. So, basically the flow rates are very high, you may have to worry about having number of expanders more all right, you may have to have more expanders in that case. But normally, the numbers of expanders are even number, because the vibrations have to get cancelled if you go for a reciprocating expanders.

(Refer Slide Time: 35:46)



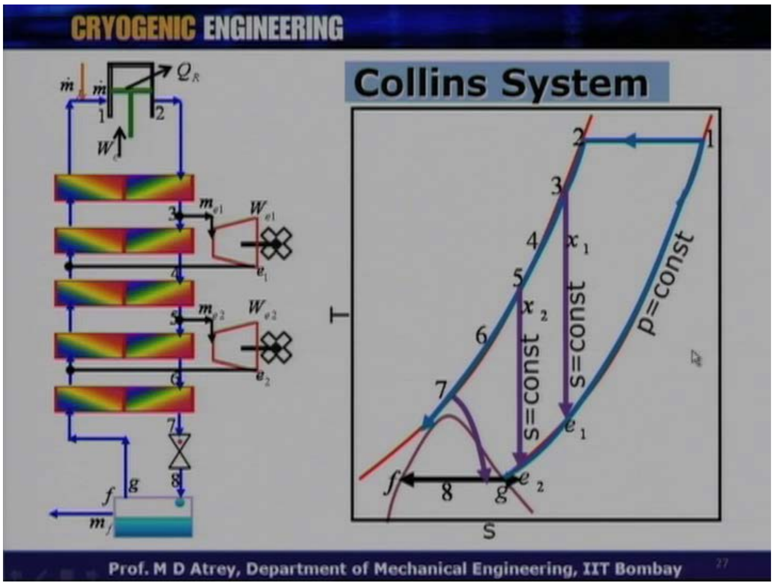
The expansion engines are used to remove the heat from the gas and thereby to reach lower and lower temperatures. So, ultimately these are the two expanders, which basically produce cold and once the temperature at 0.6 and 0.7 goes much below 45 Kelvin, the gas can get expanded producing Liquid. Till that time, there is no meaning to send in the gas at this point, because the isenthalpic expansion would actually result in warming of the gas.

The inversion temperature of Helium is around 45 Kelvin and in order to have a yield, the T 7 point has to be less than 7.5 Kelvin. It can be seen from a T - s diagram that, if the temperature at point T 7 is around 7.5 Kelvin, then only after isenthalpic expansion the point 8 would lie in the dome.

So, if you want to have Liquid Helium temperature at 0.7 should be less than 0.75 that is less than 7 Kelvin or 6.5 Kelvin or around those values, then only when you expand the gas isenthalpically from 7 to 8, the point 8 would lie in the dome. And therefore, you can imagine that we have to first decrease down the temperature of 0.7 at around 7.5 Kelvin below, then only you will get liquid Helium; the Helium is a working fluid.

Depending upon the mass flow rates as I said 2 to 6 expanders are used. So, two expanders are not being enough sometimes, it could be 4 expanders or sometimes it could be 6 expanders also.

(Refer Slide Time: 37:15)

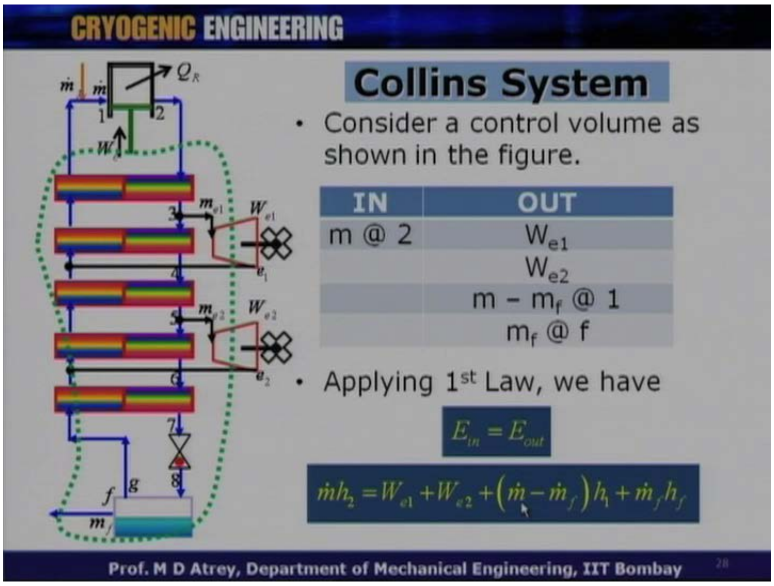


Now, this is a corresponding T - s diagram for the Collin system and what you can see here? The 1 to 2 is a compressor process, 2 to 3 is a heat exchanger process and at point 3 you got an isentropic expansion in the expander number 1. The remaining gas comes over and at 5 again, at this point you again got a second expansion from 5 to this. Also, you have to ensure that point e 2 should not lie in a dome, because in that case it will be weight expander and that is that has to be designed basically that is complete in new technology.

So, great to ensure that the isentropic expansion, the results in gas only and the reciprocating expanding devices would not like to have Liquid there, because of the compressibility effects coming into picture and therefore, you have to select a temperatures of point 5 and point 3 correctly. Also, what is important is? What is the value of x 1 and x 2? How much gas to be diverted through the first expansion device and how much gas to be diverted second expansion device? Also, what is important as I said earlier? The temperature at point 7 has to be less than 7.5.

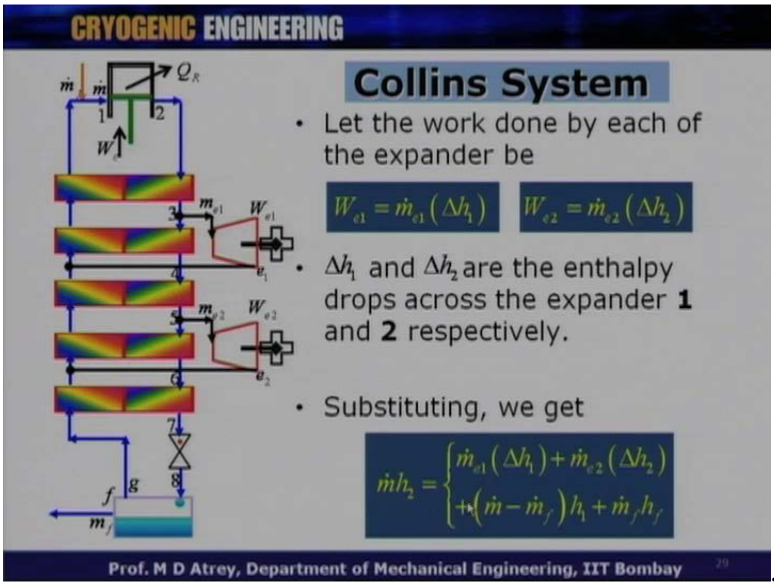
Then only the isenthalpic expansion would come in the dome. The temperature at point 7 should be less than 7.5 Kelvin. If it is more than 7.5 Kelvin, the isenthalpic expansion would come at somewhere this point and not in the dome and therefore, if you want to have liquid Helium you have to see that the point 7 is below 7.5 Kelvin. This can be seen clearly from the T - s diagram of Helium for a corresponding pressure of around 10 to 15 bar, the pressure at two will be around 10 to 15 bar.

(Refer Slide Time: 38:56)



Now, let us see what are the expressions for y or the yield and the power input for the Collin system. So, if we take these are the control volume and see the how much is going in and what is coming out. So, what is going in is basically m at point 2? What is coming out is W e 1, W e 2, m f and this point m minus m f at point 1. And if we apply the first law and if we do the energy balance what you see is m dot is 2 is equal to W e 1 plus W e 2 into m minus m f at h 1 plus m f h f. I think this is a very standard formula and we have derived it now many number of times. So, one should be able to put in this control volume and derive such expressions.

(Refer Slide Time: 39:40)

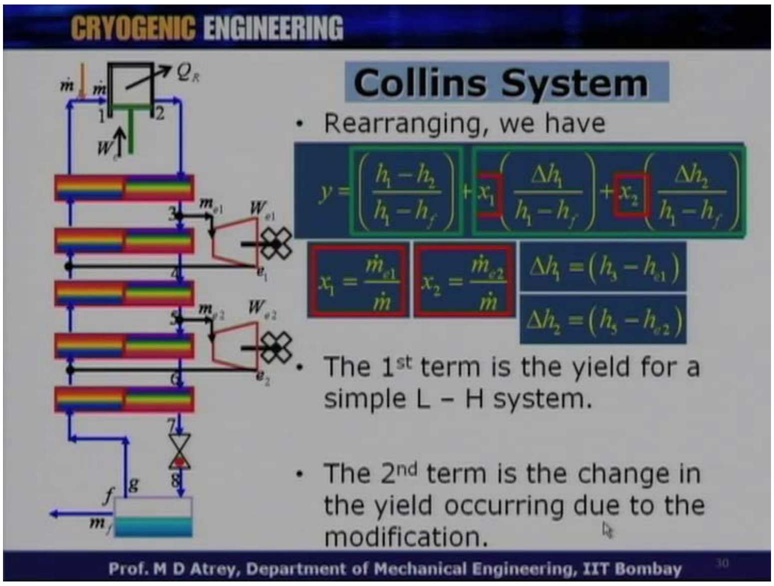


.

If the work done by each of the expander is going to be W e 1 and this W e 1 is nothing, but m dot e 1 into the enthalpy drop which is h 3 minus h e 1 and for the second expander W e 2 is nothing, but m dot e 2 into delta is to which is nothing, but h 5 into h e 2.

Delta h 1 and delta h 2 are the enthalpy drops across the expander 1 and 2 respectively. Substituting these values in the earlier equations so, what you get is? m dot h 2 is equal to W e 1 plus W e 2 plus m minus m f h 1 plus m f h f putting the value of W e 1 and W e 2 here.

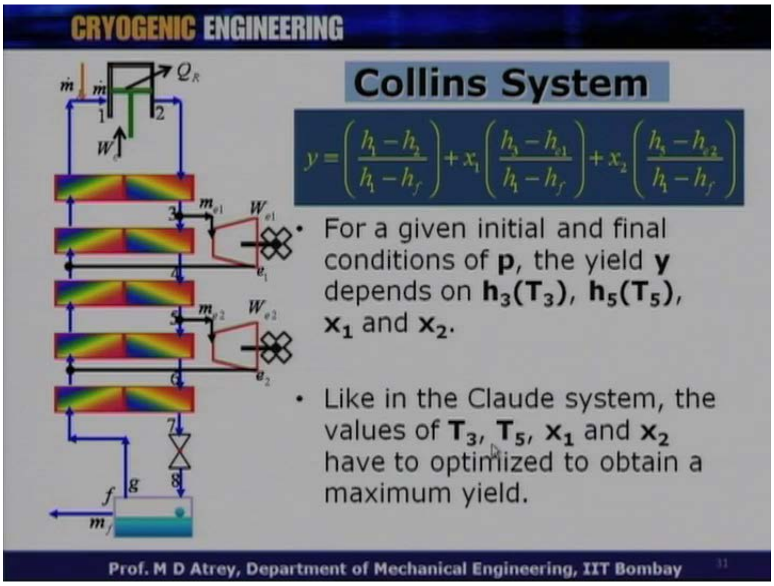
(Refer Slide Time: 40:15)



Rearranging all the terms the expression what you get is this? y is equal to h 1 minus h 2 upon h 1 minus h f plus x 1 times delta h 1 upon h 1 minus h f plus x 2 times delta h 2 upon h 1 minus h f where delta h 1 is h 3 minus h e 1 delta h 2 h 1 minus h e 2. This is the formula again to calculate y value, when you got a finite gas coming out of the container; that means, m minus m f minus x 1 minus x 2 is a finite quantity. As you remember in Claude Cycle, we have seen that x plus y cannot be more than 1 similarly, here we have to see that the gas returns, the quantity of the gas at this should be finite. So, m minus m f minus x 1 minus x 2 has to be positive quantity. So, where x 1 is equal to m e 1 by m dot x 2 is equal to m e 2 by m dot.

First term here basically nothing, but the yield due to Lindsey Hansen and additional terms which is coming, because of x 1 and x 2 is an addition to y value, because of this diverting these gases m e 1 and m e 2 to the expanders 1 and 2 respectively. These basically, give the additional yield or a y value.

(Refer Slide Time: 41:32)

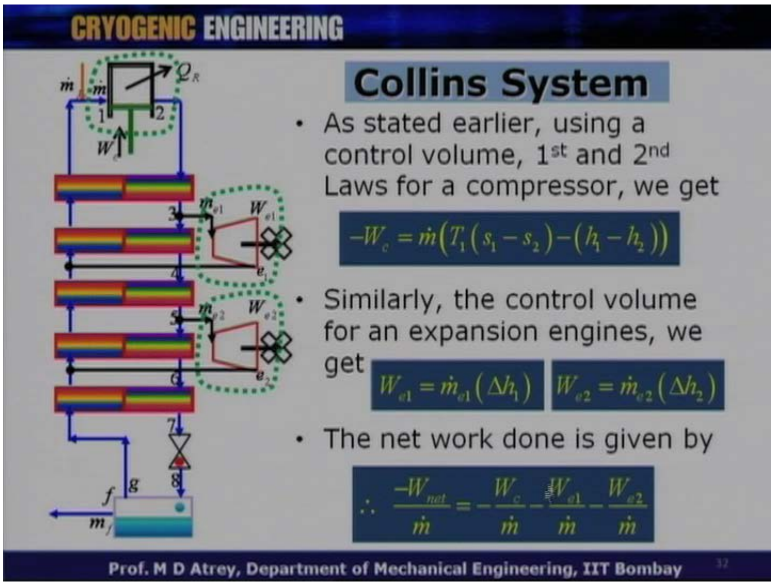


So, this is the net equation what you can see for y? For a given initial and final condition of p, the yield y depends on h 3 that is temperature T 3, h 5 that is temperature T 5 and x 1 and x 2. So, you can see that if the initial and final values are fixed here, h 1 and h 2 are immediately fixed assuming that your compression process at ambient temperature.

So, what does here y depend on the y depends on the value of x 1 and x 2 and correspondingly, the value of T 3 which determine h 3 and T 5 which is h 5. So, basically T 3, T 5, x 1 and x 2 are the critical parameters for a given pressure conditions of 1 and 2. And this has to be optimized, in order to get maximum y or minimum work done and this is very important optimization emphasize that has to be decided, that has to be calculated, that has to be solved in order to get optimum value of T 3 and T 5. And corresponding to this value of T 3 and T 5, one should get optimized value of x 1 and x 2; this is the very important exercise.

I am not going to go in the details of those; we have done that for Claude Cycle may be if you are interested, if you go into the optimization of Collin cycle. Like the Claude system, the values of T 3, T 5, x 1 and x 2 have to be optimized to obtain maximum yield or a minimum work done for getting gas liquefaction.

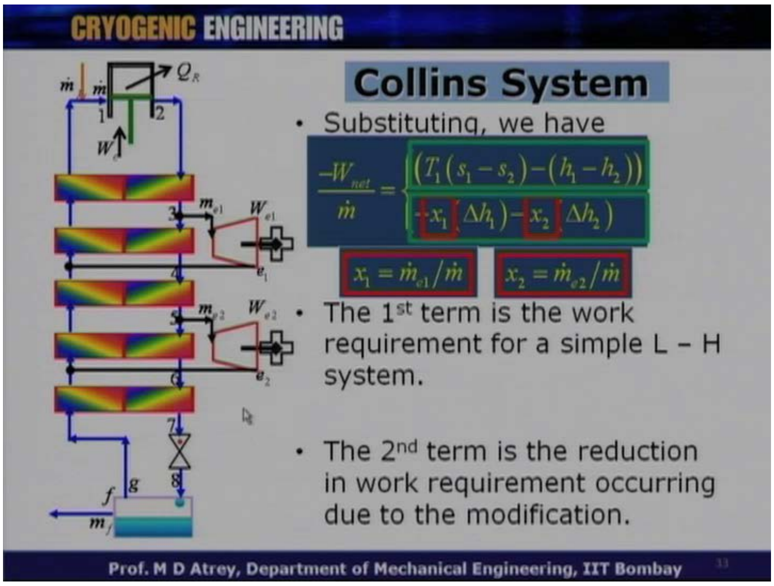
(Refer Slide Time: 43:00)



As stated earlier, using a control volume, first and second order loss for a compressor, what we get is? W c is equal to m dot T 1 s 1 minus s 2 minus h 1 minus h 2. Similarly, the control volume for expansion also, one gets W e 1 is equal m dot e 1 into delta h 1 W e 2 into m dot is equal to m dot e 2 into delta h 2.

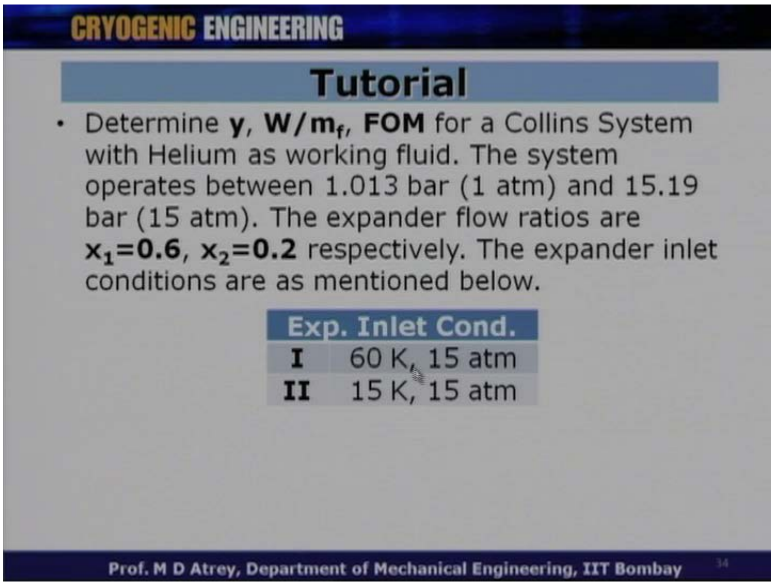
So, net work done is basically going to be this minus, this minus, this, because this is the work done by the systems. The net work done is given by minus W net upon m dot is equal to minus W c upon m dot, which is work done on the system, minus W 1 minus m dot minus W 2 upon m dot and these are nothing, but the decrease in the net work done due to the work obtained in the expansion devices.

(Refer Slide Time: 43:45)



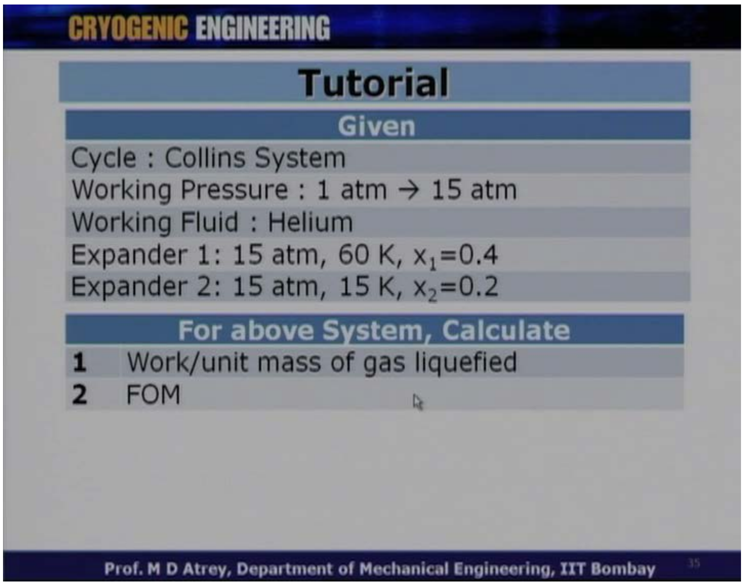
So, if you put those values W net by m dot that is net work done per unit mass of gas which is compressed is going to be T 1 into s 1 minus s 2 minus h 1 minus h 2 minus x 1 into delta h 1 minus x 2 into delta h 2. Where, x 1 is this and x 2 is this. The first term here again is basically, the simple Lindsay Hansen work and the second term is the reduction in the work done due to the expansion devices 1 and 2 respectively.

(Refer Slide Time: 44:13)



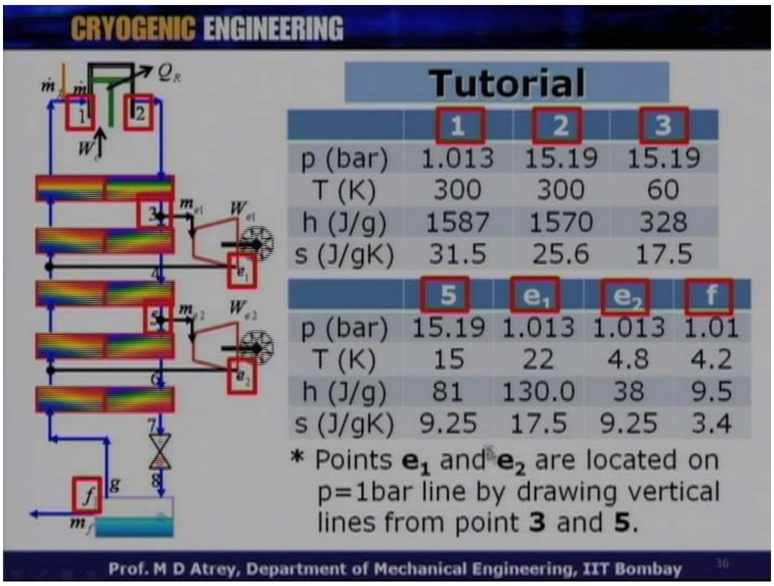
Now, we are determining the tutorial is going to be solved to understand the y W by m f and a Figure of Merit for a Collin cycle with Helium as a working fluid for 1 atmosphere and 15 atmosphere. The expanders flow rates are 0.6 and 0.2 and the expander 1 and 2 respectively. The expander inlet conditions are given here 60 Kelvin and 15 Kelvin form 15 atmosphere.

(Refer Slide Time: 44:36)



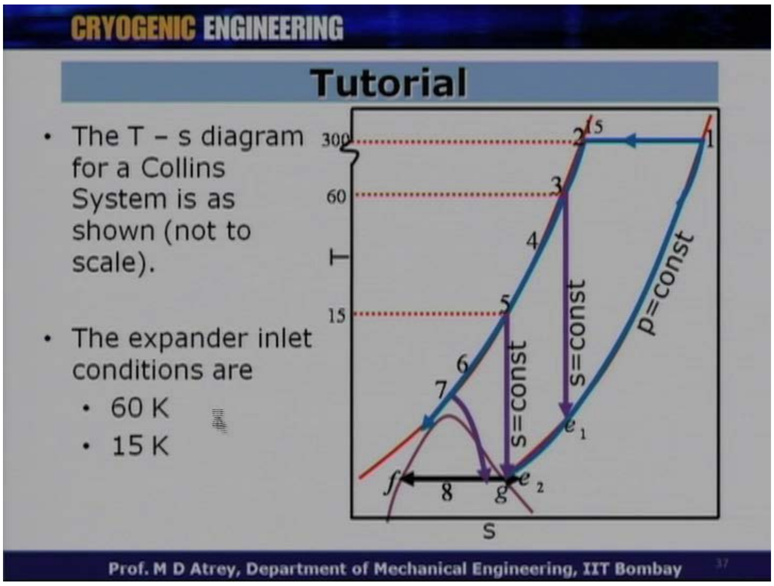
So, these are my input conditions find the work per unit mass of gas liquefied and figure of merit.

(Refer Slide Time: 44:40)



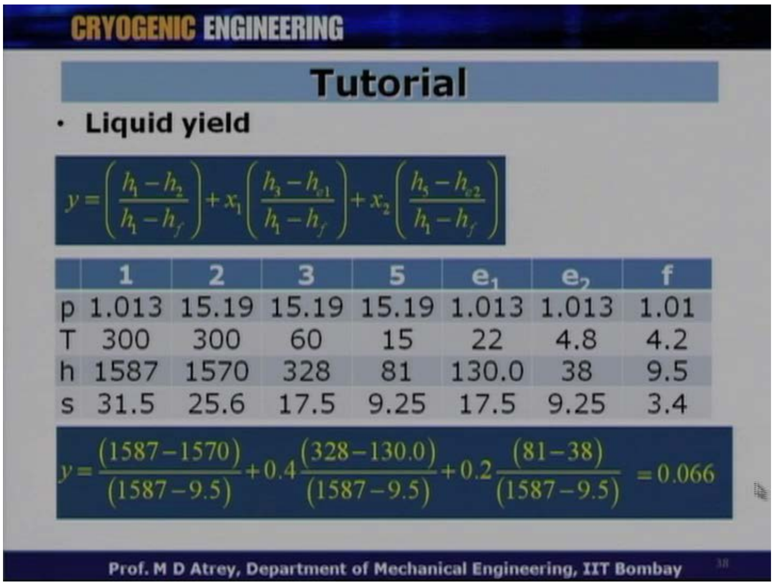
This is the Collin cycle, these are different values for 1, 2 and 3 and 5 and then even and into are nothing, but the low pressure things and the even and e 2 are basically located by drawing verticals from 3 and 5 on low pressure line.

(Refer Slide Time: 45:02)



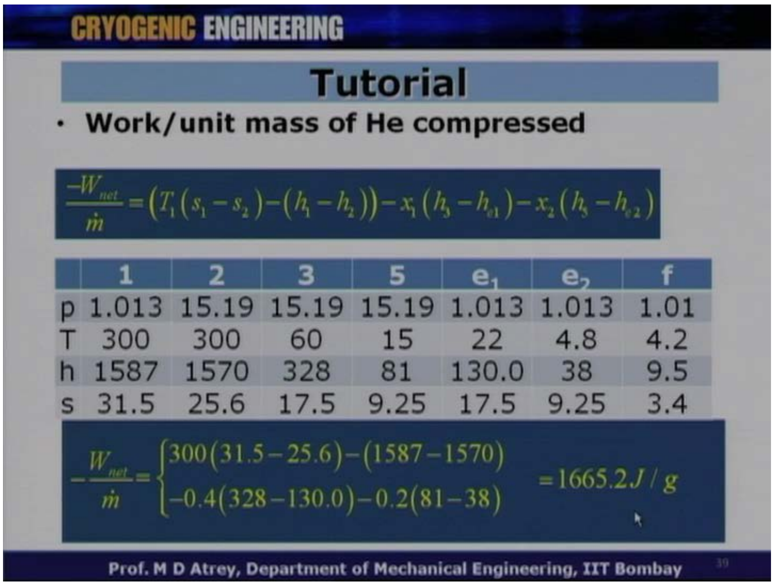
What you have to do is? Basically now, apply the formula and this is what a T - s diagram is 1 to 2 is a compression from 1 bar to 15 bar and 60 Kelvin temperature is at point 3 and 15 Kelvin temperature is at point 5. Where, the expansion happens, this is x 1 and x 2, point 6 and point 2 is respectively.

(Refer Slide Time: 45:18)



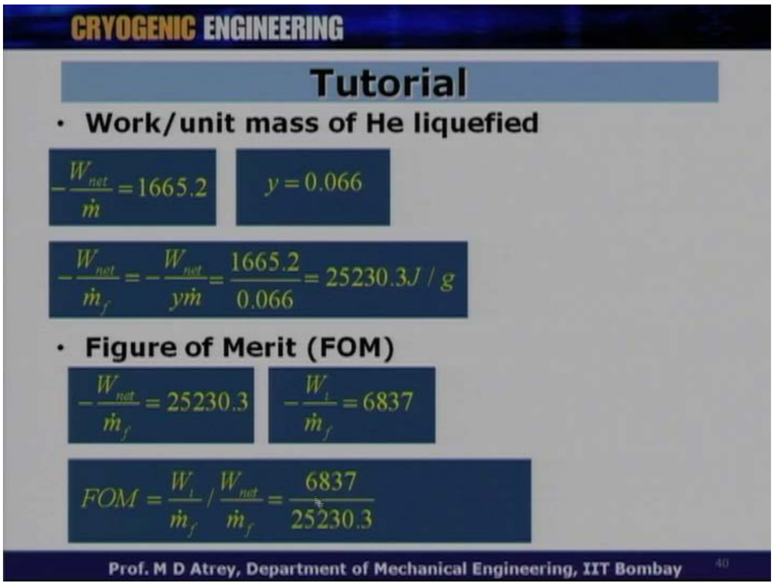
So, liquid yield given by this formula, these are my enthalpy values put up those values over here what you get y is equal to 0.066. This is straight formula application.

(Refer Slide Time: 45:30)



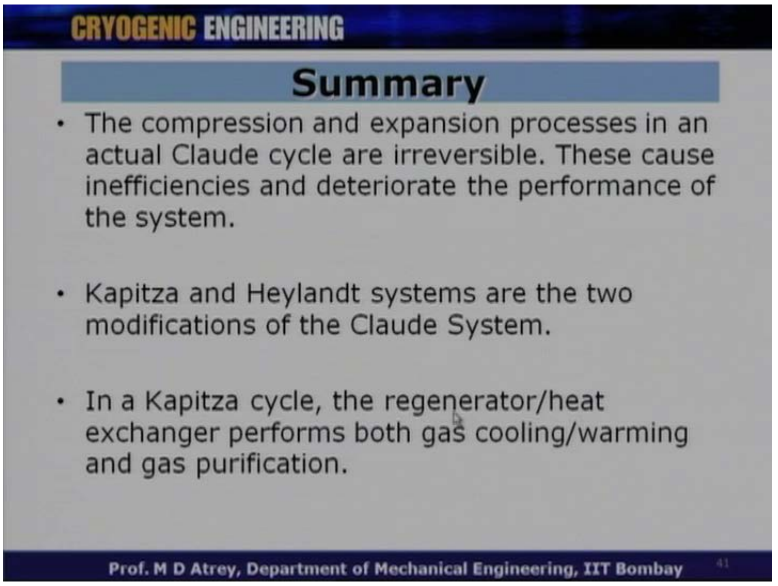
If I want to come calculate, the work per unit mass of gas compressed is again applying the same formula get the enthalpy values and this is what W net by m dot.

(Refer Slide Time: 45:41)



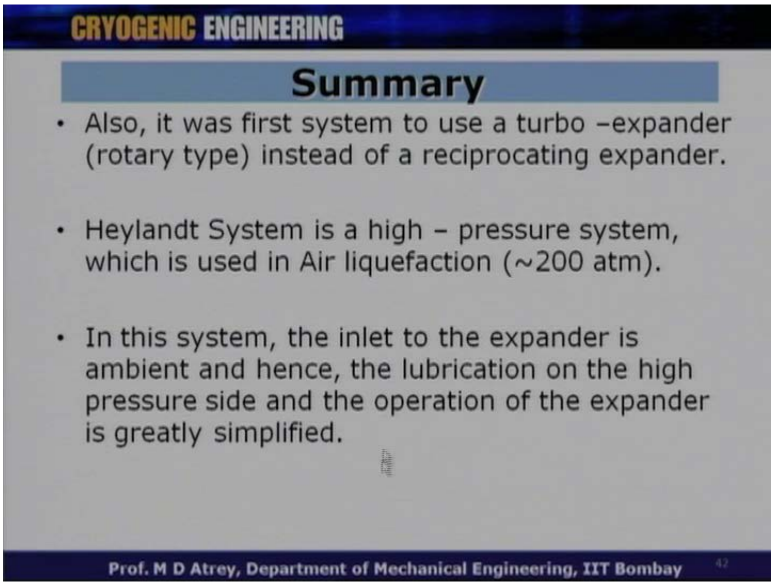
What I want is? W net by unit gas of mass of gas liquefied. So, I divide this by y and what you get is 25230.3. If I want to calculate figure of merit, it is going to be W net upon m dot f divided by the ideal work done which is just 6837. So, you can see 25230 and 6837, if one divides these values this. The Figure of Merit happens to be 0.27 and this is what is simple to tutorial of Collin cycle?

(Refer Slide Time: 46:09)



Just to summarize, what we have done? The compression and expansion processes in an actual Claude Cycle are irreversible. These cause inefficiencies and deteriorate the performance of the system. Kapitza and Heylant systems are the two modifications of the Claude system. In a Kapitza cycle, the regenerator or the heat exchanger performs both gas Cooling and the warming and gas purification. This is the first heat exchanger of the Claude Cycle, which works as a gas purifier also and actually, it is a rotary regenerator or a rotary heat exchanger. Why is called regenerator, because it is regenerates. It gets purified of it is own, because of the rotation of the heat exchanger.

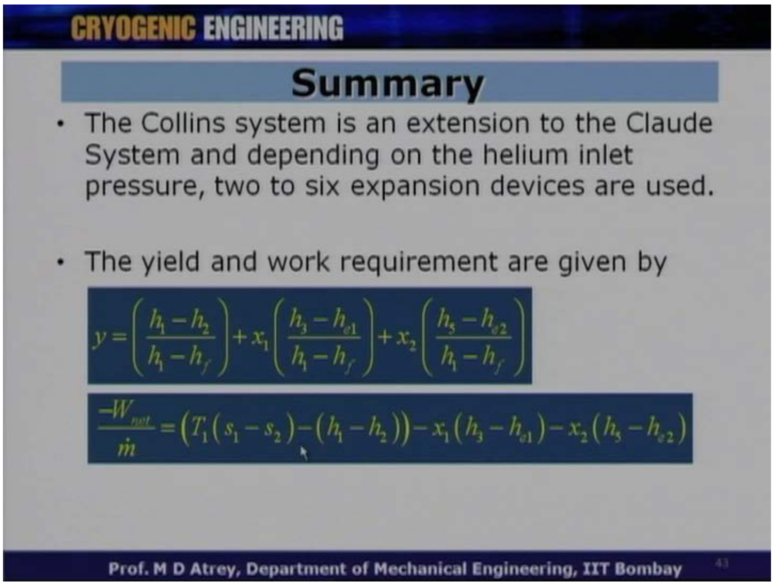
(Refer Slide Time: 46:54)



Also, it was the first system to use turbo expander, rotary type expander instead of a reciprocating expander. So, lot of changes took place in a Kapitza cycle so, as to bring it to a commercial level. Heylandt system is a high pressure system, which is used for air liquefaction and normal pressure is on 200 atmosphere.

In this system, the inlet to the expander is ambient and hence, the lubrication on the high pressure side and the operation of the expander is greatly simplified. So, Heylandt system also has got it is relevance, because the expander is working on the high pressure side at ambient temperature.

(Refer Slide Time: 47:30)

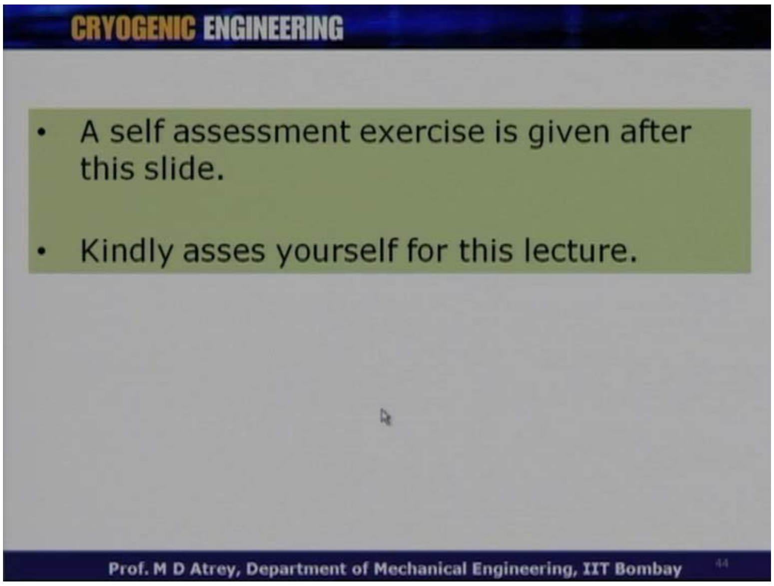


The Collin system is an extension of the Claude system basically, it is called as modified Claude Cycle also and depending on the Helium inlet pressure, two to six expansion devices are used. The Collin cycle is normally used to reach down lowering temperature of let say around 4.2 Kelvin temperature and therefore, the number of heat exchangers increase, the number of expanders also increase depending on the flow rates what we are talking about?

The yield and work requirements are given by, for Collin cycle as this formula. So, you can see that first term is basically Simple Linde - Hampson and the yield, increases amounting to whatever x 1 into delta h that is happening across the first expander plus x 2 into delta h that is happening around the second expander. So, effectively there is increase in the yield, amounting to the gas which is diverted in x 1 and x 2, but as I said that you have to consider that the return stream also, has to have a finite mass flow rate during calculations.

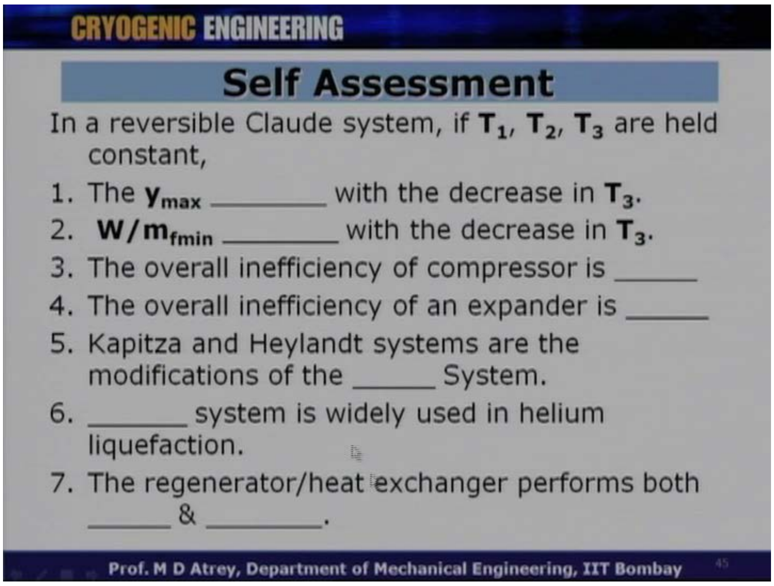
You cannot go on increasing the values of x 1, and x 2 like that. They have to be optimized with corresponding value of T 3, and T 5. The net work input also gets reduced, because of the work done by the system given by x 1 to delta h minus x 2 into delta h. So, in the reduction in the work done as compared that of Linde - Hampson cycle.

(Refer Slide Time: 48:50)



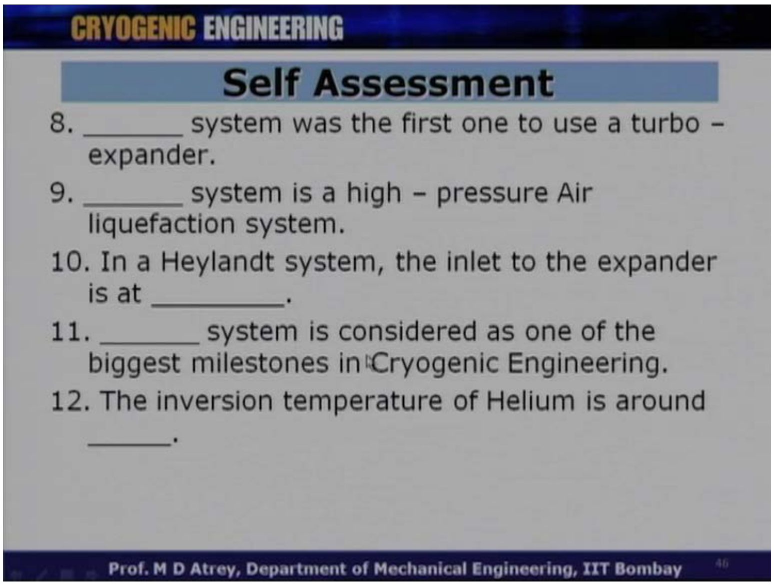
A self assessment exercise is given after this slide. Kindly asses yourself for this lecture.

(Refer Slide Time: 48:57)



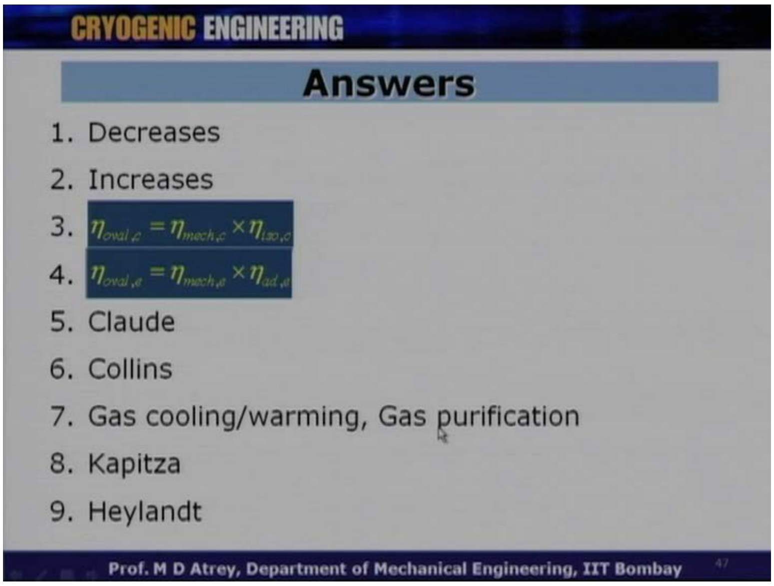
And there are various questions asked over here and I would like to go through self assessment try to answer those questions and write yourself across and see how much you have gathered from this lecture.

(Refer Slide Time: 49:10)



There are around 12 questions and this is just a quick response for you basically to know where, you stand as well as this lecture is considered.

(Refer Slide Time: 49:20)



There are answers given over here. Thank you very much.