Cryogenic Engineering
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Lecture No. # 12
Gas Liquefaction and Refrigeration Systems

So, welcome to the twelfth lecture of cryogenic engineering. We are talking basically on the gas liquefaction and refrigeration at very low temperature.

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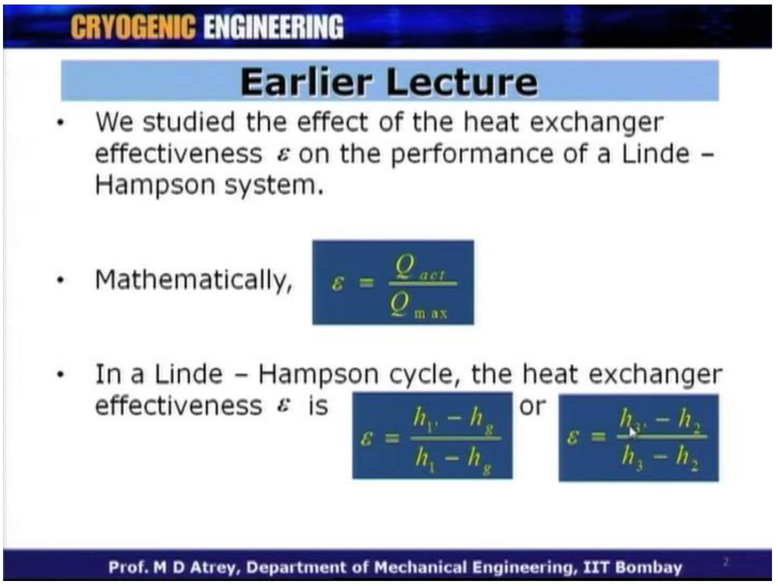

Just to take an overview of the earlier lecture, we had studied earlier the Linde - Hampson system for gas liquefaction and we studied the effect of heat exchanger effectiveness that is epsilon on the performance of this cycle, which is called as Linde - Hampson system. Before this we had studied ideal thermodynamic cycle and then we had the first cycle called Linde - Hampson system, in which we studied the effect of heat exchanger effectiveness.

Mathematically, the heat exchanger effectiveness epsilon is actual heat transfer divided by maximum possible heat transfer. Thereby, the epsilon value will be between 0 to 1; that is 100 percent effectiveness, when epsilon is equal to 1.

We also saw that in a Linde - Hampson cycle, the heat exchanger effectiveness epsilon is h 1 dash minus h g upon h 1 minus h g meaning that h 1 dash minus h g is the enthalpy difference, which represent actual heat transfer that is occurring in the heat exchanger divided by h 1 minus h g. This is the enthalpy difference between point 1 and g and this is the ideal or maximum possible heat transfer that can take place, when the effectiveness is 100 percent.

This is, we are talking at lower pressure region or the suction pressure of the compressor side and if we talk about the discharge pressure of the compressor side; that means high pressure side. The same value can be interpreted as the actual heat transfer in this case now, becomes h 3 dash minus h 2 at point 3 dash and 2 divided by maximum possible heat transfer which is h 3 minus h 2, these being the enthalpy values at point 3 and 2 respectively.

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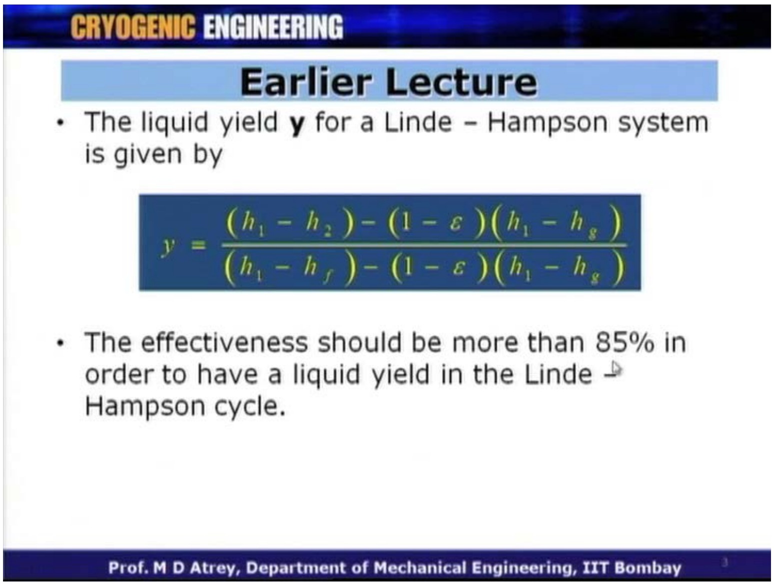

At the same time, the liquid yield y for a Linde - Hampson system is given by y is nothing, but the ratio of m dot f upon m that is the mass fraction of the m dot which gets liquefied which is called as m dot f. So, y is equal to h 1 minus h 2 minus 1 minus epsilon into h 1 minus h g divided by h 1 minus h f minus 1 minus epsilon into h 1 minus h g. So, you can see in this term that the epsilon represents, the effectiveness of the heat exchanger and when epsilon is equal to 1 or 100 percent, y is getting reduced to h 1 minus h 2 divided by h 1 minus h f all this right hand side, which is a negative side to this numerator and denominator becomes equal to 0.

So, here you can understand that how sensitive the value of y is to the value of epsilon in this case. We have also seen the effectiveness should be more than 85 percent in order to have a liquid yield in the Linde - Hampson cycle. We had seen with a help of a numerical that as the value of epsilon decreases and when it decreases below 85 percent.

The value of y is very very close to 0 or almost 0, meaning which that the heat exchanger effectiveness should be very high, it should much higher than 85 percent. If you want to have a good value of y and normally this value will be around 95 percent or above in order that you get a high value of y or a significant value of y in this case.

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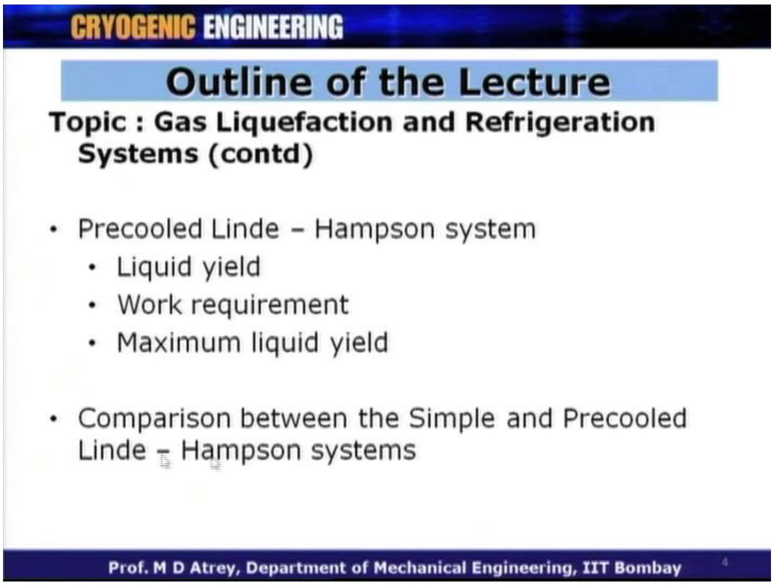

With this background the outline of today's lecture, the topic of which is gas liquefaction and refrigeration systems. We will talk about now, a new system which is a precooled Linde - Hampson cycle. In the earlier time, we had seen Linde - Hampson system now, we will see precooled Linde - Hampson system. Under which we will study the expressions or we will talk about how much y could be obtained with the precooled Linde - Hampson system that is liquid yield what is the work requirement for this cycle? And what is the maximum liquid yield for this cycle? And then we will compare the results obtained, using this cycle with simple Linde - Hampson systems. So, what we will do is comparison between the simple and precooled Linde-Hampson systems.

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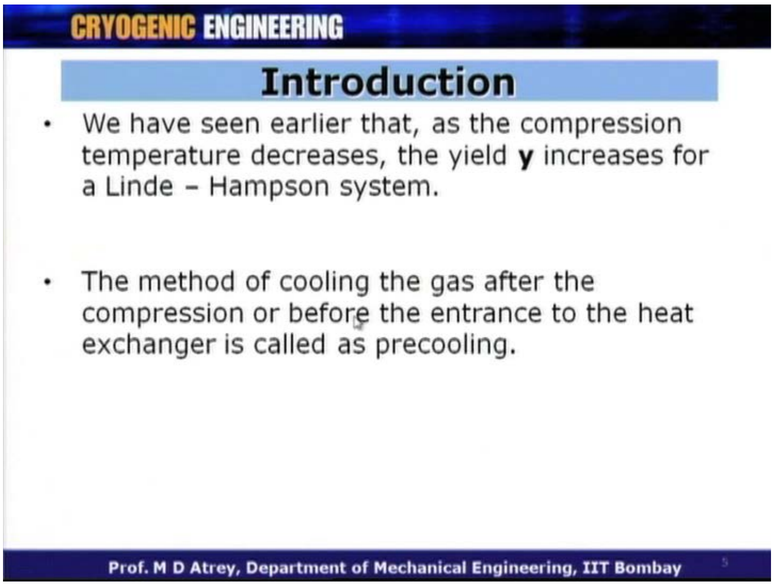

We have seen earlier that, as the compression temperature decreases, the yield y increases for a Linde - Hampson system. This we had again seen with an example that, if the compression temperature instead of happening at room temperature of 300 Kelvin, if happens at 200 Kelvin, the value of y increases or the yield increases. The method of cooling of the gas after the compression or before the entrance to the heat exchanger is called as precooling. So, when we are precooling basically, what we are doing is? We are precooling the gas and we are precooling the gas at the entrance to the heat exchanger or the first heat exchanger after the compressor.

So, one way of doing this is basically, we can reduce the compression temperature which is normally not possible, because compressor cannot work at lower temperature. So, normally the process of compression would occur at room temperature or at 300 Kelvin and if you want to precool the gas this has to be done after the compressor and therefore, the gas would enter the first heat exchanger at a lower temperature than room temperature and this is what we call as precooling the gas.

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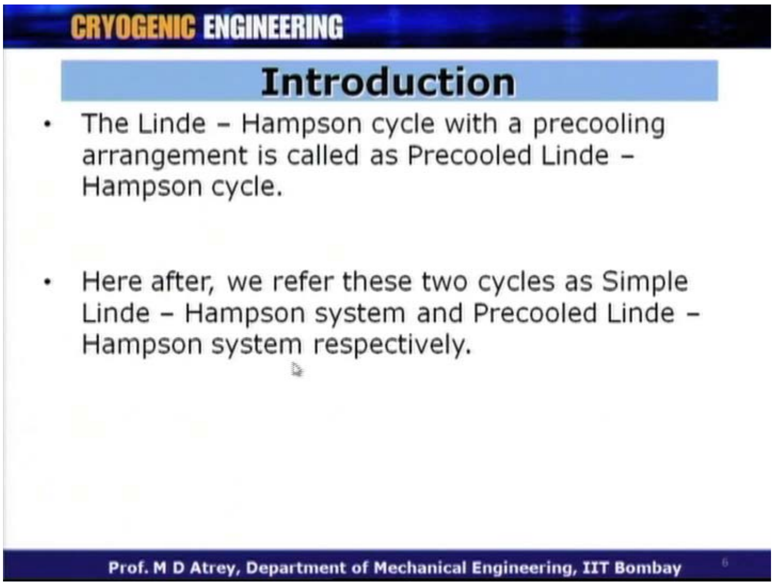

The Linde - Hampson cycle with a precooling arrangement is called as precooled Linde - Hampson cycle All right. So, normally we will call Linde - Hampson cycle; that means a normal or a simple Linde - Hampson cycle, but whenever it has got a precooling arrangement, it will always be called as precooled Linde-Hampson cycle. Hereafter, we refer 2 cycles as simple Linde - Hampson system and precooled Linde - Hampson system respectively.

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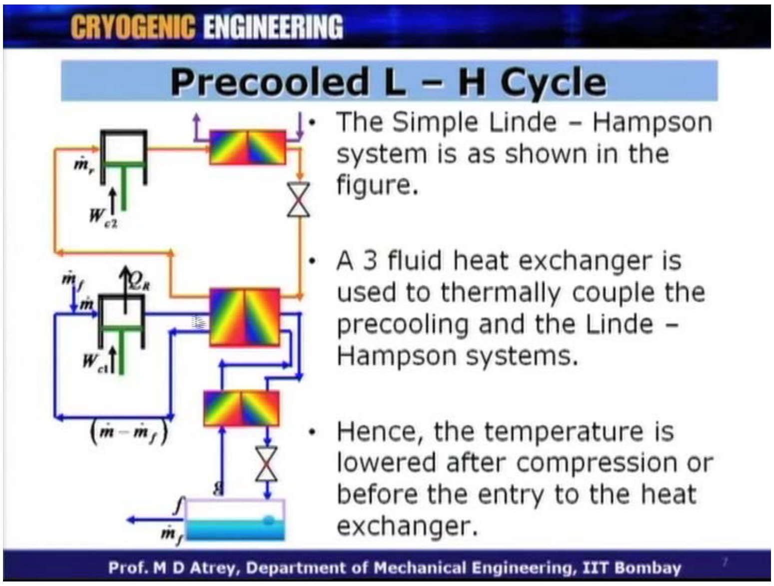

So, let us see now, what is included in the precooled Linde-Hampson cycle? The simple Linde - Hampson system is shown in the figure and this is what you can see? So, here you can see the simple Linde - Hampson cycle with a compressor, then the compressed gas comes to the heat exchanger, the gas expands what you get here is, m dot f liquid.

The return gas goes to this heat exchanger precooling the gas which is coming at high pressure and then the gas goes back to the compressor m dot f is obtained at this point the returned gas is m dot minus m dot f and again m dot f is added at this point as replenishment and the cycle continues. So, this heat exchanger is a part of Linde - Hampson system in addition to this, Linde - Hampson heat exchanger what will you have is one more heat exchanger and which is called as precooling heat exchanger.

So, this is the second heat exchanger, which is added over here and now, you can see that the high pressure gas which is coming out of the compressor is getting precooled in this heat exchanger. Now, how is it getting precooled? It is getting precooled by other gas which is passing through it and this gas is going to pass through this heat exchanger at a much lower temperature or at a temperature at which you want to precool this gas.

So, this gas which is coming out room temperature at this particular point will get precooled, because of other refrigerant or other precooling circuit thereby, making this heat exchanger as a three-fluid heat exchanger. You can see already there are 2 fluids passing through it, we have got a third fluid coming through this heat exchanger and therefore, this is called as a three-fluid heat exchanger.

So, for precooling what we are having, In addition to the Linde - Hampson system is we got a one more heat exchanger which is now, a three-fluid heat exchanger. So, a three-fluid heat exchanger is used to thermally couple the precooling and the Linde - Hampson system. So, this is now, a Linde-Hampson system with a precooling heat exchanger in addition to this now, how is this pre coolant or how this refrigerant coming, it has got one more circuit and this is called as a precooling circuit. Now, this precooling circuit will have it is own refrigerant depending on the temperature of our interest. A refrigerant has to be selected in such a way that this refrigerant will precool the high pressure gas at this point.

Now, as soon as you have got one more refrigerant, you have got one more compressor and this fore this will be called as refrigerant compressor and this follows a simple vapor compression kind of a cycle and therefore, it has got a condenser at this point and this condenser could be air cooled or could be water cooled. So, we got a one more arrangement which is shown over here, this basically does the condensing of this refrigerant and it could be air cooled condenser or it could be a water cooled condenser also.

So, what you have got? Now, here 2 circuits, one is a precooling circuit and one is a Linde - Hampson system or a simple linde - Hampson system with a precooling heat exchanger and this whole arrangement is called as precooled Linde - Hampson cycle. Hence, because of this three-fluid heat exchanger, the temperature is lowered after compression or before the entry to the heat exchanger.

So, why are we doing all this exercise, we are doing all this exercise. So, that the working fluid at this point could be nitrogen, oxygen or air whatever you want to liquefy is entering this heat exchanger at much lower temperature than what it used to be? Basically, it was coming at room temperature earlier. Now, with this precooling arrangement, the gas enters this heat exchanger at a lower temperature than the ambient temperature here all right. So, the whole exercise is basically being done in order that, the gas enters this heat exchanger at lower temperature than it used to be and this is what a precooling circuit is doing?

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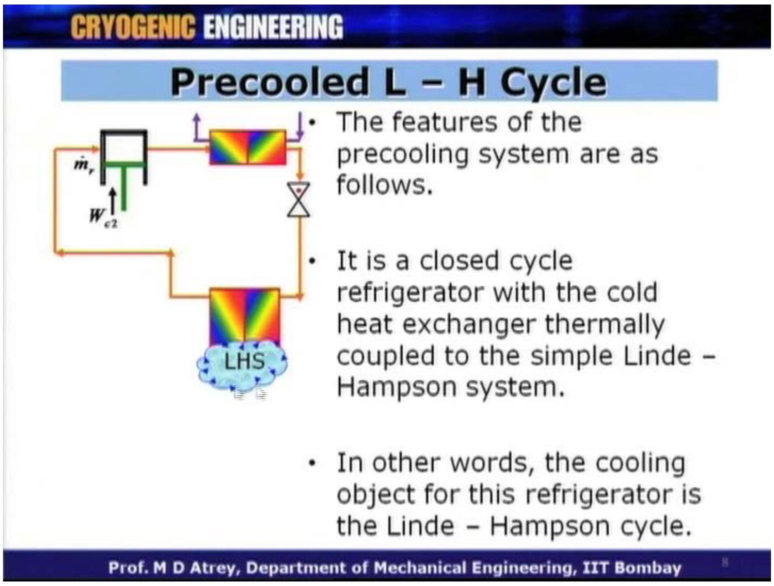

So, this is a precooling circuit, which is comprising of this compressor, condenser, a J-T valve and a precooling heat exchanger over here. Now, this precooling heat exchanger is basically, precooling the linde - Hampson cycle. The features of the precooling system are as follows, it is a closed cycle refrigerator with the cold heat exchanger thermally coupled to the simple Linde - Hampson system. So, this is basically the connecting point and this is thermally coupled with the simple Linde - Hampson cycle.

Now, what you can see here is? m dot r is the flow of refrigerant at this point. So, you got a compressor, which is compressing refrigerant of mass flow rate m dot r. Naturally, when you got a compressor you got to supply the power to it and the power to this compressor is W c 2, while power to the main Linde - Hampson cycle will be W c 1. So, nothing is coming free, here you got to have more power input to be done for this compressor and we are compressing m dot r, which is the mass flow rate in this circuit or the precooling circuit.

This system is basically, the Linde - Hampson system or this is a load on this precooling circuit all right. So, here you can see that the heat exchanger is thermally coupled to the simple Linde - Hampson system in other words, the cooling object for this refrigerator is Linde - Hampson cycle. So, what it is cooling? It is cooling basically, the Linde - Hampson cycle.

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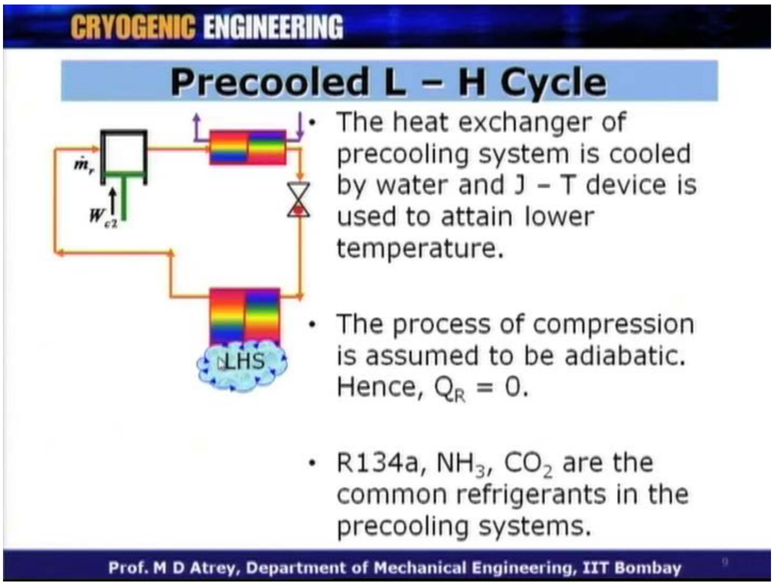

The heat exchanger of the precooling system is cooled by water. So, this could be cooled by water sometimes, it could be by air also and a J - T device is used to attain lower temperature. So, what you have as a compressor the heat exchanger, a J-T expansion valve and a precooling heat exchanger. The process of compression is assumed to be adiabatic in this case. So, we have not shown Q R value over here. So, we can assume that this compressor is adiabatic while as you know in the Linde - Hampson cycle, we can assume that the process of compression is close to isothermally. So, in this case Q R will be equal to 0, because it is assumed to be adiabatic in this case.

What could these precoolants be? These precoolants are basically refrigerant and depending on their choice or depending on your precooling temperature whatever, you want to consider depending on what you want to liquefy in the main circuit? We can have different refrigerants R 1 34a, NH 4, c o 2 etcetera are the common refrigerants in the precooling systems. Now, depending on this refrigerant one has to choose what kind of compressor, condenser, expander should be used and depending on this refrigerant also you will get the precooling temperature at this point.

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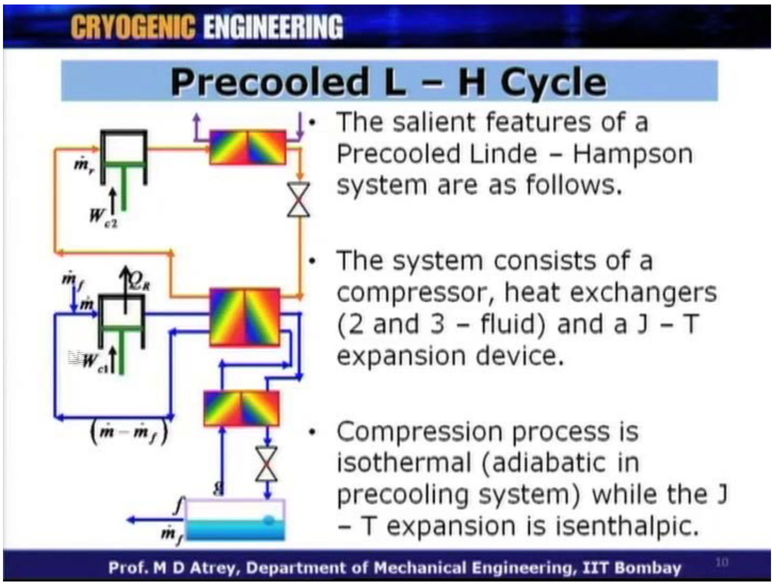

So, this is the whole arrangement with the precooling circuit and Linde - Hampson cycle. The salient features of a precooled Linde - Hampson system are as follows. The system consists of a compressor, this is a compressor heat exchanger which is a 2 fluid and a 3-fluid. So, it has got 2 compressor, one is a 3-fluid compressor and one is a 2 fluid compressor and a J - T expansion device. In the complete circuit what you have is a 1, 2 and 3 heat exchangers, but if you talk about only precooled circuit in the Linde – Hampson. We have got 2 heat exchangers now, one is a 3-fluid, other one is a 2-fluid and we have got a one J - T expansion valve. The compression process is isothermal here in this case and that is why you have got a value of Q R and W c 1 associated over here, while as I said earlier that the process of compression here in this precooling circuit could be assumed to be adiabatic in nature, while the J-T expansion is isenthalpic you know that the expansion through J-T is always isenthalpic.

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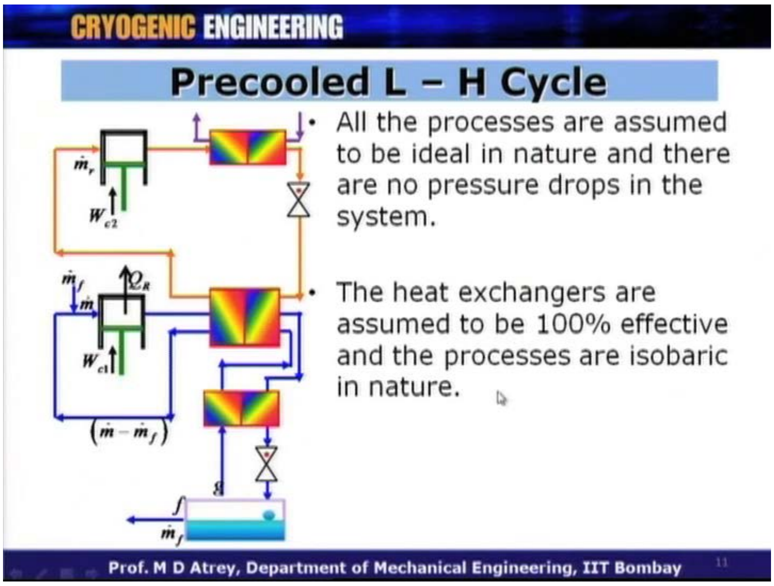

All the processes are assumed to be ideal in nature and there are no pressure drops in the system. So, when we are analyzing this cycle now, we will assume that all the processes are ideal; that means, all the heat exchangers are ideal the adiabatic compressor over at this point and the isothermal compression process at this point. The heat exchangers are assumed to be 100 percent effective and the processes are isobaric in nature.

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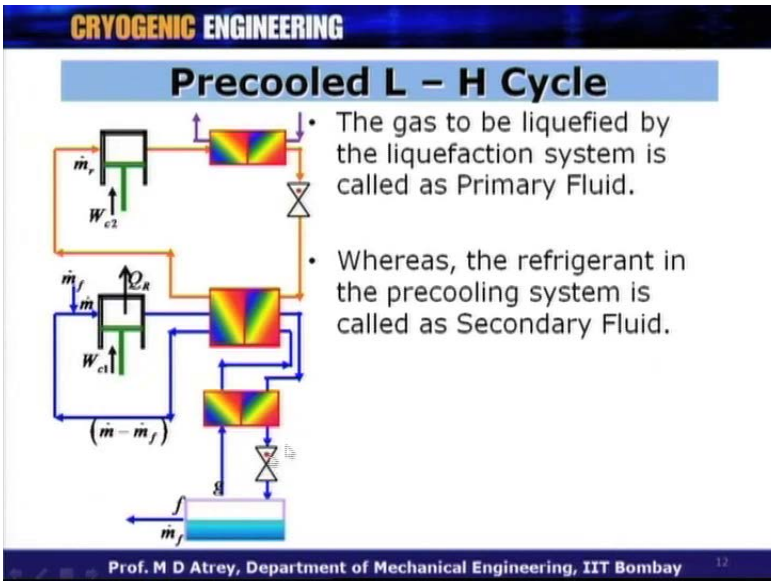

The gas to be liquefied by the liquefaction system is called as primary fluid. So, we can call this as a primary fluid which could be nitrogen, oxygen, air whatever you want to liquefy whereas, the refrigerant in the precooling system is called as secondary fluid. So, you can call this as the primary fluid or a primary system you can call this as a secondary fluid or a secondary system or a precooling system also. So, when depending on the references you can call this as the primary circuit secondary system or a Linde - Hampson cycle and a precooled Linde - Hampson cycle etcetera lot of connotations, lot of ways of addressing this system.

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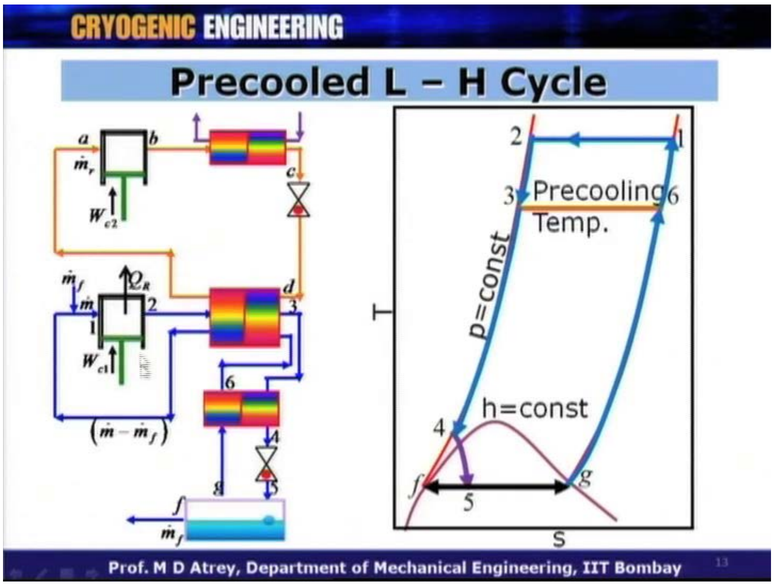

So, now if I want to represent the whole system on a TS chart which is what a very important task is, it will look like this. So, process we are talking about this now, here 1 to 2 is a compression and 2 to 3 is a precooling. So, here the gas gets precooled from 2 to 3 at a temperature which is which could be called as the precooling temperature all right. And then the gas gets further precooled from 3 to 4 in a major heat exchanger at this point as you can see, then there is an isenthalpic expansion.

The return gas goes at g it goes up to 6 at this point and then the gas gets warmed up to point 1 in this precooling heat exchanger. So, the whole processes are shown over here and this temperature at point 3 or 6 is going to be determined based on the precooling circuit, based on the refrigerant which is flowing in the circuit, based on the pressure of this precooling circuit etcetera. So, this is the most important thing now, is what is the precooling temperature and it will be decided by the precooling circuit and also the requirement of the main Linde - Hampson system.

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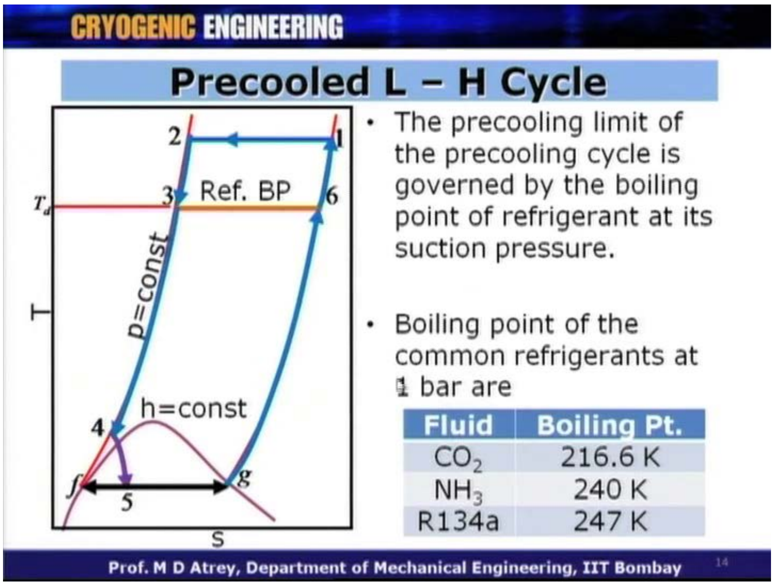

Fluid	Boiling Pt.
CO_2	216.6 K
NH_3	240 K
R134a	247 K

So, this is what it would like a precooled Linde - Hampson system, the precooling limit of the precooling cycle all right. So, how much that temperature should be is governed by the boiling point of the refrigerant at it is suction pressure. So, what this temperature could be, we want this temperature to be as low as possible all right and the lowest temperature that could be achieved by this is basically, is going to be decided by the boiling point of the refrigerant in the precooling circuit all right. Because we cannot come below that thing the suction pressure is going to be the limit of this, the lowest limit of this temperature would be all right.

So, this temperature is going to be decided by the precooling circuit and is also going to be decided by the type of refrigerant and it is pressure that will decide this temperature. So, this temperature we can call it as T d, which is the temperature that is shown in the precooling circuit and this is nothing, but equal to the boiling point of the refrigerant at the suction pressure of the precooling circuit all right. This will be the lowest temperature at which it enters the heat exchanger.

The boiling points of the common refrigerants at 1 bar are, if we assume that the suction pressure is at 1 bar. The boiling points of these refrigerants will be for example, for CO 2 it is 200 and 16 Kelvin for ammonia or NH 3 it is 240 Kelvin or for R 134a that temperature could be 247 Kelvin. So, if we assume that the return pressure or the suction pressure is around 1 bar. This is what the lowest temperature, they can achieve in the precooling circuit. So, the gas would enter the heat exchanger at this lowest temperature, if these conditions are maintained.

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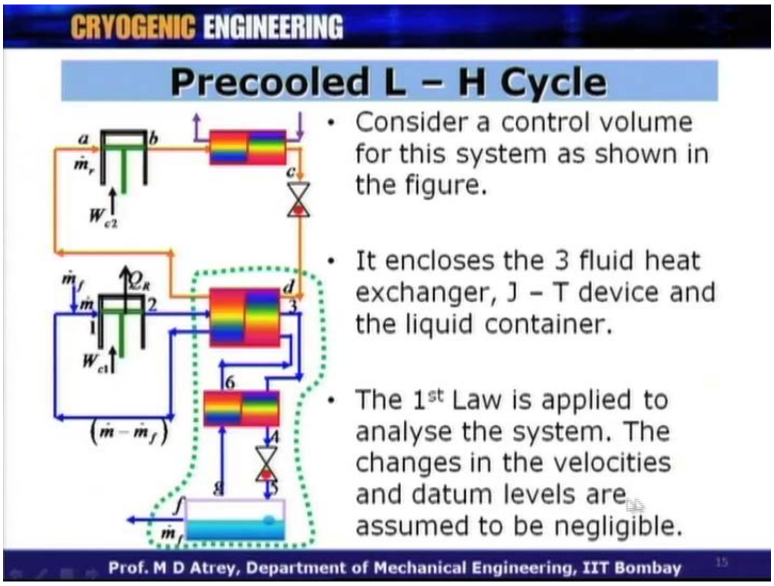

So, this is what the circuit would be? Now, if I want to analyze this circuit further, I will consider a control volume for this system as shown in the figure and this is my control volume. In which, I am excluding the compressor and I am taking precooled heat exchanger main heat exchanger and the container.

So, it encloses 3-fluid heat exchanger this is one, then J - T device and a liquid container. So, this is what enclosed in this control volume and we apply the first law as we have done always in earlier lectures, also the first law is applied to analyze the system. The changes in the velocities and the datum levels are assumed to be negligible as what we have been doing?

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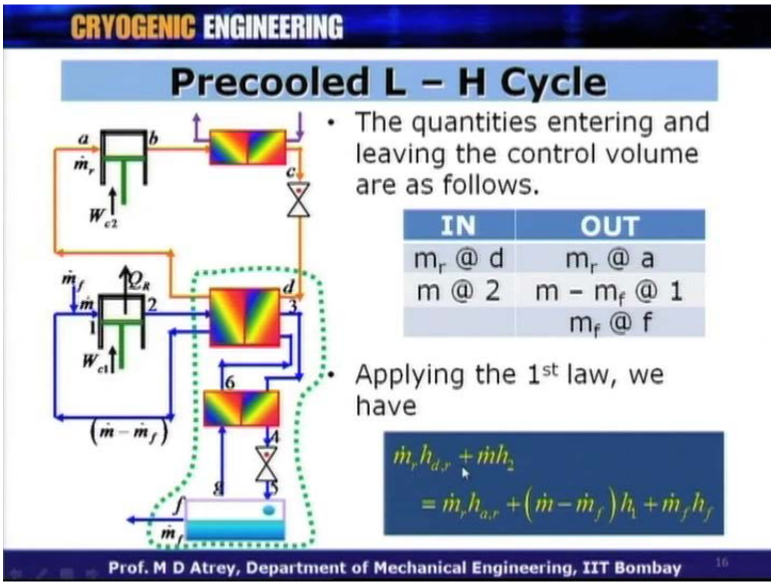

So, what is entering this control volume is? m dot r at point d. This is a flow rate this system, which is m dot r refrigerant flow rate and it is entering at this point d and also what is entering is m dot at point 2. So, these are the 2 quantities, which are entering the control volume. All of the quantities are leaving the system or leaving the control volume what are they m dot r which is leaving at point a similarly, m dot minus m dot f leaving at point 1 and m dot f at point f.

So, we say that whatever is coming in is equal to whatever is leaving the system and therefore, applying first law what we have is m dot r h d, we are taking enthalpies at various points and various temperatures and add respective pressures. So, m dot r h d r, this is the energy at this point which is entering the control volume plus m dot h 2 which is entering at this point.

So, whatever is coming in are these 2 energies and whatever are leaving are m dot r h a r which is at this point, m dot minus m dot f at h 1 which is at this point and m dot f h f at this point. So, the energy which is coming in is equal to the energy, which is leaving the control volume.

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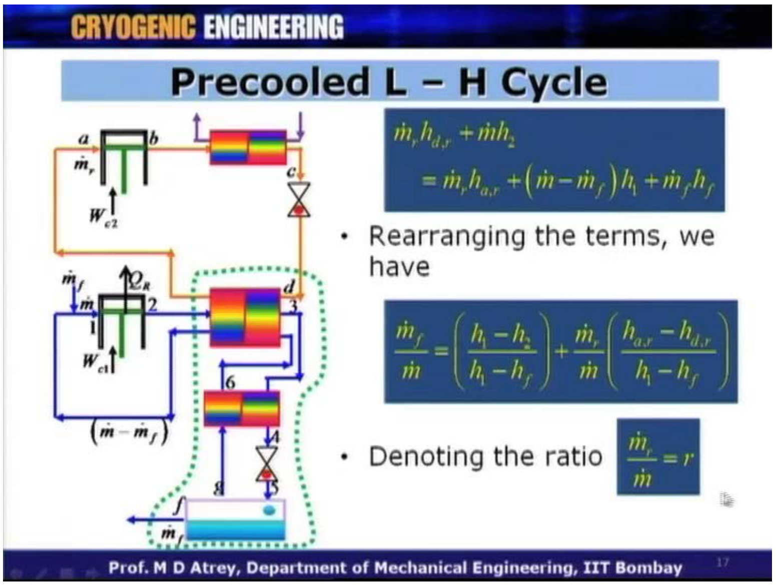

So, if I could do the same thing here rearrange the terms, what we get ultimately is m dot upon m dot m dot f upon m dot which is nothing, but y is equal to h 1 minus h 2 upon h 1 minus h f plus m dot r upon m dot into h a r minus h d r, that is enthalpy difference across this heat exchanger divide by h 1 minus h f.

So, what you can see? We have got an expression now, from these rearranging this term is the yield that is y is equal to the term which is simple Linde - Hampson cycle yield plus and additional yield over here which is coming, because of the precooling circuit. So, if we denoting the ratio m dot r upon m dot is equal to r that is the ratio of how much mass flow through refrigerant divided by the mass flow in the main circuit.

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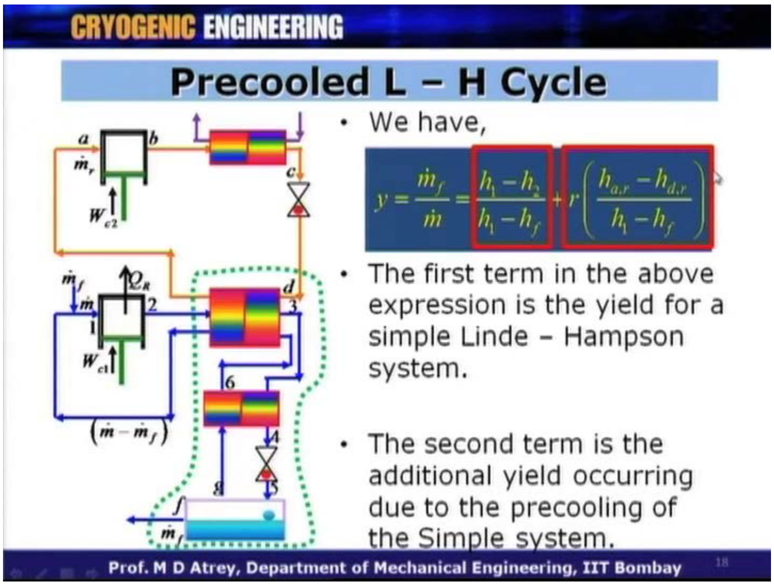

So, if we have a relationship between the m dot r in the precooling circuit to the m dot in the main circuit as r the expression could be now, written as y is equal to m dot f upon m dot is equal to h 1 minus h 2 upon h 1 minus h f plus r times h a r minus h d r upon h 1 minus h f. The first term in the above expression is the yield for a simple Linde - Hampson system.

So, what you get normally in a Linde - Hampson system will be this. In addition to that this is a second term now, and this second term is coming as an additional yield, because of precooling arrangement. The second term is the additional yield occurring due to the precooling of the simple system all right. So, this is an additional yield which we are getting, because the gas after the compressor here is getting precooled to temperature T 3 or T 6, because of the refrigerant coming at this point in this 3-fluid heat exchanger. So, this is the role which is played by the precooling circuit.

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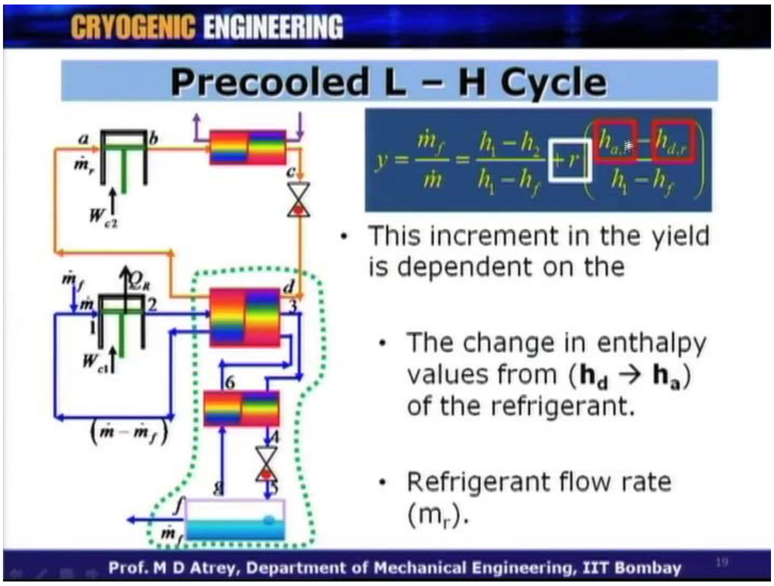

So, the expression is now, y is equal to m dot f upon m dot is this. This is the increment in the yield is now, dependent on what. So, what is this y additional increment in y is depending on what we can see from this is, the change in enthalpy of the values h d and h a. So, h a minus h d is going to basically, determine the additional value of y or additional increment in the value of y while h 1 minus h f is same in both the cases and the second point is the refrigerant flow rate m dot r.

So, these two things what is the enthalpy change across this three-fluid heat exchanger in the precooling circuit that is h d minus h a and the value of r that is what is the ratio of m dot r upon m dot. So, from here you can see that ratio of r is high and if this enthalpy difference is high you will have more and more increment to the value of y as compared to the simple Linde - Hampson cycle.

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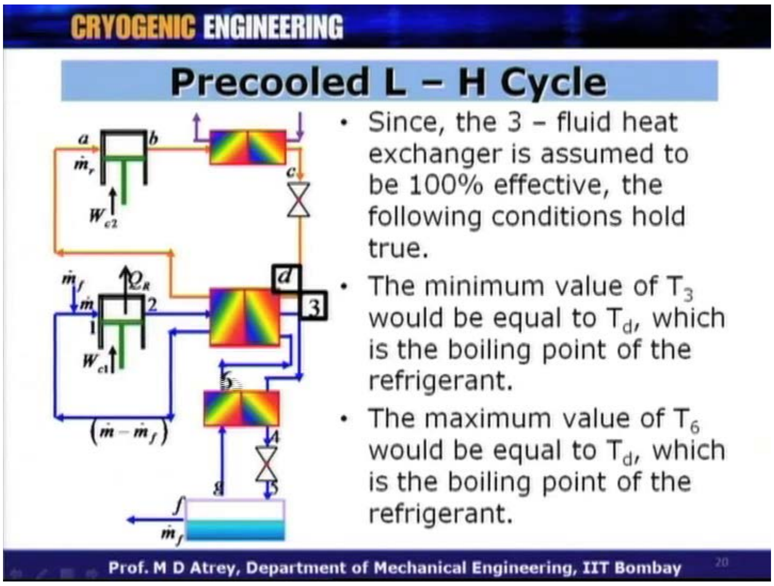

Since, the three-fluid exchanger is assumed to be 100 percent effective, the following conditions hold good. The minimum value of T 3 would be equal to T d, the value of T 3 at this point will be equal to the value of T d, because the gas is getting precooled depending on what is the temperature at point d is. So, the minimum value of 0.3 at 0.3 which is T 3 would be equal to T d, which the boiling point of the refrigerant.

So, in the racket the minimum temperature at which the gas enters the heat exchanger is going to be equal to the boiling point of the refrigerant in this circuit. So, boiling point of the refrigerant corresponding to the suction pressure of this compressor, which is at this point and this is going to decide what is the lowest temperature at which this gas can enter the heat exchanger?

The maximum value of T 6 similarly, if we assume that this heat exchanger is a perfect an ideal heat exchanger. The maximum value of T 6 will be equal to T 3, the minimum value of T 3 equal to T d, the maximum value of T 6 is also equal to T 3 or equal to T d. So, the maximum value of T 6 would be equal to T d which the boiling point of the refrigerant. So, we are talking in a case when the heat exchanger effectiveness is 100 percent.

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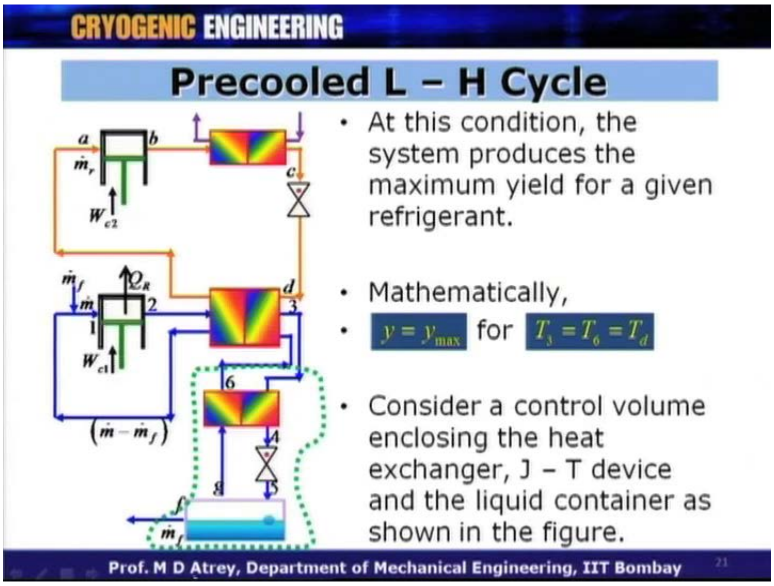

So, at this condition, the system produces the maximum yield for a given refrigerant. So, as we were talking earlier that, if the temperature at which the gas enters the heat exchanger is lowest you will get maximum yield. So, in this case, the lowest temperature at which the gas can enter this heat exchanger is going to be the boiling point of this refrigerant at it is suction temperature at a suction pressure.

So, in this case, if the value of temperature 3 at point T 3 is going to be equal to the boiling point of this refrigerant, then the yield what you get y is going to be equal to y max or the maximum yield. So, at this condition when the gas enter the heat exchanger at the boiling point of this refrigerant, whatever yield you get is going to be the maximum yield for a given refrigerant, the maximum yield for a given liquefier also.

So, mathematically, if we want to have y is equal to y max if we want to have maximum yield, then T 3 is equal to T 6 is equal to T d and T d is nothing, but equal to the boiling point of the refrigerant in the in this circuit or at this particular pressure.Now, if I consider this as a control volume. So, consider a control volume enclosing the heat exchanger J - T device and the liquid container as shown in the figure. Earlier, we had taken a bigger enclosure, but if I take this as an enclosure now, and do the energy balance.

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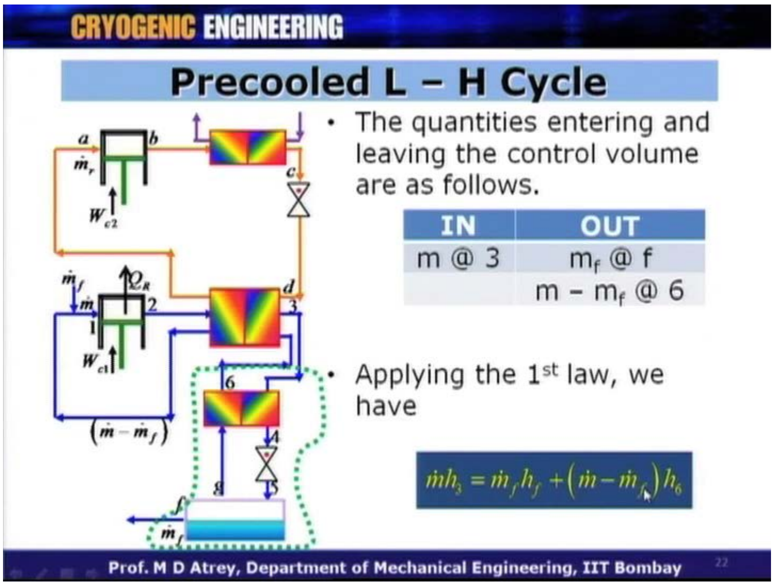

So, again we find the quantities entering and leaving the control volume. So, what is entering is mass at point 3 that is m dot at 3 what are leaving is m dot f at point f, m dot minus m dot f at point 6. So, applying the first law again what you get is m dot h 3 is equal to m dot f h f plus m dot minus m dot f h 6.

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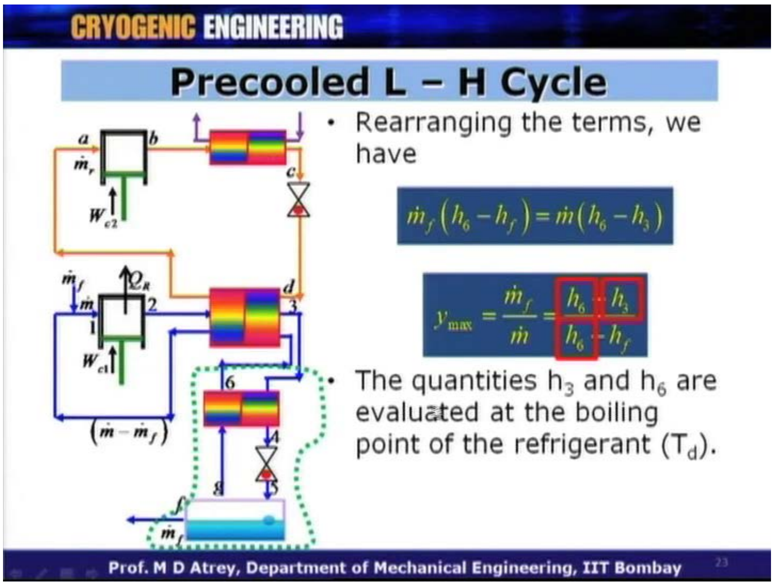

And if we rearrange these terms, what you get is these and if I write expression for y what you get here? y max is equal to m dot f upon m dot is equal to h 6 minus h 3 divided by h 6 minus h f.

So, basically now, I am taking the control volume at this point and enthalpy difference at this point is going to decide what is my y max value is? So, in order that I get y max now, the properties of h 6 and h 3 are evaluated at the lowest temperature which is possible at this point. So, the quantities h 3 and h 6 are evaluated at the boiling point of the refrigerant T d. So, if we do these, then whatever we get as y is going to be the y max value or the maximum yield that is possible from this particular circuit. So, this was as far as the liquefaction was concerned. Now, we will talk about the compressors and do not forget that there are 2 compressors. Now, one is the adiabatic compressor, one is the isothermal compressor.

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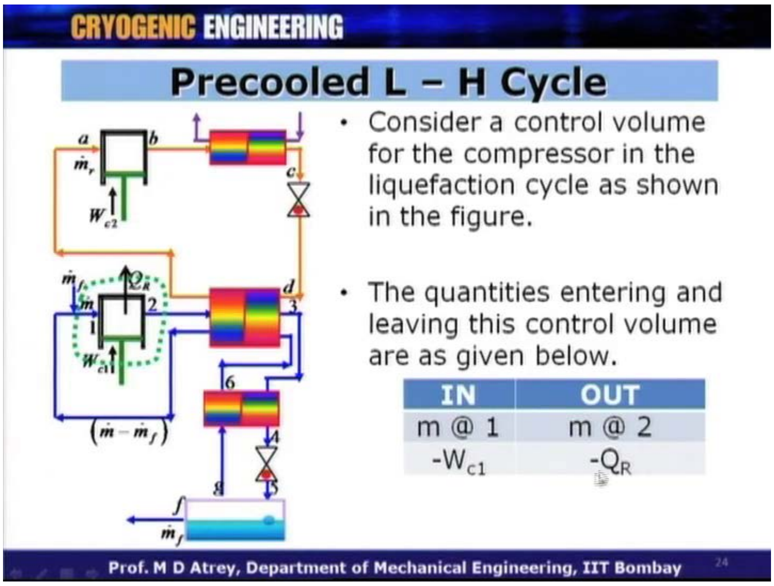

So, consider a control volume for a compressor in the liquefaction cycle as shown in this figure, the quantities entering and leaving the control volume are as given here. So, again we have got a m dot entering at point 1 and m dot leaving at point 2. The work is given at this point which is as we earlier know, we have pointed out earlier whatever is entering whenever the work is done on the system. It is written as minus W c 1 is the work done on the system and whatever is leaving the heat, which is leaving the heat of compression is also being written indicative minus Q R and if we write the heat balance.

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Now, using the first law for the following table what we are getting is? This energy in is equal to energy out and therefore, we have got a m dot h 1 minus W c 1 is equal to m dot h 2 minus Q R rearranging this term, what we get is? Q R minus W c 1 is equal to m dot into h 2 minus h 1.

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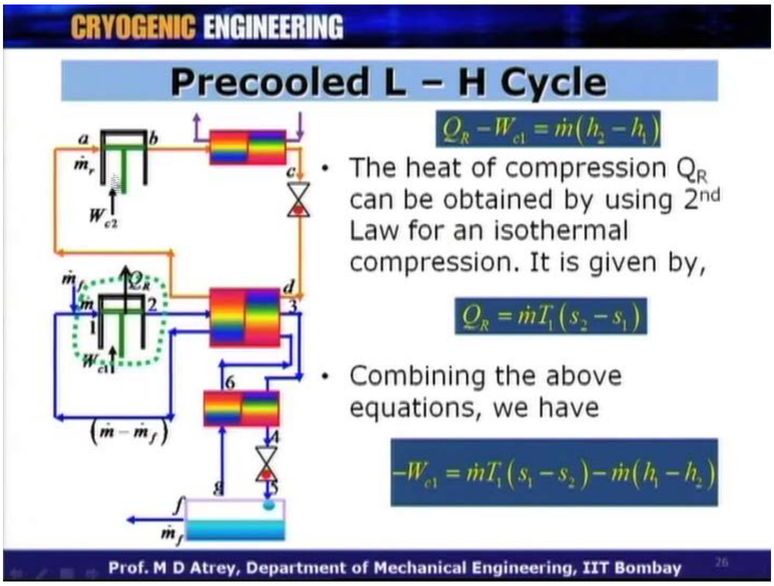

The heat of compression Q R can be obtained by using second Law for an isothermal compressor. It is given by; Q R is equal to m dot into T 1 into s 2 minus s 1 if you put this value of Q R over here. Combining these 2 equations, what we get is an expression for minus w C 1 or the work of compression done on this circuit. So, minus w C 1 is equal to m dot T 1 into s 1 minus Ss2 minus m dot into h 1 minus h 2. This is the amount of work done on this compressor and this point. In addition to this, we have got a one more compressor we have to supply the work to this compressor also. However, we have assumed that this compressor works in a adiabatic fashion; that means, Q R for this compressor is equal to 0.

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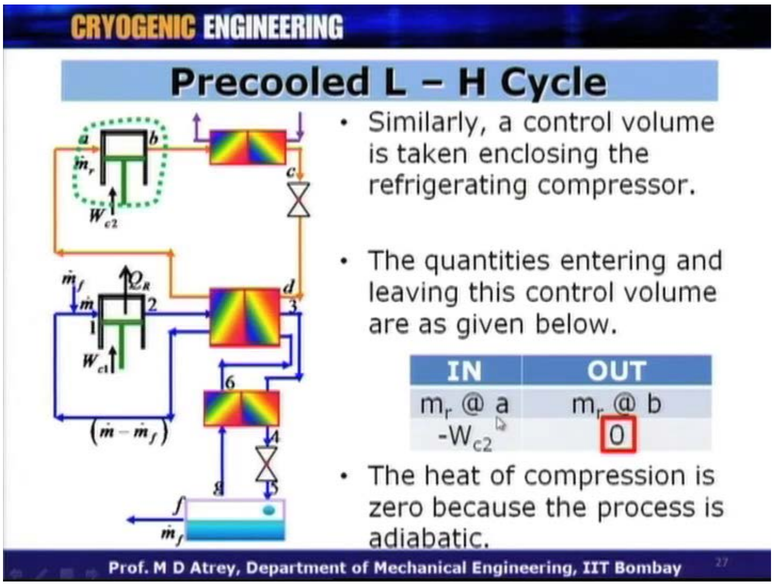

Similarly, now let us have a control volume for this compressor. A control volume is taken enclosing the refrigerating compressor at this point in this circuit. The quantities entering and leaving this control volume are as given below. So, what is entering is m dot r at a and the work done on the compressor is minus W c 2, what are leaving is m dot r at point b, but there is no Q R leaving. So, I have just written 0 in order to match earlier tables. The heat of compression is 0, because the process is assumed to be adiabatic in this case.

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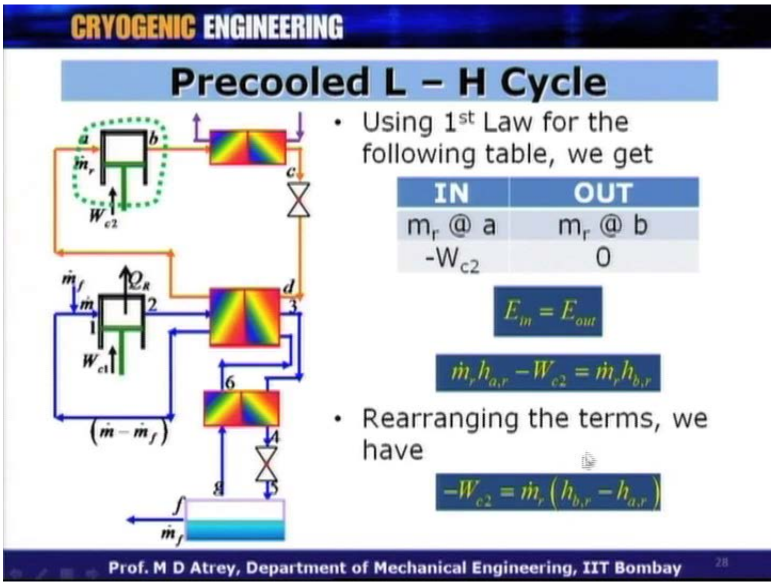

So, using the first law for the following table, what we get is whatever entering is leaving and therefore, E in is equal to E out and therefore, m dot r into h a r enthalpy at point a minus W c 2 is equal to m dot r into h b r. So, rearranging these terms as we have done earlier, what you get now, is the work to be done on the precooled circuit or on this compressor, which is minus W c 2 is equal to m dot r into h b r minus h a r. This is nothing, but the enthalpy difference across this compressor.

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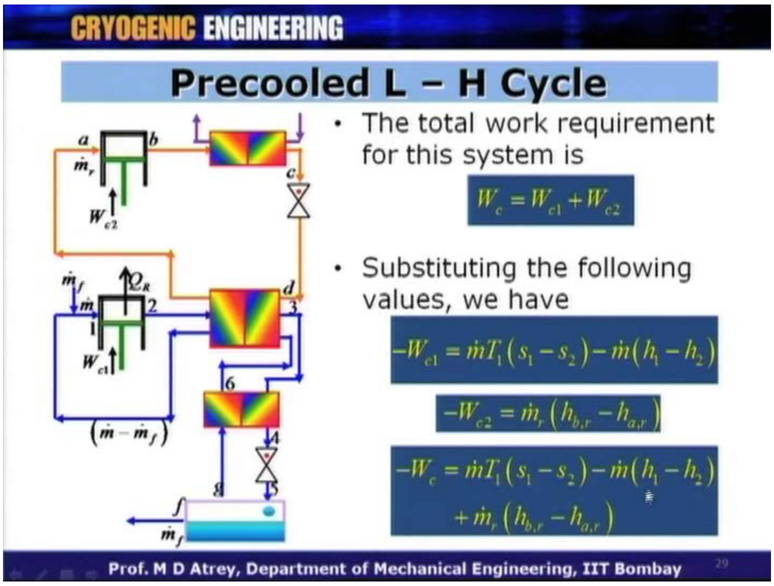

So, the total work requirement of the system is work done on this compressor plus work done on this compressor all right. When you are adding the precooling circuit no doubt we get advantage of the precooling, but at the same time we have to do some work on this compressor also. So, the total advantage of this precooling circuit should be made with respect to this additional work, which is required to be done on this compressor also.

So, the total work done is equal to W c is equal to W c 1 plus W c 2, if we add these values of minus W c 1 for the work done for this compressor plus minus W c 2 which is the work done on the refrigeration compressor, if we put them together we get this expression.

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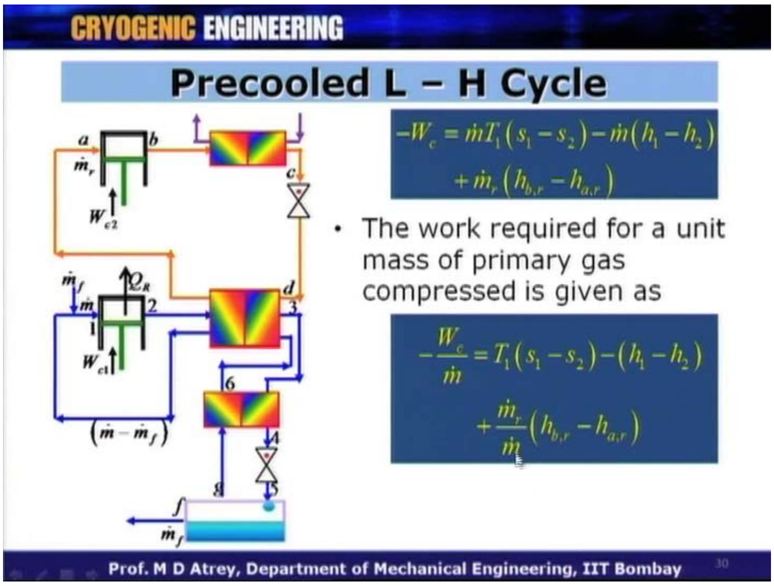

So, minus W c is equal to m dot T 1 into s 1 minus S 2 minus m dot into h 1 minus h 2 plus m dot r into h b r minus h a r. The work required for a unit mass of primary gas compressed is given by. So, if I want to reduce and find out the work done per unit mass of gas compressed in the primary circuit or in the Linde - Hampson cycle which is m dot, then I get minus W upon m dot is equal to T 1 into s 1 minus s 2 minus h 1 minus h 2 plus m dot r upon m dot into h b r minus h a r and if you recollect we have called m dot r upon m dot at it is r value.

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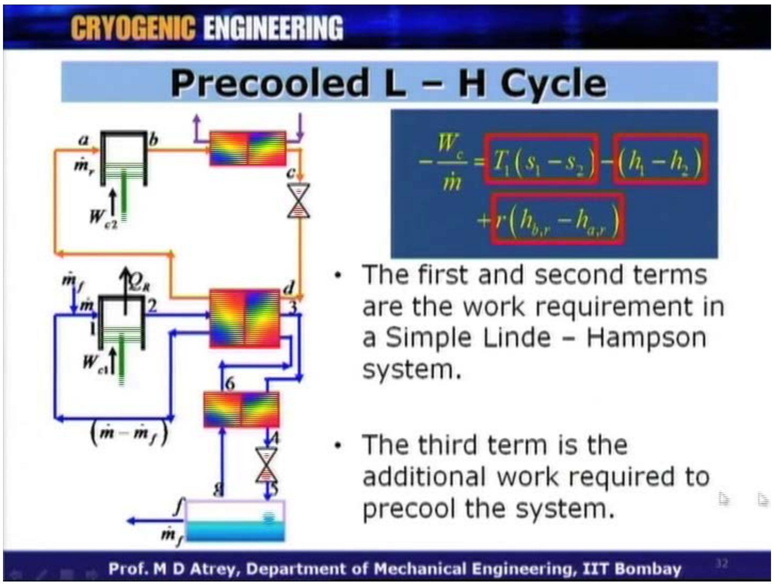

As r which is the ratio of the two mass flow rates. So, denoting the ratio of m dot r upon m dot as r the expression now, gets reduced to minus W c upon m dot is equal to T 1 into s 1 minus s 2 minus h 1 minus h 2 plus r, which is over here into h b r minus h a r. So, this is the expression which I get for the total work done on this precooled Linde - Hampson cycle.

So, here you can understand that the first two terms are coming from this primary cycle or the primary circuit. The first and the second terms are that work requirement in the simple Linde - Hampson system. This was our expression earlier this expression has come, because of the additional circuit or the precooling circuit and the third term is the additional work required to precool the system. So, one can really find what is the work done on this cycle from the precooling cycle and from the primary cycle. So, just find out 2 work done add them together and this should justify the additional circuit or the precooling circuit that has been incorporated in a precooled Linde - Hampson cycle right.

Now, with this background of the precooling circuit what we now, do is a tutorial here and this tutorial will help you to understand what we have learnt till now. This tutorial has got all the components that one needs to understand from a precoolant circuit and a precooled Linde - Hampson cycle. So, please read the problem again correctly and as I said every time one has to really understand the language of this problem.

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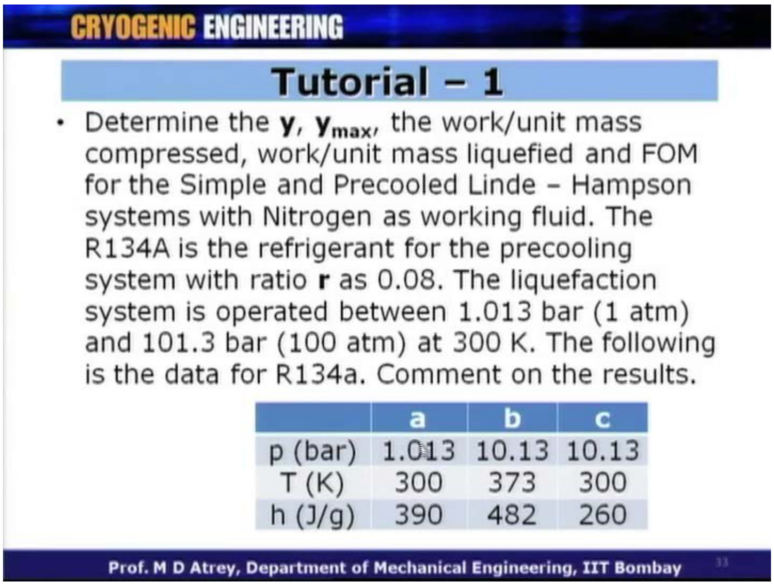

So, let us see the tutorial now, please read it correctly. Determine the y that is yield y max that is the maximum yield, the work per unit mass of gas compressed work per unit mass liquefied and FOM which is nothing, but figure of merit for the simple and precooled Linde - Hampson systems with nitrogen as working fluid.

Now, this is very important to understand what is asked in the problem. So, what is your working fluid? It is nitrogen, what are we talking about? We want to talk about both the cycles that is simple Linde - Hampson cycle as well as precooled Linde - Hampson cycle. The R134A is the refrigerant for the precooling system with ratio r is equal to 0.08 that is m dot r upon m dot is 0.08. The liquefaction system is operated between 1 atmosphere and 100 atmosphere or 1.013 bar and 101.3 bar. This compression is carried out at 300 Kelvin. So, this pressure change is happening at 300 Kelvin which is a isothermal compression process. The following is the data for R134A and what ultimately what we want is you comment on the results.

So, the data for 134a is given in terms of point a, b and c. The a , b, c are referring to the conditions what you saw earlier in a precooled circuit that could be called as 1,2,3,4 whatever, we want to have, but this is in the reference to the circuit which I have already shown to you. What you can see from here is? The point a is at the entrance of the refrigeration compressor which is at 1 bar or 1.013 bar, the point b is after compression which is 10.13 bar; that means, a pressure ratio of 10 is at this point. The point c is after the condenser or after the heat exchanger and corresponding to these 3 points what you have is a temperatures and what you have is an enthalpy at this point.

So, this information regarding precooling circuit is sufficient enough for you to carry out different calculations required to find out all these parameters as specified in this problem. So, as I said again and again from this language convert the information as to what exactly we want? So, what is given? What is the data which is known to you? And what is asked in this problem? This is very important to understand.

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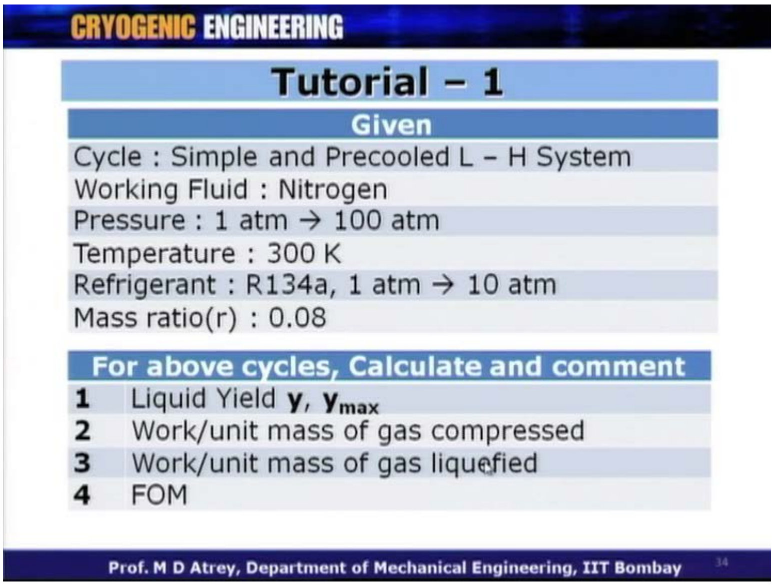

So, if I could write all these information properly, we see the second slide which is this. What is given we have been asked do a simple and precooled Linde - Hampson cycle, we have we've to consider simple and precooled Linde - Hampson system. There are 2 system; that means, the working fluid is nitrogen, the pressure for this nitrogen refrigerant is 1 atmosphere and 100 atmosphere, the temperature is 300 Kelvin for this compressor process. Then the precooling circuit has a refrigerant R134a, which is compressed from 1 atmosphere to 10 atmosphere and the mass ratio r the ratio of the mass flow rate of the refrigerant to the mass flow rate of nitrogen in the primary circuit is m dot r is r is equal to 0.08.

For these 2 cycles, calculate and comment on various values you get from the system that is liquid yield y and y max, work per unit mass of gas compressed, work per unit mass of gas which is liquefied and Figure of Merit FOM. So, this is what is asked in this problem? And this is what the data is for this problem?

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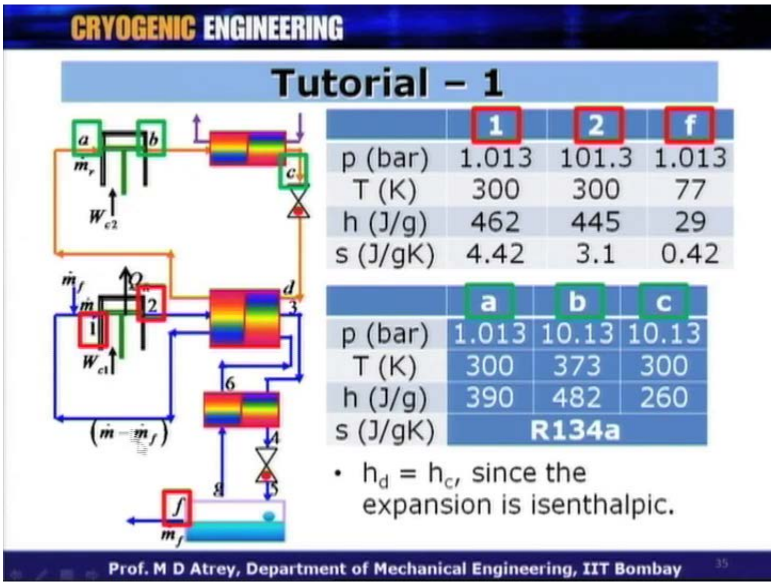

So, as we can this is our circuit for a precooled Linde - Hampson cycle. This is the precooling circuit and this is the primary circuit or a Linde - Hampson cycle m dot r comes in this compressor, m dot comes in this compressor. So, if I now, get the enthalpy entropy values for different temperatures and pressures in this cycle at a points are (1,2,3) 1,2 and f are the points which are required for calculations of all the parameters, which are asked for in the problem.

So, you got a point 1, 2 and f corresponding to pressures of 101 respectively. The temperatures at these 3 points are 300,300 and point f what you have is a boiling point of nitrogen which is 77 Kelvin. Corresponding to these temperatures and pressure you got enthalpy values, which are given as these 462 445 and 29 joule per gram and similarly, we have got entropy values for these 3 expressions. Now, these values are either taken from chart and many times it was taken from temperature entropy charts.

So, whenever we have got this problem, we should have a temperature-entropy chart of nitrogen, air, oxygen whatever is the primary working fluid in this case. So, first make this kind of a table so, that you will never make mistakes. So, point 1 is at this here, point 2 is after the compression which is at this point and point f is the point which is at this all right.

Similarly, now let us go to the precooling circuit or the refrigeration R134a circuit and let us look at these points again which are a ,b and c. So, where is a point we can see the point a (( )) here, which is at the entrance to the refrigeration compressor, where is point b the point b is located after the compressor and therefore, it is at high pressure of 10 bar 10.133 at this point, then what you have is a point c, which is at this point that is before the expansion before the J - T expansion is point c.

So, again similar to what we did for nitrogen as a working fluid. We similarly, make a table for the properties of enthalpy and entropy for different value of pressure and temperature for the precooling circuit and this is done for R134a. So, what are required here are mostly the enthalpy values. So, you can see that we have not written the entropy values, because these values are not required in the calculations. What is to be noted here is? The enthalpy at point d, it is what is required for us.

Now, h d value is the value which is used in the calculation over here. The point to be noted here the enthalpy at point c is equal to enthalpy at point d, because this is a isenthalpic expansion process and therefore, many times you find that the enthalpy maybe given at point c and you might be wondering what do I do about the enthalpy at point d, but one has to understand that the enthalpy at point d is nothing, but enthalpy at point c since the expansion is isenthalpic process. Many times this is considered as a twist in the problem, but one should note that the point d has a enthalpy which is same as point c.

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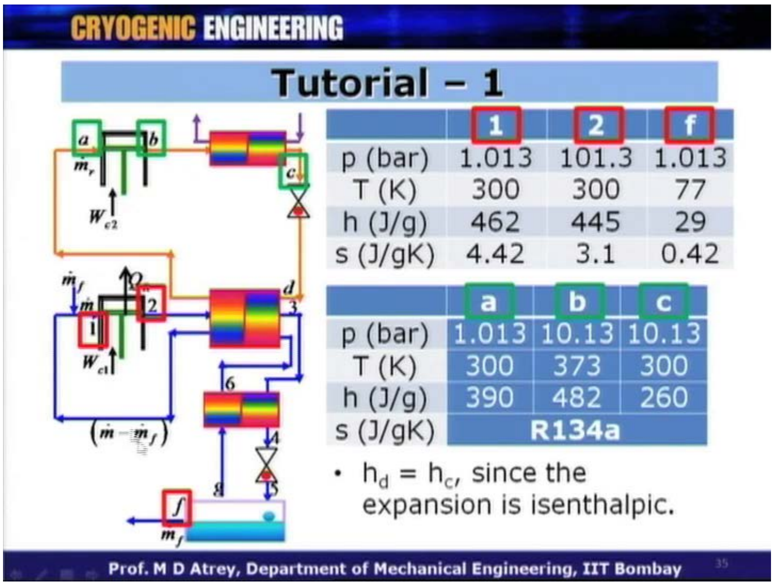

So, first our calculations start with an ideal thermodynamic cycle, because we want to calculate the figure of merit and therefore, we have to consider about ideal work requirement to the cycle. So, the ideal work requirement for the cycle is assumed on the fact that whatever is compressed is expanded and is liquefied all right. So, the ideal work of requirement is minus W I upon m dot is equal to T 1 into s 1 minus s f minus h 1 minus h f and the point f is decided by the point 1 only.

So, as soon as the point 1 is fixed, we get a point f also fixed taking the values at 1, 2 and f from the earlier table and we have to consider only 1 and f point in this case. So, get a value of enthalpy at 1 and f and entropy at 1 and f, we can calculate minus W c upon m dot is equal to 300 into s 1 minus s f which is s 1 minus s f minus h 1 minus h f which is h 1 minus h f and this is equal to 767 joule per gram. This actually is now, a known to us, because we have solved various problems for this. So, this is an ideal work requirement which is working on an ideal thermodynamic cycle.

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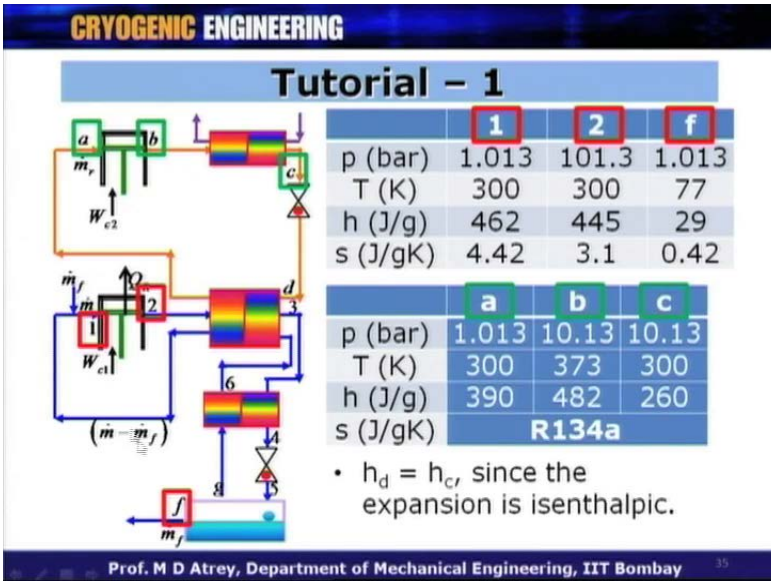

Now, we see the liquid yield for the simple Linde - Hampson cycle which is h 1 minus h 2 upon h 1 minus h f again take the value of enthalpies at 1 and point 2, we can calculate the value of y is equal to h 1 minus h 2 upon h 1 minus h f which is equal to 462 minus 445 upon 462 minus 29 with the enthalpy value as 1, 2 and f respectively putting those values you get y is equal to 0.04 all right. So, m dot f upon m dot for a Linde - Hampson cycle for a simple Linde - Hampson cycle comes out to be 0.04.

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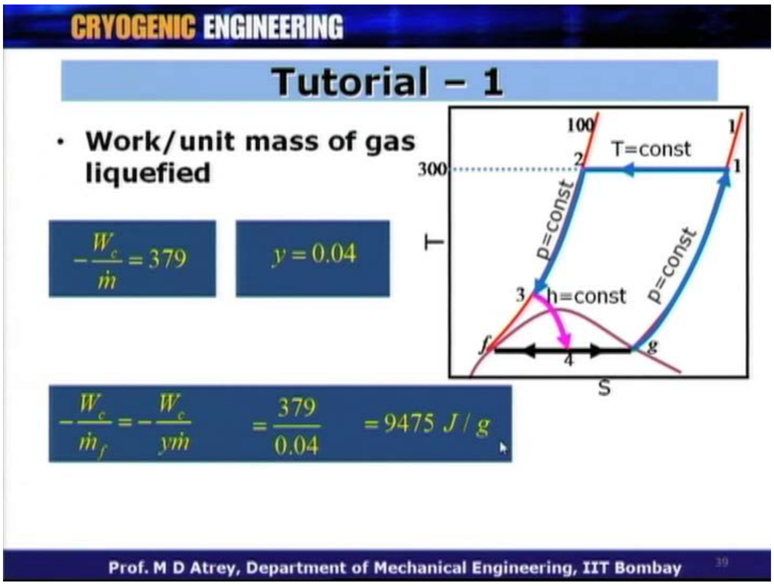

So, if I want to calculate work per unit mass of gas which is compressed is minus W c upon m dot is equal to T 1 into s 1 minus s 2 minus h 1 minus h 2. Now, we are talking about 1 and 2 and not 1 and f as we have done earlier in ideal thermodynamics cycle. So, putting those values again for enthalpies and entropies what you get is? A 379 joule per gram as work done per unit mass of gas compressed in a simple Linde - Hampson cycle.

If I want to convert that to work done per unit mass of gas liquefied from W c upon m dot equal to 379 have to know the value of y, if I divide this by y what I get is work per unit mass of gas liquefied, we have done solved these problems in the earlier lectures. So, minus W c upon m dot f is equal to minus W c upon m dot divided by y which is equal to 379 upon 0.04 which is equal to 9475 joule per gram. So, this is the work done per unit mass of the gas which is liquefied in this case.

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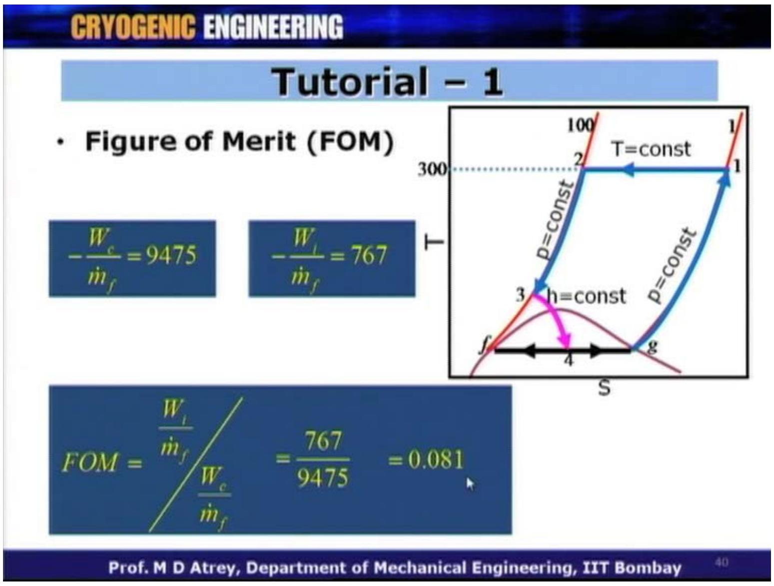

So, the Figure of Merit if I want to calculate is equal to what you get W c upon m dot is equal to 9475, what you got as W i for an ideal thermodynamic cycle is W I upon m dot f is equal to 767 and so, the figure of merit in this case is equal to 767 upon 9475 is equal to 0. 081, which is my figure of merit for the simple Linde - Hampson cycle.

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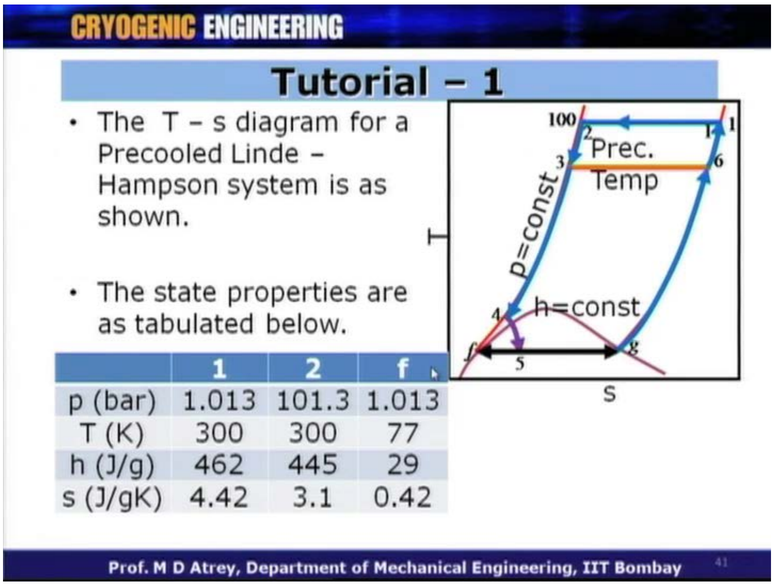

	1	2	f
p (bar)	1.013	101.3	1.013
T (K)	300	300	77
h (J/g)	462	445	29
s (J/gK)	4.42	3.1	0.42

Now, what I am now considered is a precooled Linde - Hampson system and a corresponding temperature entropy diagram for the precooled Linde - Hampson cycle is this. So, we can see now point 2 is getting precooled to point 3 and at this point the precooled gas enters the heat exchanger. So, point 3 is basically now, precooling temperature. The state properties are as tabulated below and here you can understand now, 1, 2 and f are as we saw earlier corresponding enthalpy and entropy values are given over here.

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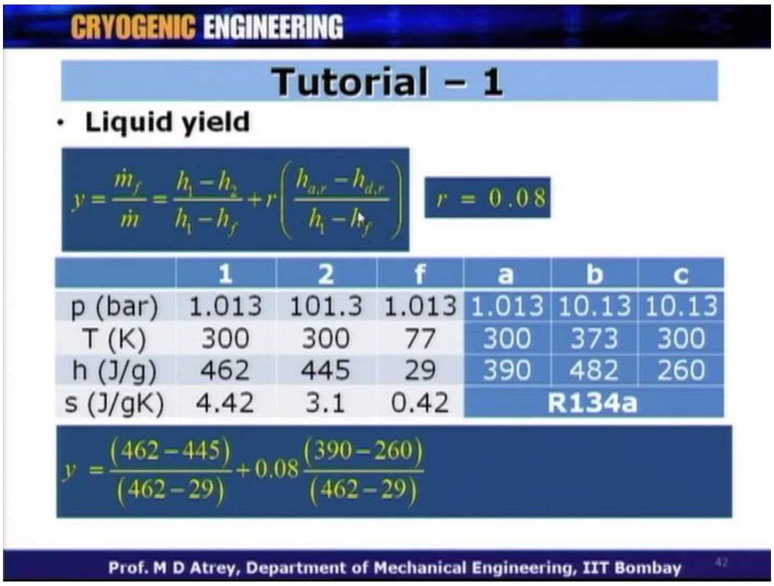

The liquid yield now, in this case is given by this formula which we have derived earlier is equal to y is equal to m dot f upon m dot is equal to h 1 minus h 2 upon h 1 minus h f plus and this is the additional increment in the value of y which is coming, because of the precooling. So, into r into h a minus h d upon h 1 minus h f well as you remember this h a and h d are the enthalpy of the refrigerant at point a and d respectively, which is nothing, but the enthalpy across the heat exchanger across the 3-fluid heat exchanger or across the precooling heat exchanger of the precooled linde - Hampson system.From here what we know is the value of r is equal to 0.08 all right.

So, if I put these 2 tables together, 1 table is for 1, 2, f which is for nitrogen and point a, b, c are meant for R134a that is the refrigerant precooling refrigerant and corresponding to those pressures, which is 1 bar and 10 bar what you have is a enthalpy values. So, at point a, b and c, we have got enthalpy values over here and at as you know that the value h d in this case is equal to the enthalpy at point c, as it is undergoing isenthalpic expansion from point c to point d.

So, putting these values in this expression now, y is equal to h 1 minus h 2 upon h 1 minus h f which is a standard value plus the additional increment that is going to come, because of precooling circuit is 0.08 into h a minus h d which is 390 minus 260 divided by h 1 minus h f again 462 minus 29, thereby giving the value equal to 0. 063. So, the yield now, has increased to 0.063 for the precooling cycle.

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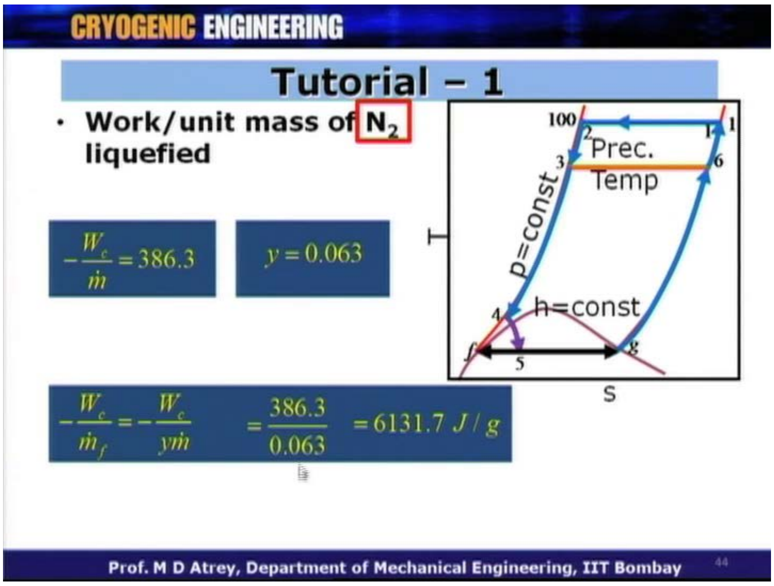

And again I will do the same exercise of calculating work per unit mass of gas compressed and work per unit mass of gas liquefied. So, if I want to calculate the work per unit mass of gas compressed, I have to use the formula for this. This is the additional increment in the compressor which is going to come, because of the refrigeration compressor. So, what you get is? A normal compressor which is first 2 terms in addition to that what you have is plus r into h b r minus h a r, this is nothing the additional work that has to be done for the precooling circuit. For which the value of r is 0.08 and if I add those enthalpy again from this table what I get is? 386.3 joule per gram. So, work done per unit mass of gas which is compressed is 386.3.

Now, I want to calculate work per unit mass of gas nitrogen which is liquefied. So, we will calculate for the unit mass of gas which is liquefied W c by m dot is 386.3 y is equal to 0. 063 and therefore, W c upon m dot f is equal to W c upon m dot divided by y is equal to 386.3 divided by 0. 063 is equal to 6131.7 joule per gram.

I want to calculate and I will want to compare the value of work done per unit mass of gas liquefied for the precooled Linde - Hampson cycle to simple Linde - Hampson these are the values to be compared in order to justify the usage of precooling circuit or the precooled Linde - Hampson cycle.

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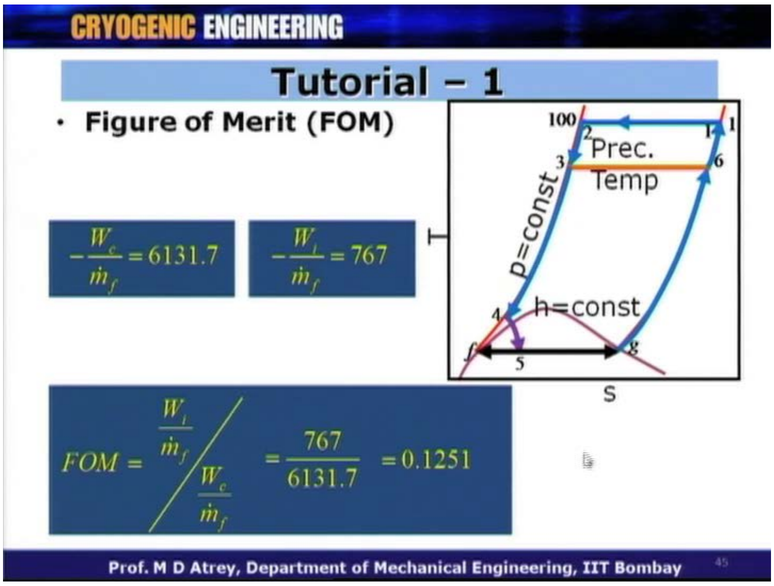

The figure of merit is this divided by this the ideal work input divided by the actual work and therefore, Figure of Merit is this divided by this which is equal to 0.1251. So, this is the Figure of Merit for this case for the precooled cycle. So, what we have done is? We have considered ideal thermodynamic cycle, we have considered simple Linde - Hampson cycle, we have also considered precooled Linde - Hampson cycle and we will like to compare all the values obtained from these three cycles.

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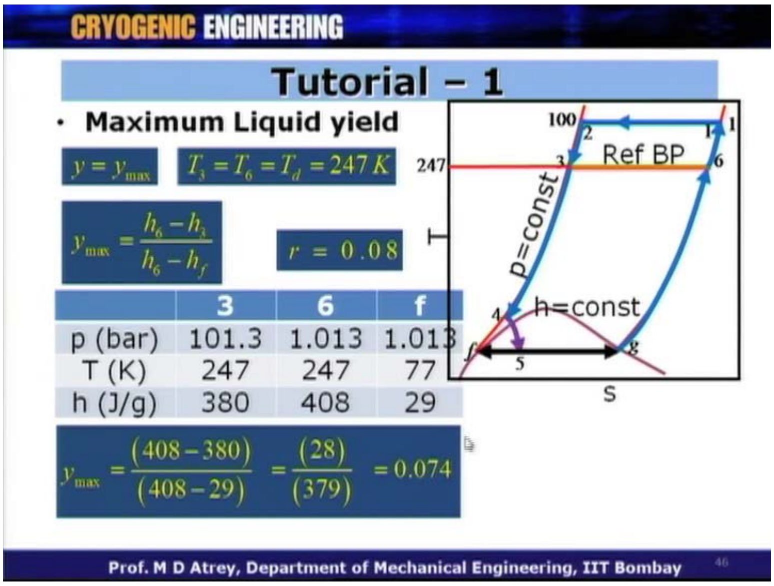

The problem also wanted to understand the y max value also. The y max value or the maximum liquid yield is going to come when the precooling temperature is equal to the boiling point of the refrigerant which is nothing, but 247 Kelvin. See if I get y is equal to y max when T 3 is equal to T 6 is equal to T d is equal to 247 Kelvin. We have studied this earlier and from this formula y max is equal to h 6 minus h 3 upon h 6 minus h f for r is equal to 0.08. We get 0.074 the y max value happens to be 0.074 for temperature of precooling equal to 247 Kelvin.

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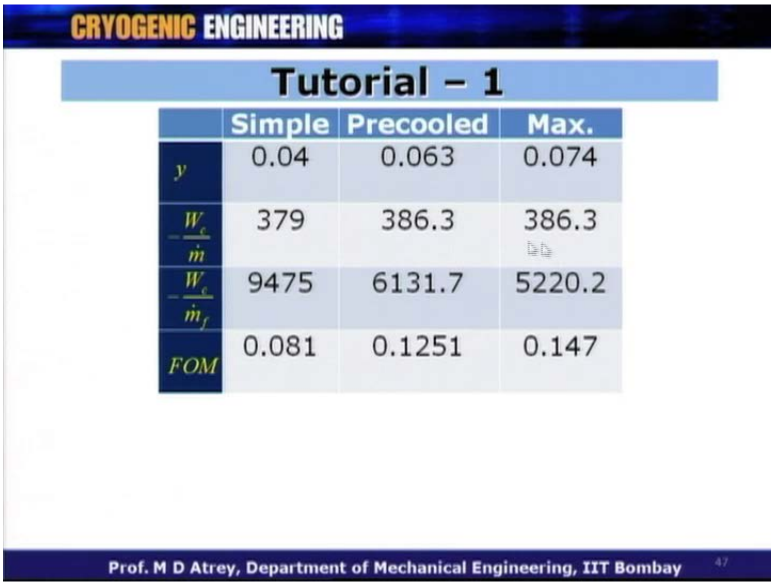

And therefore, if I want to have a comparison between the simple precooled circuit, we can see that for a simple cycle, it was 0.04 y value was 0.04 which got increased to 0. 063. If I talk about work done per unit mass of gas compressed, this has increased from 379 to 386. This work done has been increased, because there is additional work which has come from the refrigeration compressor in this case for the precooling circuit. However, if I want to understand what is the work done per unit mass of gas liquefied and that is what is very critical? we have we can see that it has reduced down from 9475 to 6131, which justifies the usage of precooling circuit and the Figure of Merit is has increased from 0.081 to 0.1251.

If I want to compare the same thing for the y max value. So, that the precooling is done to 247 Kelvin corresponding to that you can see that the y value increased to 0.074 provided that precooling temperature is now 247 Kelvin. The work of compression remains the same and the work done per unit mass of gas, which is liquefied has still further decreased justifying the lowering of temperature further and the Figure of Merit has increased to 0.147 in this case and this is the most important table, which justifies the usage of precooling circuit or the precooled Linde - Hampson cycle.

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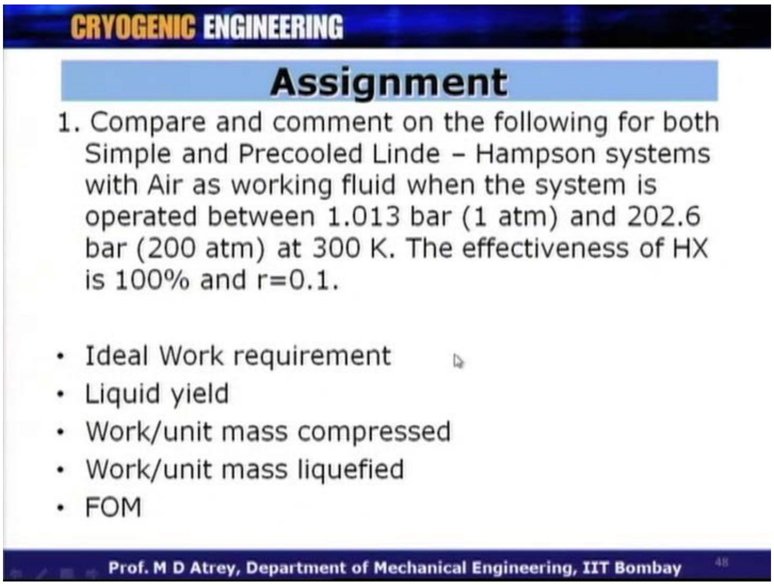

Based on this, we have given this assignment for the simple and precooled Linde - Hampson system with air as the working fluid and again find out these values. For r is equal to 0.1 in this please do this assignment and the answers to these questions will be given.

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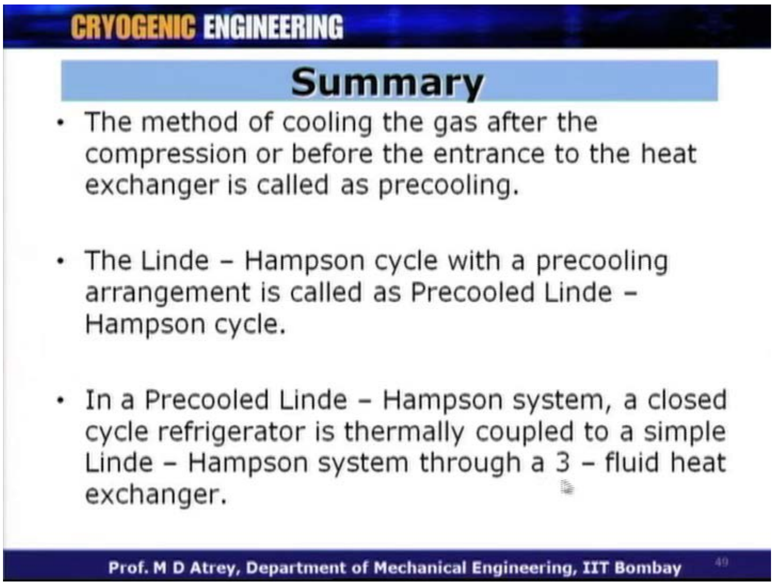

In order to summarize what we have learnt in this particular lecture. The method of cooling of the gas after the compression or before the entrance to the heat exchanger is what is called as precooling. The Linde - Hampson cycle with a precooling arrangement is called as precooled Linde - Hampson cycle. In a precooled Linde - Hampson system, a close cycle refrigerator is thermally coupled to a simple Linde - Hampson system through a 3-fluid heat exchanger. So, what is important is a 3-fluid heat exchanger existence in a case of a precooled Linde - Hampson system.

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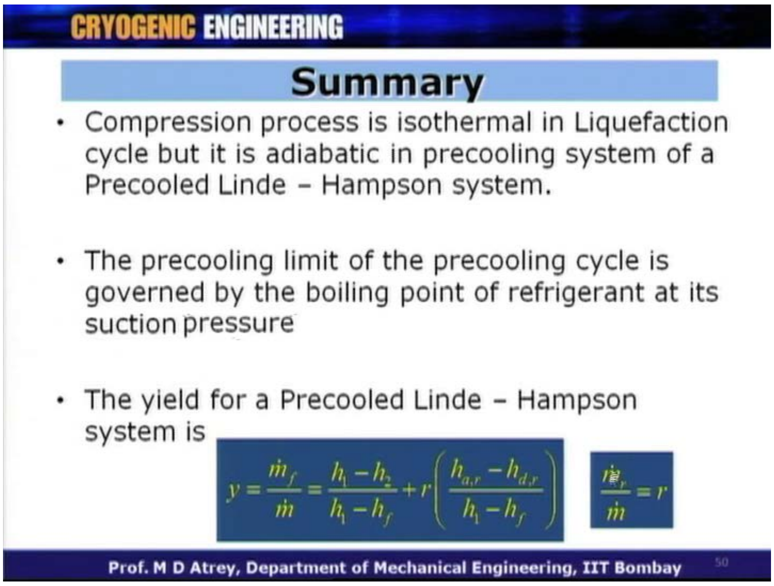

The compression process is isothermal in liquefaction cycle, but it is adiabatic in precooling system of a precooled Linde - Hampson cycle. These are basically, the assumption or a realistic assumption I should say for a precooled Linde - Hampson system. In actual case, they will not be isothermal they will not be adiabatic and we have to consider these effects through efficiency of these particular compressors, but this is not normally what we consider for calculation purposes.

The precooling limit of a precooling cycle is governed by the boiling point of the refrigerant at it is suction pressure. So, how much can we precool? We want to precool as below as possible, as at low temperature as possible, but this is going to be governed by the boiling point of the refrigerant. So, we would definitely like to precool to the extent possible, but the refrigerant whether R134 a or ammonia, this will govern that what is the lowest temperature at which the the gas can enter the heat exchanger, it is going to be governed by the boiling point of this refrigerant at it is suction pressure all right. So, this is basically very important.

The yield for a precooled Linde - Hampson cycle is given by this formula and this right hand side gives, the additional increment that is going to come from the precooling circuit and a m dot r upon m dot is what we call as r in this case that the ratio of the mass flow ratios the refrigerant to the mass flow of the nitrogen or a primary fluid.

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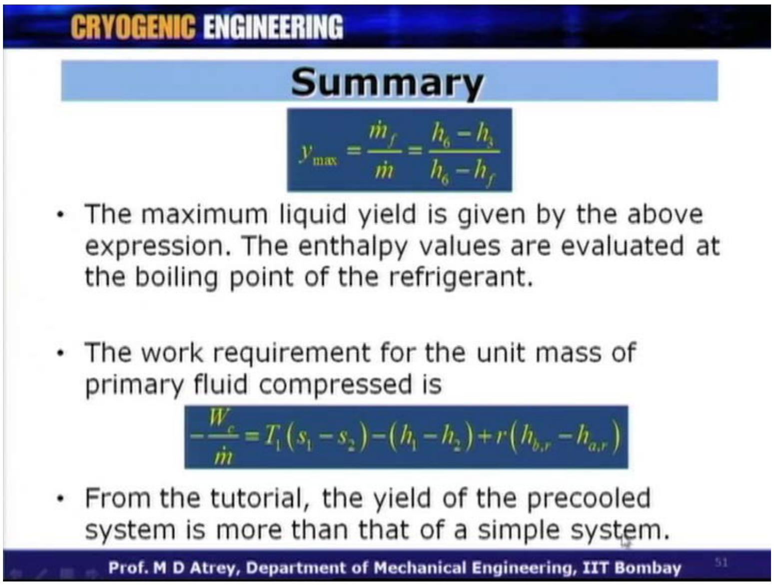

And the y max that is the maximum value of y or the yield what you can get is h 6 minus h 3 upon h 6 minus h f when this h 6 and h 3 are evaluated at the boiling point of the refrigerant. The maximum liquid yield is given by the above expression. The enthalpy values are evaluated at the boiling point of the refrigerant and this will give you the value of y max.

The work requirement for the unit mass of primary fluid compressed is, this these 2 terms are for simple Linde - Hampson while this additional term comes, because of the refrigerating compressor and based on the tutorial what we did? We have understood, the yield of the precooled system is more than that of a simple system. So, what is important is to understand whether the precooling is justified or not, because precooling adds upon an additional circuit and therefore, we have to study the effect of additional circuit or additional arrangement of this precooling in the entire system and this is what we will do in the next lecture? As to understand the effect of various parameters in terms of how much refrigerant should flow through what should be it is pressure? What is the value of r should be? So, that we justify the usage of precooling ciruit using simple Linde - Hampson cycle.

Thank you very much.