Upstream LNG Technology
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Lecture – 77
Tutorial on refrigeration and liquefaction – IV

Welcome, today we shall be doing a few more problems on the refrigeration and liquefaction.

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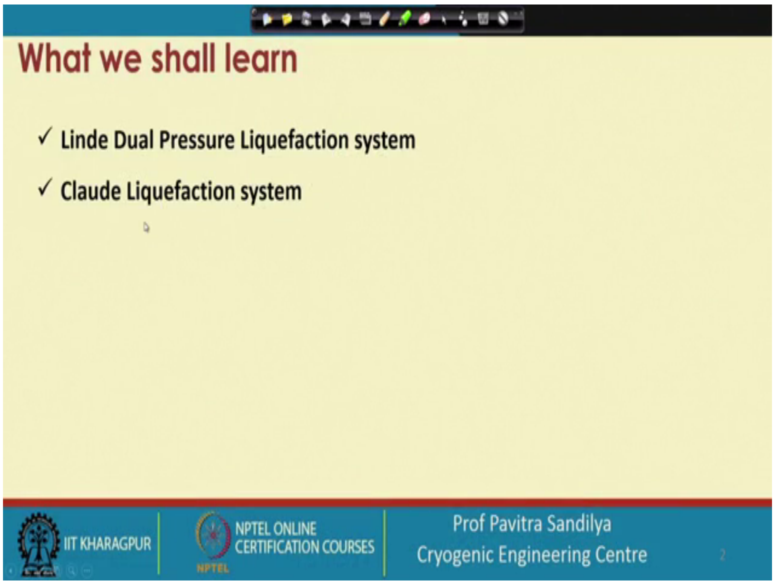

What we shall learn

- ✓ Linde Dual Pressure Liquefaction system
- ✓ Claude Liquefaction system

So, in this lecture, we shall be looking at the Linde Dual Pressure Liquefaction system and Claude Liquefaction System.

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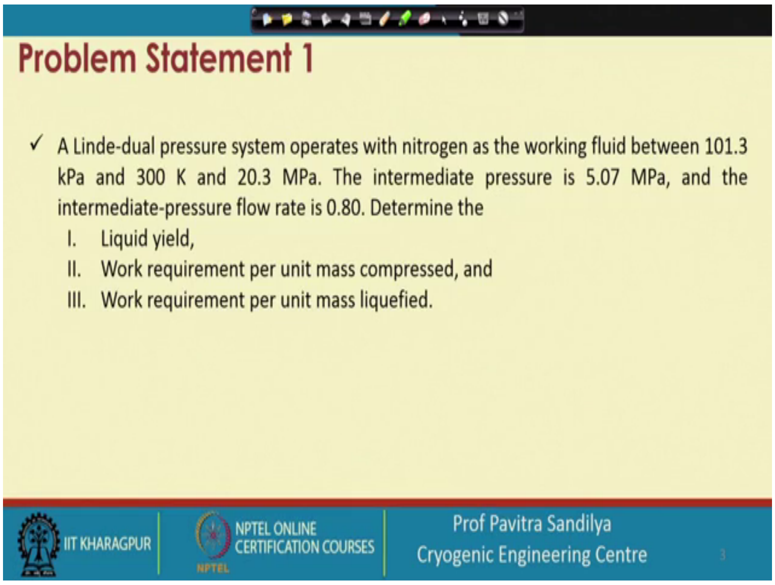

Problem Statement 1

- ✓ A Linde-dual pressure system operates with nitrogen as the working fluid between 101.3 kPa and 300 K and 20.3 MPa. The intermediate pressure is 5.07 MPa, and the intermediate-pressure flow rate is 0.80. Determine the
  - I. Liquid yield,
  - II. Work requirement per unit mass compressed, and
  - III. Work requirement per unit mass liquefied.

So, let us take the first problem. Here we are given a Linde-dual pressure system that is operating with nitrogen as the working fluid. And the lower pressure is about a 101.3 kilo Pascal that is about one atmosphere and 300 K, it means that we are taking this nitrogen at the ambient condition. And this particular gas is being now pressurize to about 20.3 mega Pascal that means at around 203 bar. The intermediate pressure is 5.07 mega Pascal, and the intermediate pressure flow rate is about 0.80. So, this has been given that this flow ratio has been given 0.8 and this is given as the intermediate pressure.

And what we determine? We determine the liquid yield, the work requirement per unit mass of the gas compressed, and the work requirement per unit mass of the gas liquefied. Now, you see here that here we are using a dual pressure system. And as we learned earlier that the dual pressure system reduces the work requirement per unit mass of the gas liquefied and it also increases the decreases the yield a bit. So, we shall be seeing that what kind of changes it brings about by doing this two stage pressure.

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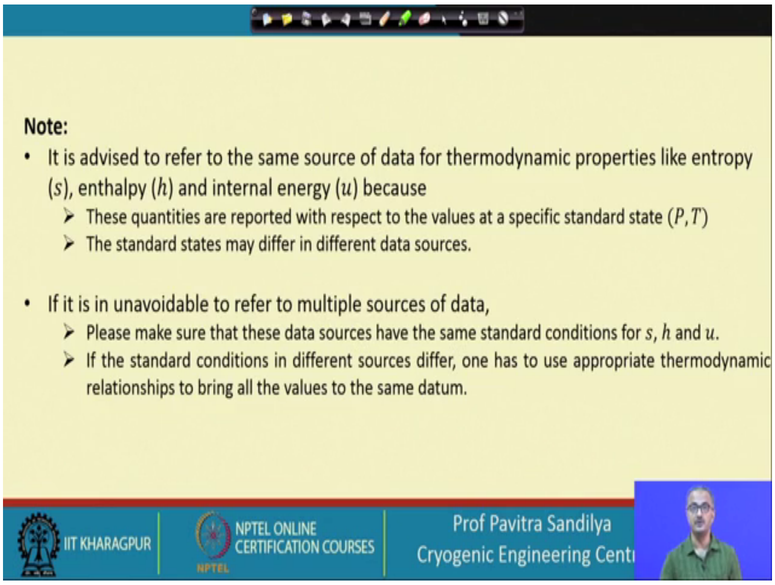

Note:

- It is advised to refer to the same source of data for thermodynamic properties like entropy (s), enthalpy (h) and internal energy (u) because
  - These quantities are reported with respect to the values at a specific standard state (P, T)
  - The standard states may differ in different data sources.
- If it is in unavoidable to refer to multiple sources of data,
  - Please make sure that these data sources have the same standard conditions for s, h and u.
  - If the standard conditions in different sources differ, one has to use appropriate thermodynamic relationships to bring all the values to the same datum.

Now, before we go onto solving the problems let us to do look at some points. And these points should be remembered whenever you are going to solve any of the problems stated earlier, and also we are going to deal with later regarding the use of the various thermodynamic property data from the various sources. So, first thing is this we should always refer to as far as possible the same source of data for thermodynamic properties like entropy, enthalpy and internal energy. Why I am talking about only these three properties, because these three properties are quite often used first.

And second reason is this all these three properties are given in terms of some reference values. And this reference value is again specified at some particular standard conditions. So, there is nothing like absolute enthalpy, absolute entropy, absolute internal energy all these three quantities all relative. And when you take the datum value as some specific value or sometimes the datum value is also taken as 0, so in that case we say that with respect to the datum value, these values are having some whatever value are you specified as the kind of a absolute values.

So, if the datum changes naturally, these values will also change, so that way this is the that a reason that one should be careful and try to stick to only one source of data, so that there is no inconsistency in the final result. Otherwise what happens that you may land up with some very absurd and non physical result. And in case you find that it is not possible for you to get all the data from the same data source, then you may have to look for different data sources as far as possible make sure that all the data sources have the same standard condition for the s h u.

And if you find that this is this condition is not being fulfilled about the same standard conditions, then you have to resort with some equations, which are given in the standard tolerance book to convert one data source datum to another datum, but there are some relations are there by which you can make the things at par. So, these points need to be always kept in mind whenever you are going for any of the thermodynamic analysis.

And in these problems earlier problems also we have been using the values of the entropy and enthalpy to calculate the work, and the yield etcetera. And you we are taking the data from those two books which we are given in the reference, but there are many more data sources available there you will find the values, which we are specifying here in these problems may differ. So, there you should be careful about taking those values.

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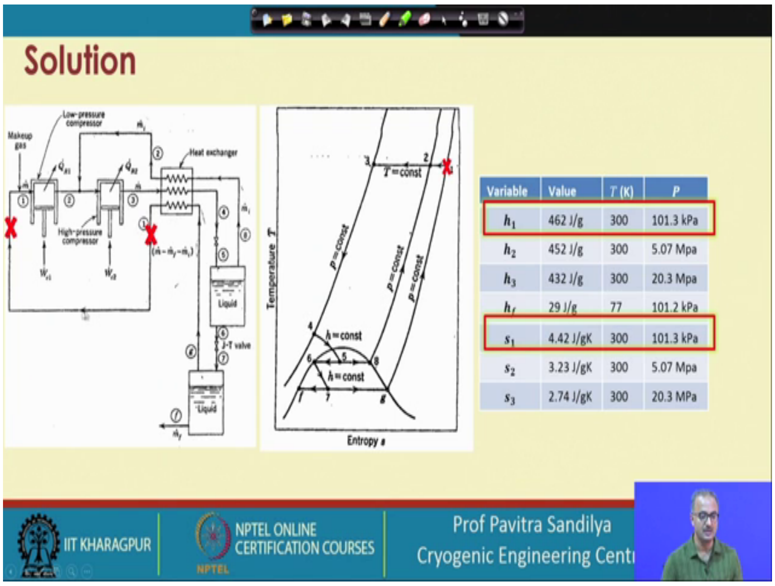

Solution

Variable	Value	T (K)	P
h_1	462 J/g	300	101.3 kPa
h_2	452 J/g	300	5.07 Mpa
h_3	432 J/g	300	20.3 Mpa
h_f	29 J/g	77	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
s_2	3.23 J/gK	300	5.07 Mpa
s_3	2.74 J/gK	300	20.3 MPa

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Let us, now get back to the problem. So, here to recapitulate this is a dual pressure system. Here first we are doing that we are using two compressors. The first compressor is taking from the initial pressure and in our case it has been given about 1 bar. And it is going to the intermediate pressure and that rather has been given as I mean near 5 a mega Pascal that is about 50 bar. And then we have been given the final pressure also. So, these we are given the p 1, p 2 and p 3, and then you should found that we have you using some kind of three channel. And here we have we are using two reservoirs. The first reservoir is simply sending the cold vapor back, and the second reservoir is the from where we are getting the liquid.

So, this particular thing we have to keep in mind. And this is also be showed earlier that is how these whole process can be represented on the T S diagram. And this is an ideal diagram, where we are neglecting all kinds of heat losses, and all kinds of enthalpy, and sorry the changes in the kinetic, and the potential energy, and a heat release are neglected. And based on all these we will generated this particular curve which I am not going to discuss now. But what you shall see that here deep or as per the given problem data, we are getting this I mean the value of the enthalpies and entropies from some thermodynamic chart and which are given in the reference books.

So, from that we are getting these values, and let us see that if you see that this h1 s 1 conditions is with respect to these two points. So, this is the inlet condition to the first compressor and that is the state one. So, and the at the state one we are getting the values of the enthalpy and the entropy. And we have also written the temperature, which is given as 300 k and 1001.3 kilo Pascal. And now we go to the second data point which we need that is the point 2.

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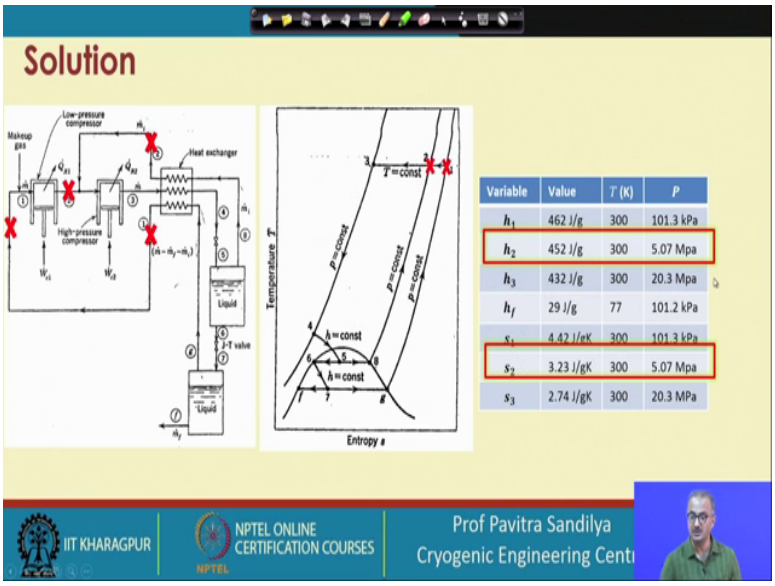

Solution

Variable	Value	T (K)	P
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h_2	452 J/g	300	5.07 Mpa
h_3	432 J/g	300	20.3 Mpa
h_f	29 J/g	77	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
s_2	3.23 J/gK	300	5.07 Mpa
s_3	2.74 J/gK	300	20.3 MPa

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Now, here you will see this 0.2 here in the TS diagram and it is also shown over here point 2. And this is also point two, why, because this particular stream, which is coming up that that is mixing up with this particular state (Refer Time: 07:41) compressor. So, these are the states of these two streams ideally should be the same. So, that is why this is also state 2 and this is also state 2, so and this is state 2 here. So, we are getting the values of the enthalpy and the entropy, and here you see that the intermediate pressure is about 5 mega Pascal.

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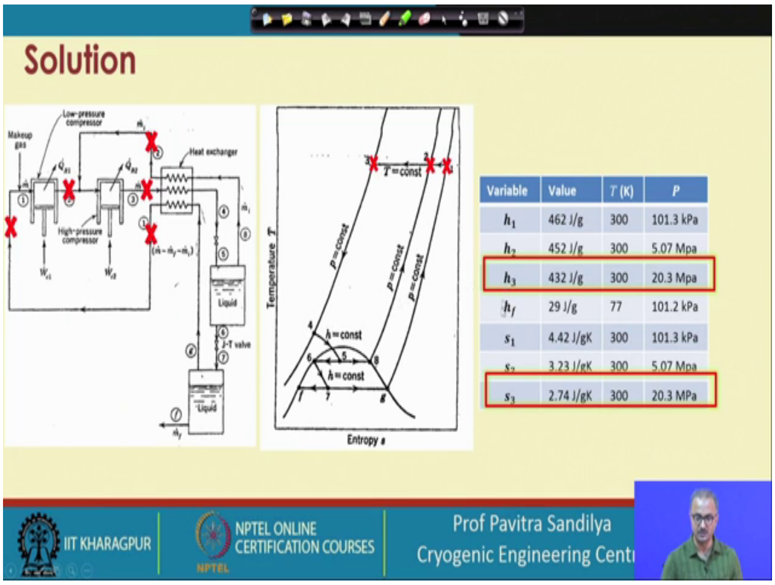

Solution

Variable	Value	T (K)	P
h_1	462 J/g	300	101.3 kPa
h_2	452 J/g	300	5.07 Mpa
h_3	432 J/g	300	20.3 Mpa
h_f	29 J/g	77	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
s_2	3.23 J/gK	300	5.07 Mpa
s_3	2.74 J/gK	300	20.3 MPa

Next we go to the third state that is here, after the second compression here we find the of a second compression that is the highest pressure attained in the system so at this point again we are getting the values of the h and s.

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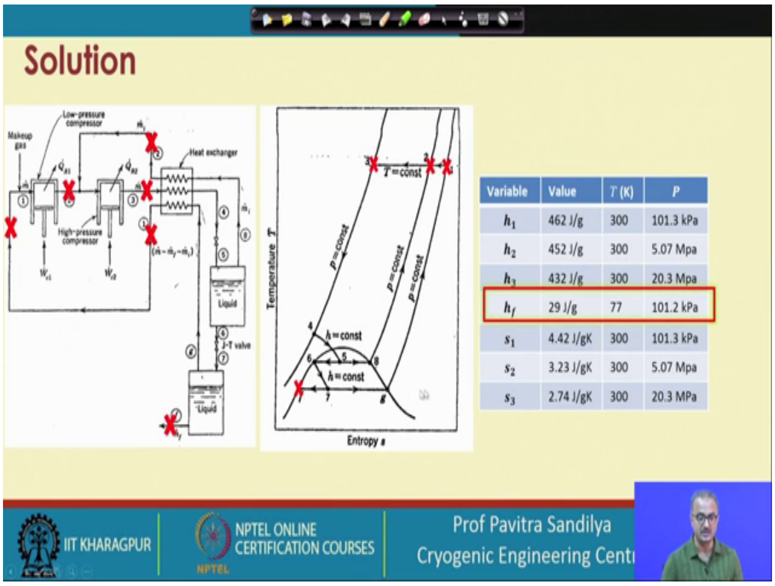

Solution

Variable	Value	T (K)	P
h_1	462 J/g	300	101.3 kPa
h_2	452 J/g	300	5.07 Mpa
h_3	432 J/g	300	20.3 Mpa
h_f	29 J/g	77	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
s_2	3.23 J/gK	300	5.07 Mpa
s_3	2.74 J/gK	300	20.3 MPa

And lastly we have a last point that is h f that is at this point that is in the second liquid this reservoir is there. So, in this that we are finding that we are doing this isenthalpic expansion. And we are getting this saturated liquid this is this liquid is being taken out from this position. So, at this point this is the h f, and please remember that we are assuming that this liquid is saturated and it is not subcooled, so that is why it is falling right on this saturated liquid curve. So, this is the value we read from the TS diagram.

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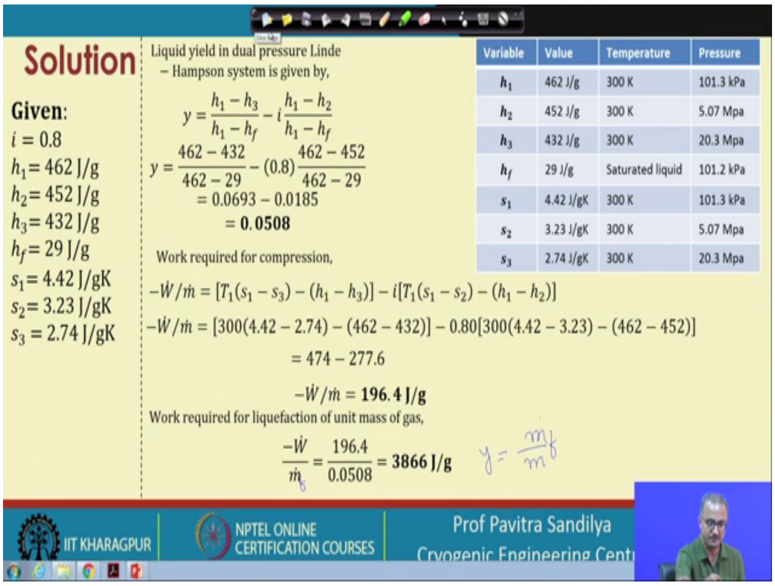

Solution

Given:
$i = 0.8$
$h_1 = 462$ J/g
$h_2 = 452$ J/g
$h_3 = 432$ J/g
$h_f = 29$ J/g
$s_1 = 4.42$ J/gK
$s_2 = 3.23$ J/gK
$s_3 = 2.74$ J/gK

Liquid yield in dual pressure Linde – Hampson system is given by,

$$y = \frac{h_1 - h_3}{h_1 - h_f} - i\frac{h_1 - h_2}{h_1 - h_f}$$

$$y = \frac{462 - 432}{462 - 29} - (0.8)\frac{462 - 452}{462 - 29}$$

$$= 0.0693 - 0.0185$$

$$= \mathbf{0.0508}$$

Work required for compression,

$$-\dot{W}/\dot{m} = [T_1(s_1 - s_3) - (h_1 - h_3)] - i[T_1(s_1 - s_2) - (h_1 - h_2)]$$

$$-\dot{W}/\dot{m} = [300(4.42 - 2.74) - (462 - 432)] - 0.80[300(4.42 - 3.23) - (462 - 452)]$$

$$= 474 - 277.6$$

$$-\dot{W}/\dot{m} = \mathbf{196.4\ J/g}$$

Work required for liquefaction of unit mass of gas,

$$\frac{-\dot{W}}{\dot{m}_f} = \frac{196.4}{0.0508} = \mathbf{3866\ J/g}$$

$$y = \frac{\dot{m}_f}{\dot{m}}$$

Variable	Value	Temperature	Pressure
h_1	462 J/g	300 K	101.3 kPa
h_2	452 J/g	300 K	5.07 Mpa
h_3	432 J/g	300 K	20.3 Mpa
h_f	29 J/g	Saturated liquid	101.2 kPa
s_1	4.42 J/gK	300 K	101.3 kPa
s_2	3.23 J/gK	300 K	5.07 Mpa
s_3	2.74 J/gK	300 K	20.3 Mpa

Now, let us go to the solution. So, we put all these things here this i represents the ratio of the intermediate stream to the total mass flow rate is 0.8. And we write all the values of the enthalpies and entropies and also in this particular table. And now we are we found that in the Linde Hampson dual pressure, Linde Hampson this is the particular expression which we derived for the liquid yield. And as I said that this particular this first one corresponds to the single a simple Linde Hampson.

And the second one is the one that is the contribution from the dual pressure system. And now we plug in the values of the enthalpies over here, and the value of the i over here, and we get this as the liquid yield. So, you can clearly see that if we do not take care take into account the second term ok, then the liquid yield is more than this value. So, there is a slight decrease in the liquid yield from 0.069 that is about 0.07 to about 1 to 05.

So, there is a slight decrease in the liquid yield. On the other hand, let us see that the work of compression that here again we write the work of compression we derived expression earlier. And here you see this first term is representing the work done for the simple Linde Hampson. And this second term is the contribution and which is of in the with negative sign is coming that means the second term is the due to the dual pressure we are reducing the total work done. And this work done is found in terms of the total mass that will being processed.

And again we plug in the values of the various quantities we wrote in the several are here. And we find this is the work done which is coming to about 196 joule per gram. So, you have to be very careful in using this particular values see this all the values that been reported in terms of dual program. So, this dual program or kilo joule per kilogram. And now we lastly we find about the work required per for liquefaction of unit mass of gas.

So, in this case, we shall be using the this is the you know this is modification over here. This will be divided by y this will be m f. So, this will be m f, so this is the this is we are getting from this is the m f. And this m f is mf you know that m f by the total m is this one you have to use that m f by m is equal to y. So, now, now you can see that from this relationship you can see that how this particular thing we can get the amount of liquefaction per unit mass of the gas liquefied.

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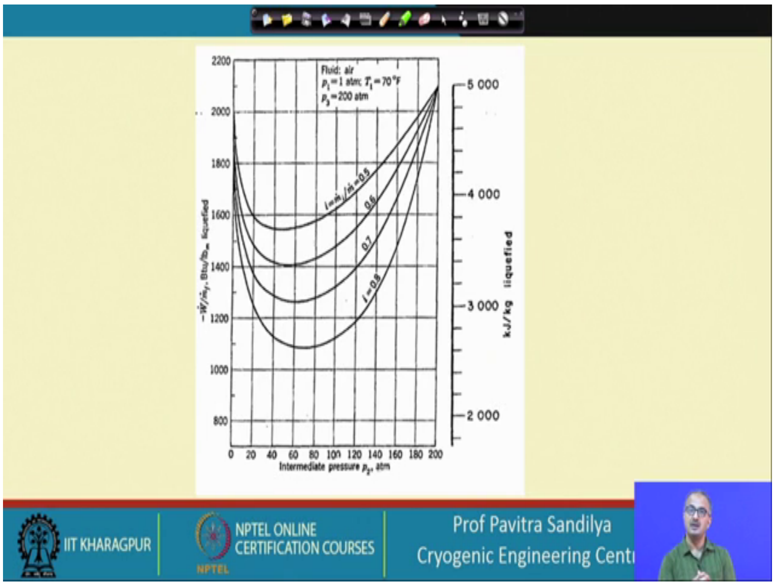

Now, we go to the this particular curve you see here. This curve shows what it shows that on the X axis we are plotting the intermediate pressure and on this Y axis on this we are plotting the amount that is liquefied and on the this Y axis we are plotting the amount that is the work per unit on the mass compressed. So, here this particular graph is showing that how with a change in the in the intermediate pressure, and with the change in the flow ratio of the intermediate mass flow ratio, how will the liquid yield will get affected and the work also get affected.

Now, you can see here that suppose I choose any value of the intermediate flow ratio. And some particular curve for i. Now, if i is constant, then you can see that as I change as I increase the intermediate pressure what we can finding that initially the work is decreasing. Work done per unit mass of the gas liquefied that is initially decreasing. And after certain value we find it is passes through a minimum and then if you further increase the intermediate pressure we find, again there is an increase in the work done that means this intermediate pressure is very crucial factor. It has to be chosen very carefully to fill to minimize the work requirement.

And on the other hand we see that this particular, for a given suppose I take the given intellectual pressure is constant. And now I see that the change in the i that the i is decreasing from bottom to top. And what we find that we go to bottom to top again we find that work done is increasing. So, this kind of curves we can generate for any problem. And in the given problem what we have just seen that in that you can change the values of the i that keeping the intermediate pressure constant or vice versa. And you can figure out the effect of these two parameters on the overall performance of the system in terms of the amount liquefied, and in terms of the work requirement. More obvious things will come to in the assignment.

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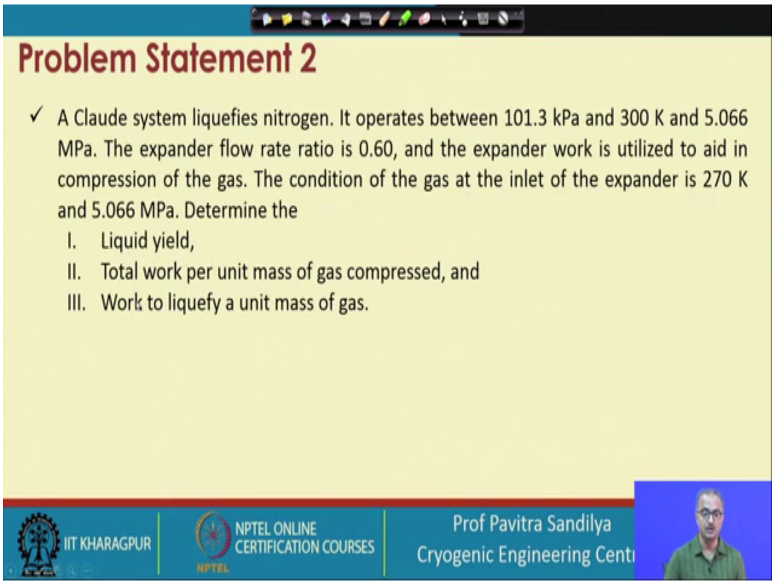

Problem Statement 2

- ✓ A Claude system liquefies nitrogen. It operates between 101.3 kPa and 300 K and 5.066 MPa. The expander flow rate ratio is 0.60, and the expander work is utilized to aid in compression of the gas. The condition of the gas at the inlet of the expander is 270 K and 5.066 MPa. Determine the
  I. Liquid yield,
  II. Total work per unit mass of gas compressed, and
  III. Work to liquefy a unit mass of gas.

Now, we go to the second problem; in this problem what we find that the we have a Claude system now. And Claude system if you recall, this is based on an expansion engine. So, this Claude system is liquefied nitrogen. And it is operating between this particular pressure and temperature and this is a higher pressure, which is the compressor doing. So, here we find that this is about one atmosphere and this is about 50 atmosphere or 50 bar. The expander flow rate ratio is 0.6 and the expander work is utilized to aid in the compression of the gas. And this is very important that when the that means the work, which is obtained from the expander is also being used in the compressor that means what that effectively we are able to reduce that work external of a requirement tool and the compressor.

Now, if we are not doing this that means we are not utilizing the turbine work or the expansion engine work to drag the compressor then we find the compressor work will remains same as in case of the symbol simple Linde Hampson. The condition of the gas at the inlet of expander is 27 K, and this and from we also determine the liquid yield, total work per unit mass of gas compress, and the work to liquefy a unit mass of gas. Now, let us do all these things.

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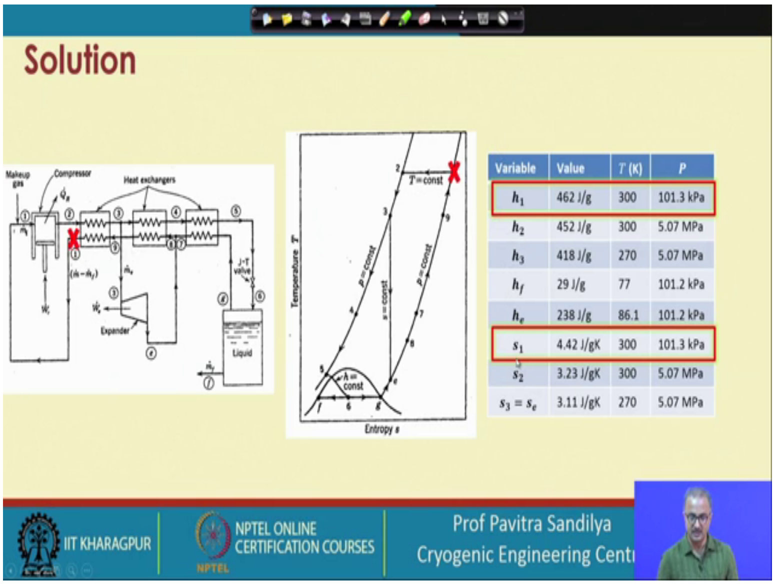

Solution

Variable	Value	T (K)	P
h_1	462 J/g	300	101.3 kPa
h_2	452 J/g	300	5.07 MPa
h_3	418 J/g	270	5.07 MPa
h_f	29 J/g	77	101.2 kPa
h_e	238 J/g	86.1	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
s_2	3.23 J/gK	300	5.07 MPa
$s_3 = s_e$	3.11 J/gK	270	5.07 MPa

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So, again we recall our this is the cloth system that we find we have three heat exchangers. And after the this is being compressed isothermally ideally. And it is do the first heat exchangers from where we are taking a stream out, and the this is being pass through the expander is a getting cooled. And this is coming through the coming through the returned stream, and here we take the rest of the stream is taken for the liquefaction, and from here we are getting the or withdrawn the liquefied mass

And again we go back to the TS diagram representation. So, here it is that from intermediate point this 3 that is 3 is here. We are withdrawing this gas that a part of it to the turbine. So, and this is ideally undergone in a isentropic expansion. So, we have find that it is going to isentropic expansion in a straight line. And rest of the things is it is getting cooled by that this heat exchanger. And ultimately at this is the valve JT valve. It is undergoing in the isenthalpic expansion. And we are getting the liquid over here this is the liquid we are getting here. And from this residues withdrawn, and rest of the vapor, this is a vapors in g, which is again getting heated up isobarically from here to here it is going heated up. It is ultimately reaching the same condition as the initial condition as the at the compressor suction.

So, this is how, and here as we said that we are neglecting all the pressure drops through the pipelines. And we are also neglecting the heat with a heat and mass leakages in the pipeline. And now let us see that these are the values as earlier problem we get the values of various enthalpies and entropies. And again we remark it to the point that these are reach the point on this curve, and on this and this is the point on the TS diagram this h 1 s 1 is there.

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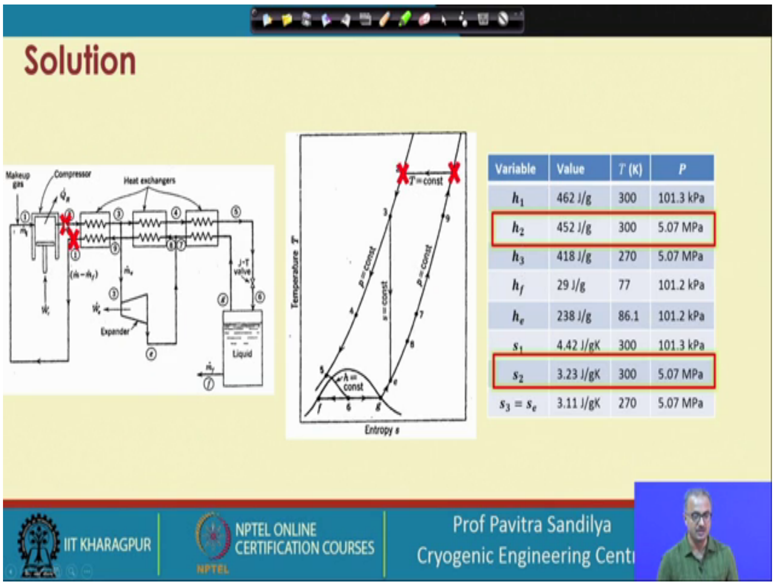

Solution

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h_e	238 J/g	86.1	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
s_2	3.23 J/gK	300	5.07 MPa
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And then we go for h 2 s 2 this is number point 2 here and here is point 2.

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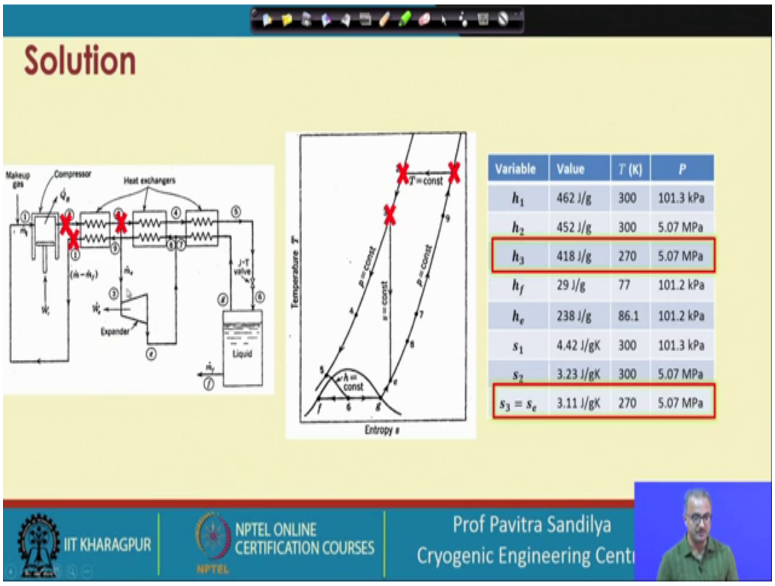

Solution

Variable	Value	T (K)	P
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h_e	238 J/g	86.1	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
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And then we go to point three this points is over here. This is the point three over here. And we read the value of s 3 and then this is the value of the s 3, and s 3, and because ideally this is an isentropic expansion. So, actually the entropy at the entry and the exit of the expansion engine will be the same, so that is why we are writing s 3 is equal to s e. And these are found at this given temperature and pressure.

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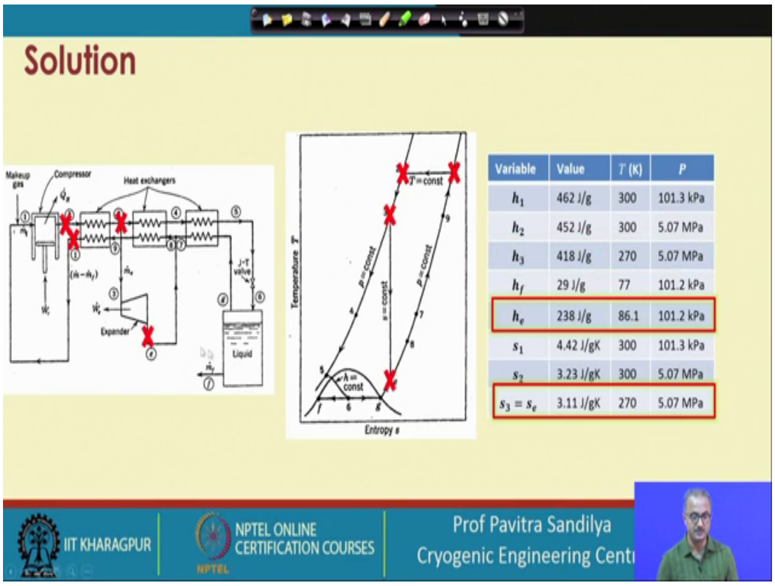

Solution

Variable	Value	T (K)	P
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Then we come to the he value at this point h e value here we have the h e value over here, and that is how we get all the values at the various points which are required to calculate the work, and the liquid yield.

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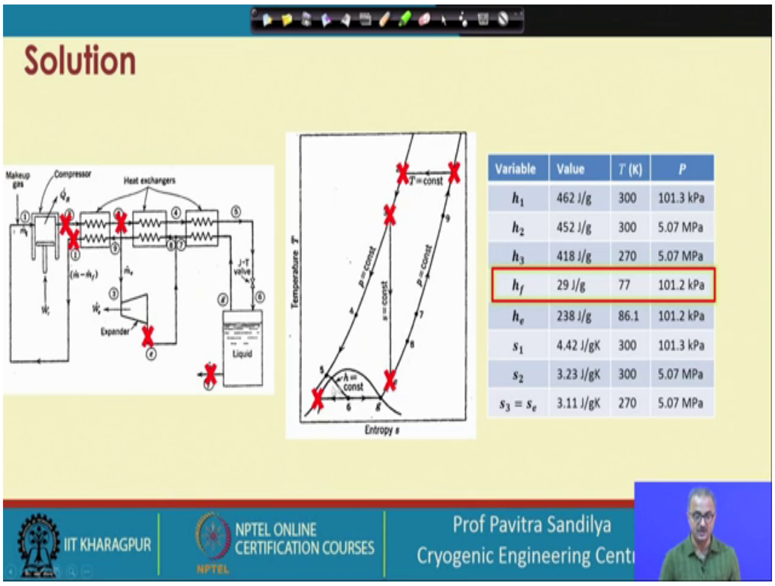

Solution

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Now, lastly we have this h f value, h f we can see that this is at the 77. So, this is corresponding to the saturated liquid.

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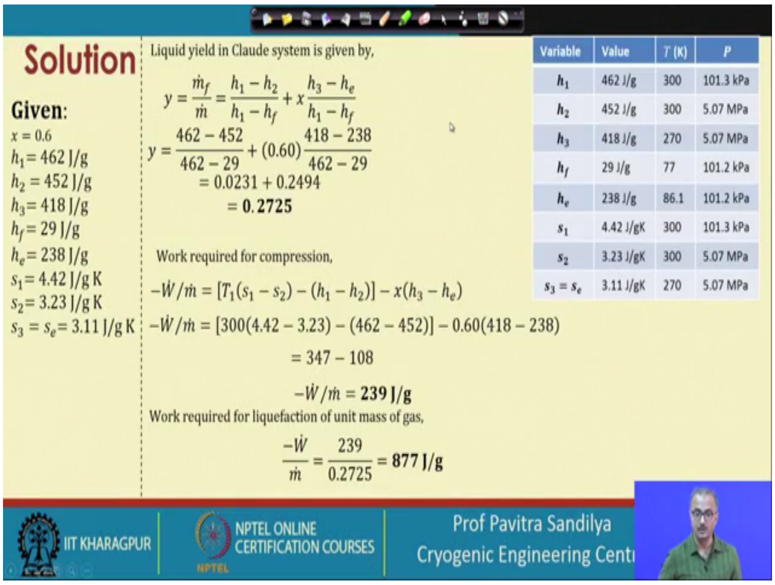

Solution

Given:

$x = 0.6$
$h_1 = 462$ J/g
$h_2 = 452$ J/g
$h_3 = 418$ J/g
$h_f = 29$ J/g
$h_e = 238$ J/g
$s_1 = 4.42$ J/g K
$s_2 = 3.23$ J/g K
$s_3 = s_e = 3.11$ J/g K

Liquid yield in Claude system is given by,

$$y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f} + x\frac{h_3 - h_e}{h_1 - h_f}$$

$$y = \frac{462 - 452}{462 - 29} + (0.60)\frac{418 - 238}{462 - 29}$$

$$= 0.0231 + 0.2494$$

$$= \mathbf{0.2725}$$

Work required for compression,

$$-\dot{W}/\dot{m} = [T_1(s_1 - s_2) - (h_1 - h_2)] - x(h_3 - h_e)$$

$$-\dot{W}/\dot{m} = [300(4.42 - 3.23) - (462 - 452)] - 0.60(418 - 238)$$

$$= 347 - 108$$

$$-\dot{W}/\dot{m} = \mathbf{239\ J/g}$$

Work required for liquefaction of unit mass of gas,

$$\frac{-\dot{W}}{\dot{m}} = \frac{239}{0.2725} = \mathbf{877\ J/g}$$

Variable	Value	T (K)	P
h_1	462 J/g	300	101.3 kPa
h_2	452 J/g	300	5.07 MPa
h_3	418 J/g	270	5.07 MPa
h_f	29 J/g	77	101.2 kPa
h_e	238 J/g	86.1	101.2 kPa
s_1	4.42 J/gK	300	101.3 kPa
s_2	3.23 J/gK	300	5.07 MPa
$s_3 = s_e$	3.11 J/gK	270	5.07 MPa

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We are coming to the solution again we write the expression for the liquid yield. And here in this case we find by using this expansion engines we are able to increase the liquid yield over what we get the symbol Linde-Hampson. This is a simple Linde-Hampson yield, and this is the contribution of the Claudes Claude expansion and required. So, now ultimately we will get this is the (Refer Time: 19:03) in the liquid yields. And you can see that the symbol Linde-Hampson we would get 0.02 whereas, in case of this Claude system we are getting 0.27. So, this is a substantial rise in the liquid yield.

On the other hand, if you look at the work of compression you see that, because we are using the work from the expander. So, it is reducing the overall work requirement by the compressor. And if we do not do this, if we do not use the this work and we find this work is same as that for the simple Linde-Hampson. Again plug in the values we find that this is the work done per unit mass of the gas being processed. And for this mass of this gas which is unit mass of the gas liquefied again it is a m f and m f y equal to m f by m.

So, we are using this relationship, and to find; and find out the value of the mass work requirement per unit mass of the gas liquefied. So, this is how we do this particular problem.

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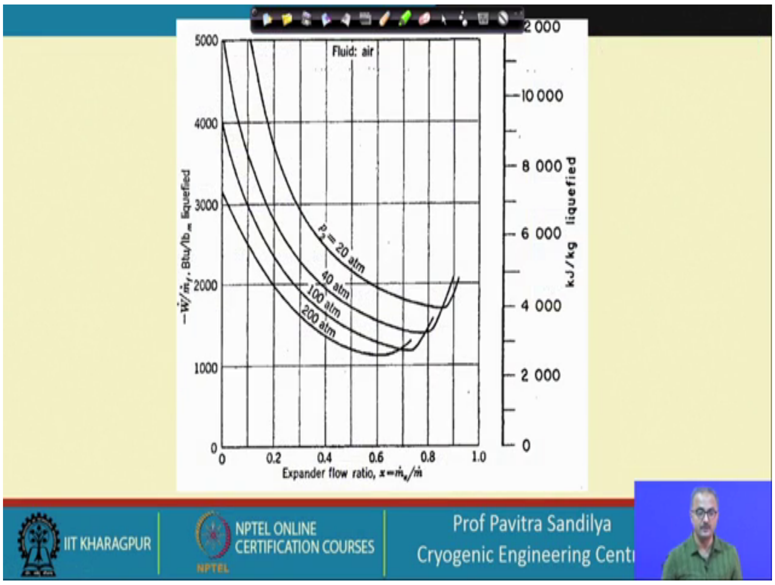

And now we see that again we are putting another curve like this. And here what we see that we are having the various pressures over here. And this is the various X values expander flow ratio. And these are the intermediate pressure to which is getting expanded at the liquid yield and again we find this sort of curve can be obtained to find out the effect of the expander flow ratio on the work done. And this is for air. So, this kind of things can also generated for different types of working gases.

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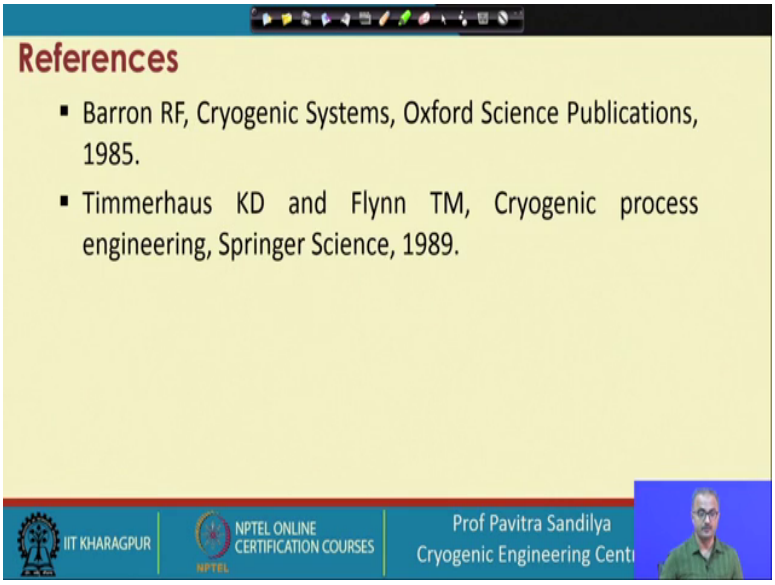

References

- Barron RF, Cryogenic Systems, Oxford Science Publications, 1985.
- Timmerhaus KD and Flynn TM, Cryogenic process engineering, Springer Science, 1989.

Now, these are the two books. And these two books may be referred to further detail about the processes, and their calculation methods and also to obtain the all the thermodynamic properties, which we have taken from this two sources.

Thank you.