Refrigeration and Air Conditioning
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Lecture No. # 18
Worked Out Examples - I

Welcome back in this lecture. I would like to work out some example problems. Before I start discussing these problems let me give the step wise procedure for solving these problems.

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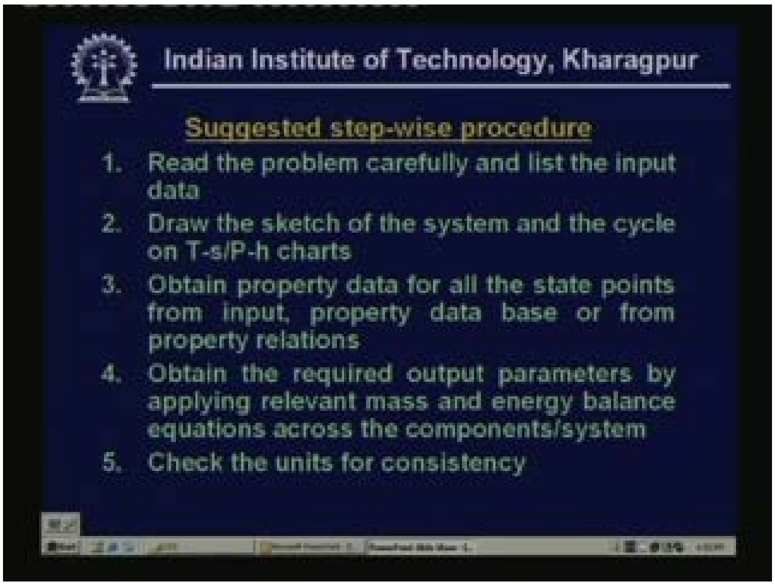

This is the suggested procedure. So first step is obviously you have to read the problem carefully and list the input data. And the second important step is you draw the sketch of the system and the cycle on T-s or P-h charts and label all the state points. And step three is, obtain property data for all the state points either from the input or from property data base or from property relations. And step number four is, obtain the required output parameters by applying relevant mass and energy balance equations across the components or system.

Finally you have to check the units for consistency. So if you proceed in a systematic manner solving these problems will be very easy okay. So systematic procedure is always better. So, now let us go to some of the typical problems.

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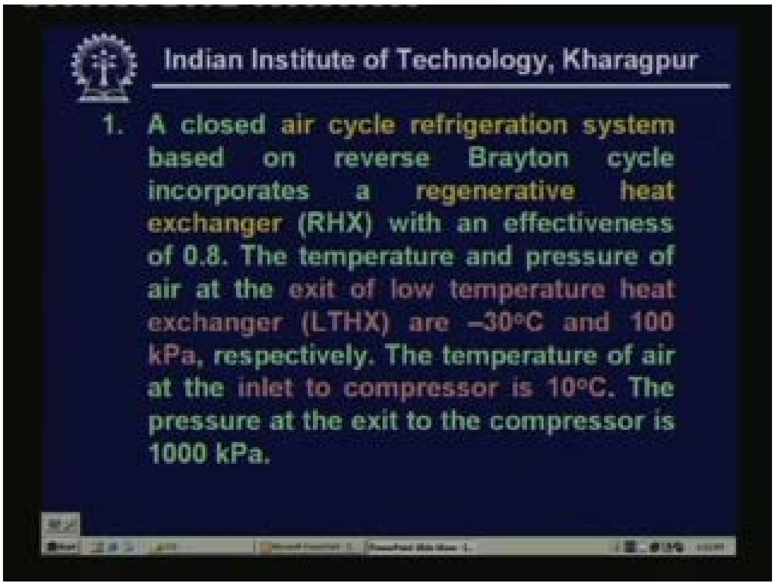

The first problem is on air cycle refrigeration system. The problem statement is like this a closed air cycle refrigeration system based on reverse Brayton cycle incorporates a regenerative heat exchanger which has an effectiveness of point eight the temperature and pressure of air at the exit of low temperature. Heat exchangers are minus thirty degrees centigrade and hundred kilo Pascal respectively. And the temperature of air at the inlet to compressor is ten degree centigrade and the pressure at the exit to the compressor is thousand kilo Pascal’s. This is the problem statement. It is a simple air cycle refrigeration system only one change is there is an additional component that is regenerative heat exchanger.

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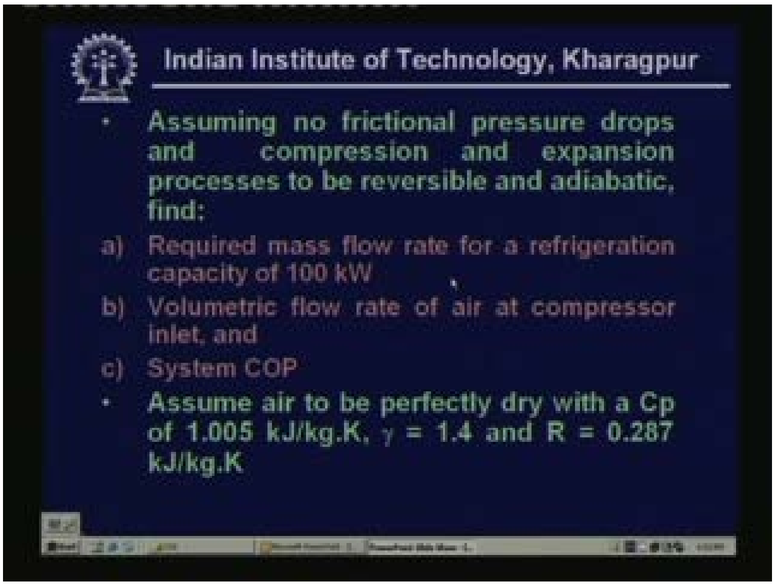

It is also mentioned that we have to assume no frictional pressure drops and compression. And expansion processes to be reversible and adiabatic and under these assumptions. And from the given data we have to find the required mass flow rate for a refrigeration capacity of hundred kilo watts required volumetric flow rate of air at compressor inlet and the system COP. And for calculation purposes we can assume air to be perfectly dry with a specific heat Cp of one point zero zero five kilo joule per kilogram Kelvin and specific heat ratio gamma of one point four and gas constant for air we can take it as point two eight seven kilo joule per kg Kelvin.

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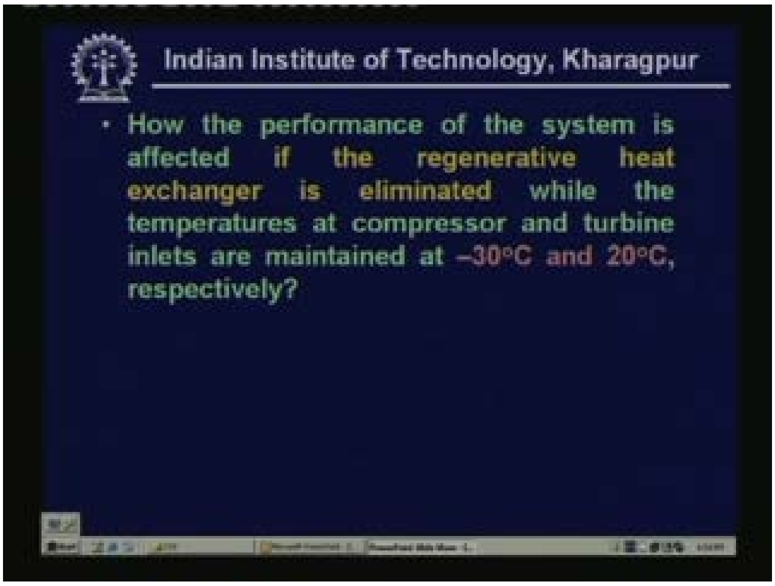

And the second part of the problem is we have to compare the performance of this system with a system which does not have a regenerative heat exchanger that means we have to compare this system with a simple system which doesn't have a regenerative heat exchanger and for the simple system the input data is the temperatures and at the compressor and turbine inlets are minus thirty degree centigrade and twenty degree centigrade respectively and pressures are same as before that is hundred kilo Pascal and thousand kilo Pascal

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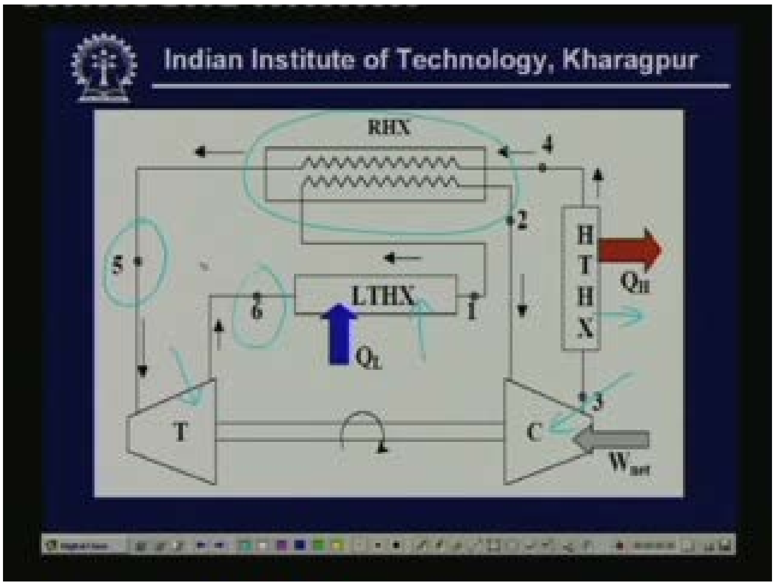

Now this figure here shows the schematic of the system. So you can see that we have the four basic components that is turbine compressor low temperature heat exchanger where the refrigeration is produced. And the high temperature heat exchanger where heat rejection takes place in addition to this four basic components we have an additional component that is the regenerative heat exchanger. Now if you look at the schematic you can understand the purpose of regenerative heat exchanger. The purpose of regenerative heat exchanger is to pre cool the air that is going to the turbine. That means the air that is going to the turbine that is point five will be pre cooled if you use a regenerative heat exchanger. How is it getting pre cooled? It gets pre cooled by rejecting heat to the cold air stream that is going to the compressor.

So you can see that in the regenerative heat exchanger cold air coming from the low temperature heat exchanger extract heat from the hot air that is going to the turbine okay. So as a result you are able to pre cool the air that is going to the turbine. And we will see that when you pre cool the air the temperature at the inlet to the low temperature heat exchanger will be reduced. So this is the purpose of using a regenerative heat exchanger.

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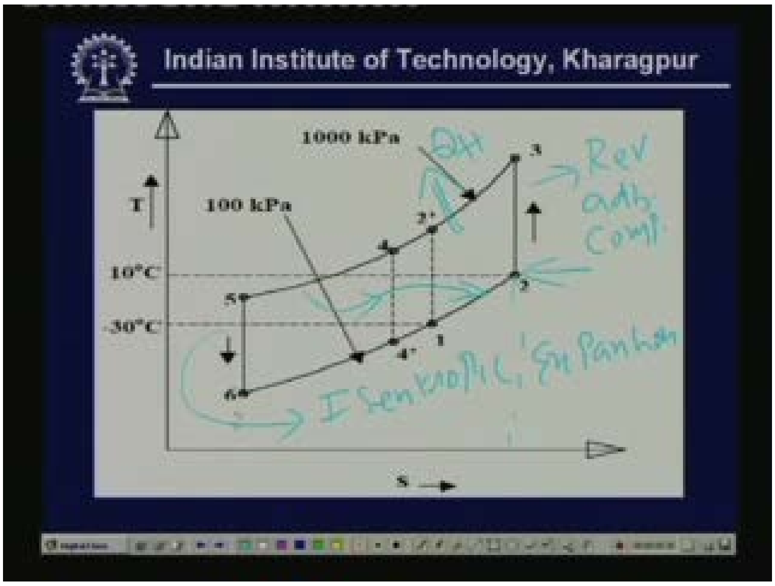

Now let me show the cycle on T-s diagram. As I said the second step is to show the cycle. So here I am using a T-s diagram and let me explain the various processes. Let me begin at this point this is the inlet to the compressor. So the air is compressed reversibly and adiabatically so entropy remains constant during this process. So this is the reversible and adiabatic compression okay. And during this process the pressure increases from hundred kilo Pascal to thousand kilo Pascal. And you can also see that temperature is also increasing because of the compression okay. Next process is process three to four process three to four is the heat rejection process in the high temperature heat exchanger okay. So this is the heat rejection process in the high temperature heat exchanger during this process the pressure remains constant that means it is an this an isobaric process.

So pressure does not change. So temperature reduces because it is rejecting heat to the external heat sink then process four to five is the heat exchange process that is taking place in the regenerative heat exchanger. So in this process the temperature drops. Because the hot air exchanges heat with the cold air that is coming from the low temperature heat exchanger okay. So as a result this during this process the pressure or temperature reduce from four to five whereas the pressure remain constant at thousand kilo Pascal and process five to six this process is isentropic expansion isentropic expansion in the turbine. So during this process as you can see the pressure reduces from thousand kilo Pascal to hundred kilo Pascal. As a result the temperature drops okay. And since this is an isentropic process the entropy remains constant okay. And process finally process six to four six to four is a heat.

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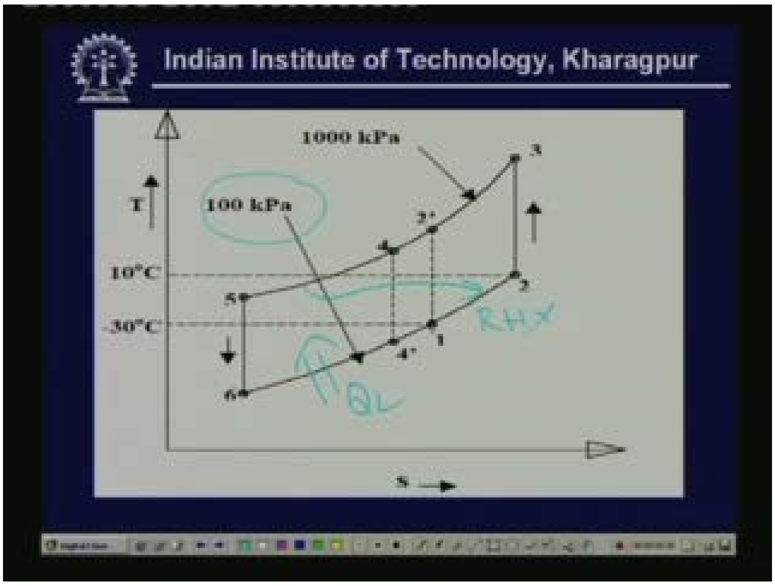

This process six to four is a actual heat extraction process during which you get the useful refrigeration okay. And this is again an isobaric process this process is taking place at hundred kilo Pascal pressure. And during this process because the heat transferred to the air temperature increases from six to one okay. So this is the process. And finally process one to two process one to two is what is taking place in the regenerative heat exchanger. As I have already explained, during this process heat is transferred from the hot air that is from four to five to the cold air that is going to the compressor. As a result the temperature increases whereas the pressure remains constant. So these are the six processes in this cycle.

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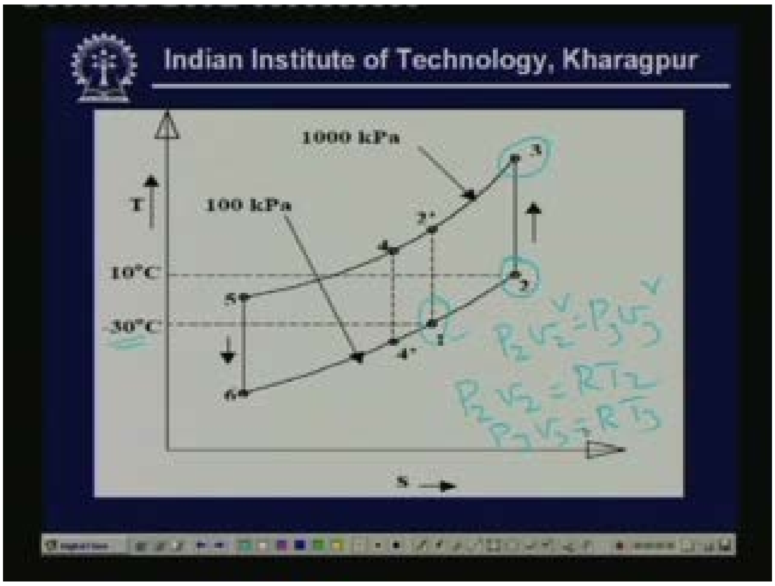

Now let me, from the input data we know that the temperature at this point that is at the exit of the low temperature heat exchanger is minus thirty degree centigrade. We know this temperature okay, and we also know the pressure. So immediately we can locate this point and it is also given that the temperature at the inlet to the compressor is plus ten degree centigrade that means this temperature is also given. Since this pressure is also same as hundred kilo Pascal. We can also locate this point that means this point is known to us and this point is known to us. Now we have to find out remaining points state points. First let us look at point three how do we find the point three we know that this process is isentropic compression process.

So for this process we can write one equation as P two V two to the power of gamma is P three V three to the power of gamma. This is one equation and for each point we can write, for example P two V two you can write it as RT two because we are assuming A to be an ideal gas. Similarly you can write P three V three is RT three okay. So these are the equations.

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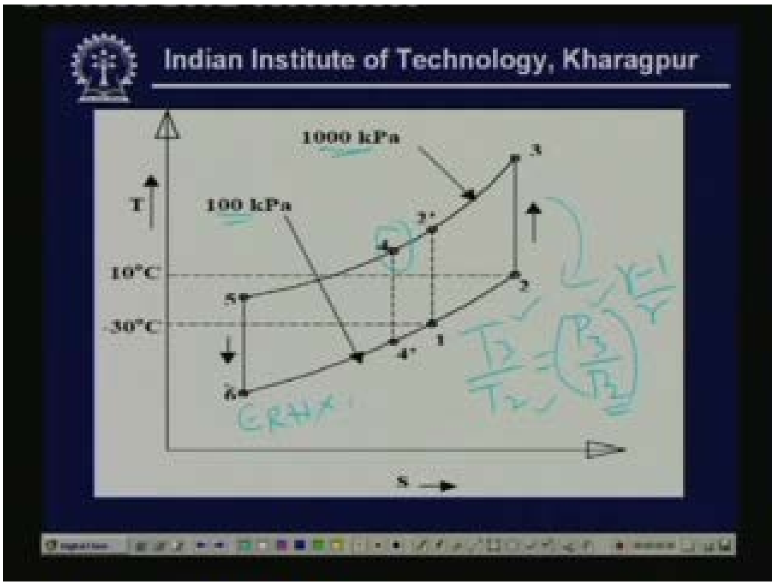

From these equations we have seen that, you can finally write for this process if you are eliminating specific volume for this process ultimately you can show that the temperature T three by T two is given by P three by P two to the power of gamma minus one by gamma okay. This is the expression which relates the temperatures with pressures and we know the pressures P three is known P three is nothing but thousand kilo Pascal P two is known which is equal to hundred kilo Pascal. So this side we know and gamma is one point four and T two is known to us which is given as an input okay. So for using this equation we can find out what is T three okay. Then comes point four how do you find the temperature at point four then temperature at point five okay. Temperature at point four and five will be found using the effectiveness of the heat exchanger okay that i will explain little later. So these two points will be obtained using the effectiveness of heat exchanger and the energy balance across the regenerative heat exchanger okay.

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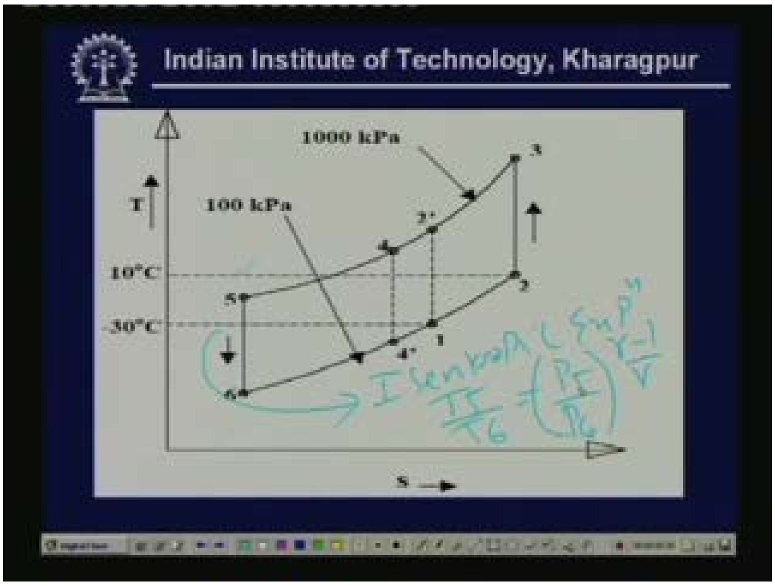

And for the process five to six which is this process this process is again an isentropic expansion process isentropic expansion process. So again we are similar to isentropic compression we can write for this process T five divided by T six equal to P five by P six to the power of gamma minus one by gamma again P five and P six are known P five is thousand kilo Pascal P six is hundred kilo Pascal. So this right hand side is known to us and from the left hand side if you can find out T five we can find T six using this expression okay. So this is how we will be finding the different state points.

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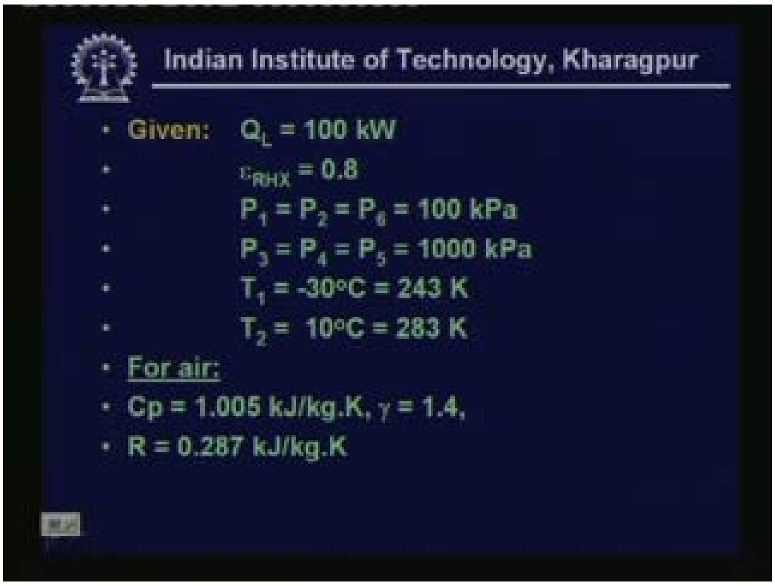

Okay, so the given information is like this QL is hundred kilo watt and effectiveness of the heat exchanger is point eight and the low side pressure. That means the suction pressure is hundred kilo Pascal. And the discharge pressure is thousand kilo Pascal and temperature T one is minus thirty degree centigrade that is two forty-three Kelvin and temperature T two is ten degree centigrade that is two eight three Kelvin. And for air the properties are given as Cp is one point zero zero five gamma is one point four and R is point two eight seven kilo joule per kilogram Kelvin.

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Okay, so as I have already explained uh let us find out the temperatures at various points first the temperature at the exit of the compressor. As I have already told you this is an isentropic compression process. So temperature at the exit of the compressor if find by using this equation T three is equal to T two into P three by P two to the power of gamma minus one by gamma and if you substitute the values you find that T three is five forty-six point four Kelvin. Now we have to find out other temperatures T four T five etcetera for this. As I told you we will be using the definition of heat exchanger effectiveness from the definition of heat exchanger effectiveness, how do you define that?

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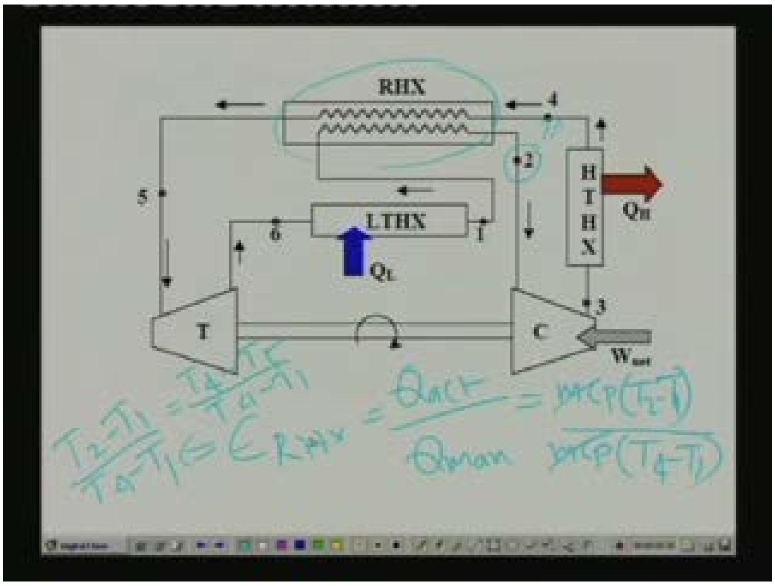

Let me explain so here the for this one i am talking about the regenerative heat exchanger you can define effectiveness as Q actual divided by Q maximum okay. And Q actual is a actual heat transfer between the two streams which is given by for example if you are taking the cold stream Q actual is nothing but MCp into T two minus T one okay. MCp into T two minus T one where m is the mass flow rate of air Cp is the specific heat T two and T one are the exit and inlet temperatures. This is the Q actual what is the Q maximum heat transfer rate will be maximum when the exit temperature T two is equal to T four. So these are the conditions under which the heat transfer rate will be maximum that means Q maximum is equal to MCp into T four minus T one. So same mass is flowing MCp get cancelled. So finally you find that effectiveness of heat exchanger is given by T two minus T one divided by T four minus T one.

Of course you can also write this in terms of the hot air stream or that means you can write this also in terms of T four minus T five divided by T four minus T one okay. So you can use either this expression or this expression.

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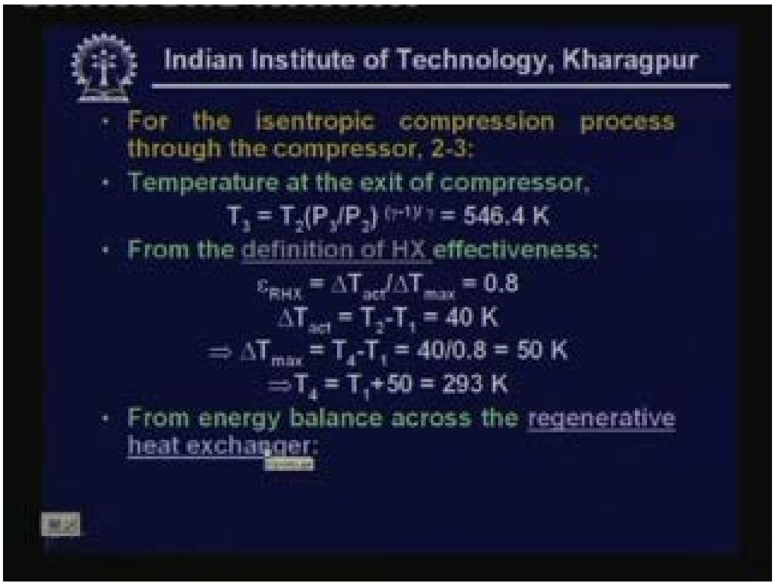

So from there that expression del as I have already told you effectiveness is delta T actual by delta T maximum and that is given to be point eight delta T actual is T two minus T one T two is two eighty-three Kelvin and T one is two forty-three Kelvin. So the delta T actual is forty Kelvin from this you can find out delta T max which is equal to T four minus T one that is equal to forty by point eight that means fifty Kelvin. So from this you can find out T four because T one is known to us okay. So T four is T one plus fifty that is two ninety-three Kelvin. Now what we do is we have to find out the temperature at the inlet to the turbine that is point five for that we apply the energy balance across the regenerative heat exchanger.

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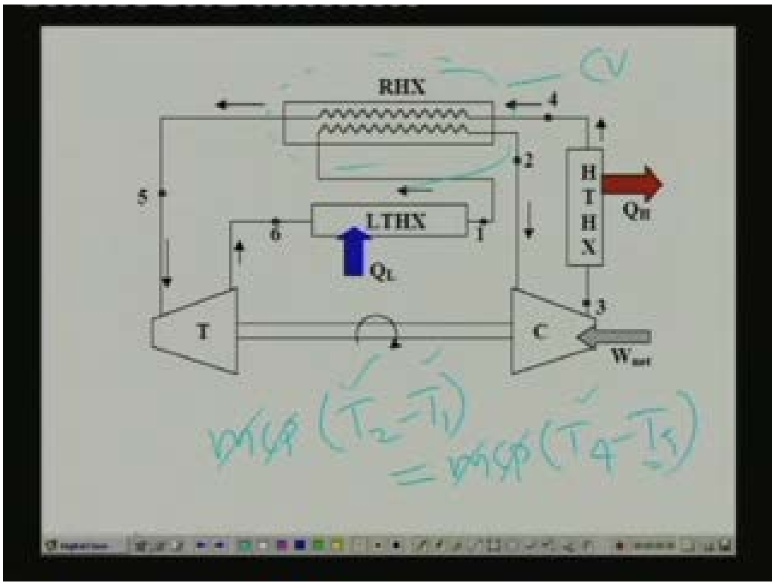

This is again very simple if you are assuming steady-flow across the regenerative heat exchanger and take a control volume takes a control volume across the regenerative heat exchanger. And if you apply the energy balance energy balance is energy gained by the cold stream is equal to energy lost by the hot stream okay. So energy gained by the cold stream is nothing but MCp into T two minus T one this should be equal to energy lost by the hot stream which is equal to MCp T four minus T five. So in uh for this cold air standard cycle analysis Cp value remains same mass is flowing so this value is get cancel. So finally from energy balance we see that T two minus T one is equal to T four minus T five and T two and T one are known to us T four we have computed.

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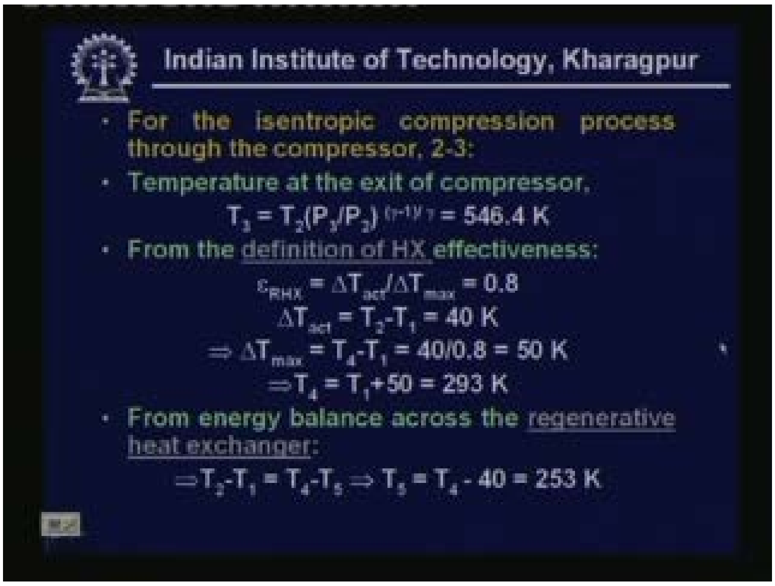

So from this we can find out T five that is what is done here T two minus T one is equal to T four minus T five. That means T five is equal to T four minus forty because T two minus T one is forty. So from this we get T five as two fifty-three Kelvin.

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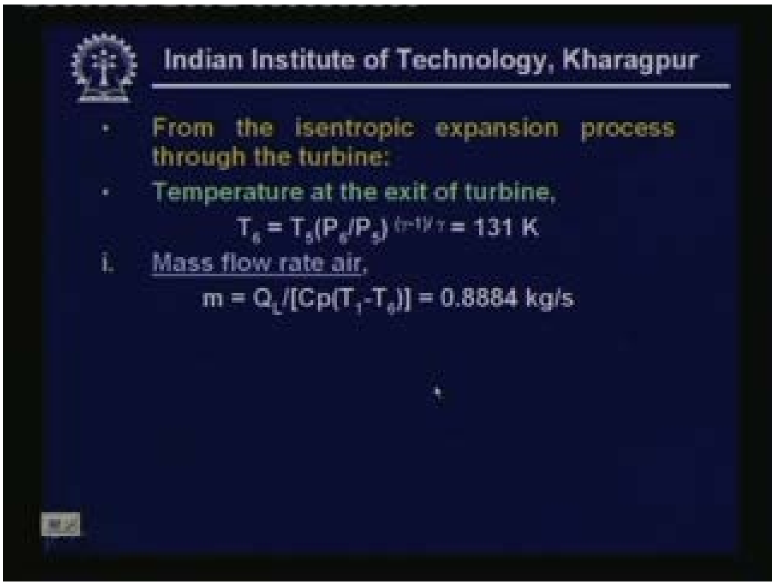

So finally we have to find out what is the temperature at the exit of the turbine okay. So this process as I have already told you is an isentropic expansion process. So temperature at the exit of turbine is given by T six is equal to T five into P six by P five to the power of gamma minus one by gamma and T five just now we have found is two fifty-three Kelvin and P six is thousand kilo Pascal and P five is hundred kilo Pascal. So if you substitute these values you find that T six is equal to one thirty-one Kelvin. Now mass flow rate of air we have to find out mass flow rate of air is simply given by refrigeration capacity by CP into delta T.

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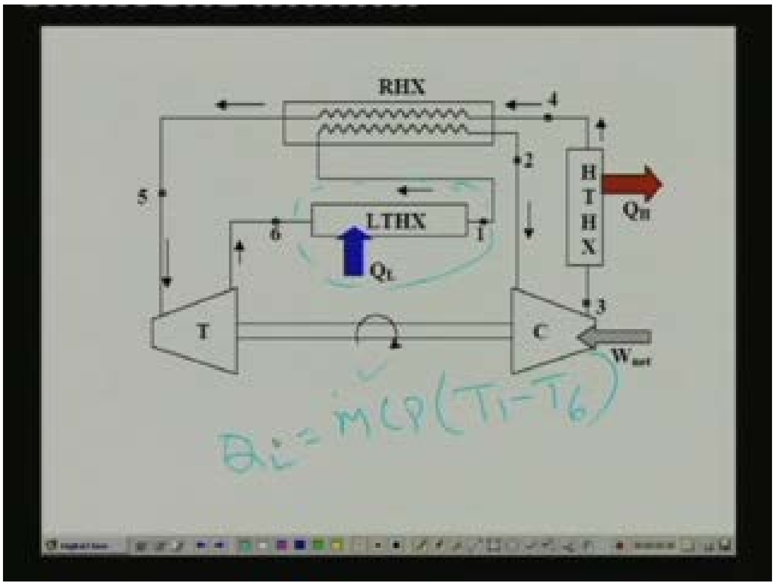

This you get by applying energy balance across the low temperature heat exchanger. So from energy balance across the low temperature heat exchanger Q L is equal to m dot into CP into temperature that is T one minus T six okay. So from this you can find out what is m dot okay.

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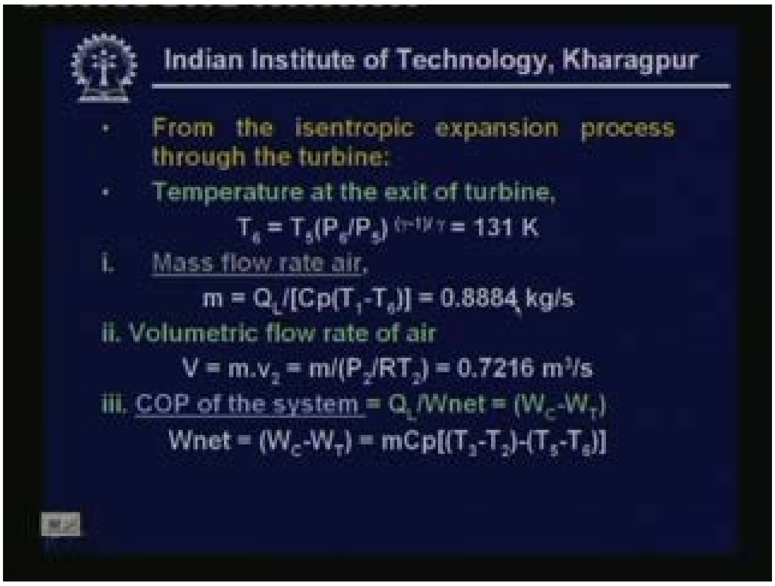

So m dot is given to be point eight eight eight four kilo kilogram per second QL is given as hundred kilo watts CP is one point zero zero five and T one and T six are known to us okay. Next is we have to compute the volumetric flow rate at compressor inlet so volumetric flow rate at compressor inlet is simply equal to mass flow rate into specific volume of air at that point and since we are assuming the air to be perfect gas specific volume of air is given by P by RT at compressor inlet. That means ultimately the volumetric flow rate V is equal to m divided by P two by RT two okay where P two is the suction pressure that is hundred kilo Pascal R is the gas constant and T two is the inlet temperature which is equal to two eighty-three Kelvin.

So if you are substituting these values you will find that volumetric flow rate is given by point seven two one six meter cube per second. Finally we have to find the COP of the system COP of the system is given by QL divided by W net that is the net work input to the system. And net work input to the system is equal to work input to the compressor minus work output from the turbine okay.

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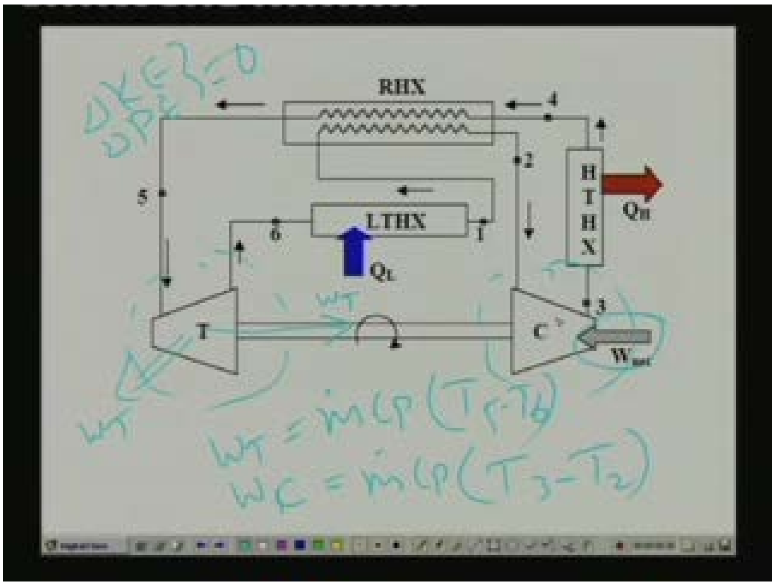

This you can easily find out by again applying energy balance across turbine and compressor if you are applying energy balance across the turbine. And neglect delta KE and delta PE that means delta KE delta PE are negligible for both the components then from energy balance. And this is an reversible adiabatic process there is no heat transfer. So you find that work output from the turbine. Okay, is simply equal to m dot CP into T five minus T six okay. This is from the energy balance across the control volume similarly work input to the compressor WC is equal to m dot CP into T three minus T two okay, m dot CP m dot CP is same. So the network input is nothing but the work input to the compressor minus work output from the turbine you can see that the turbine is supplying its useful work output to the compressor okay. So network uh output is network input is the difference between these two.

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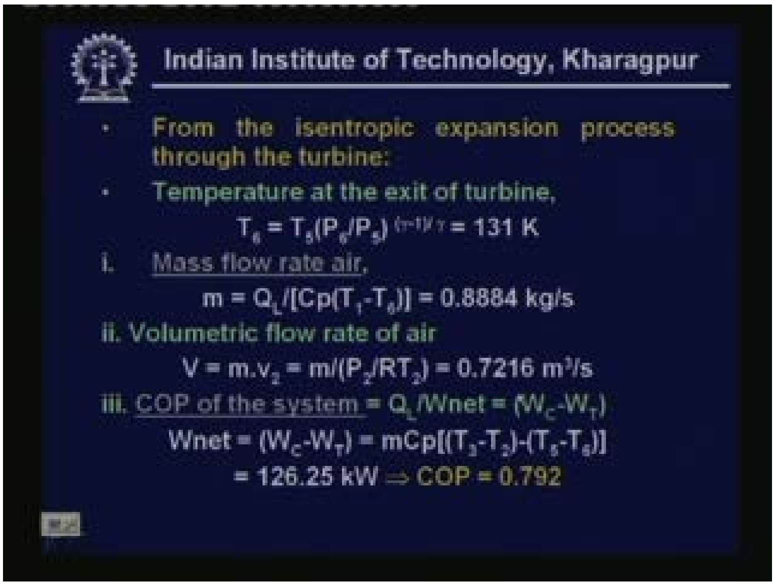

So that is what is written here W net is equal to WC minus WT that is equal to mCP into T three minus T two minus T five minus T six all the temperatures are known to us. So if you substitute these values you will find that net work input to the system is one twenty-six point two five kilo watt therefore the COP is QL divided by net work input that is hundred divided by one twenty-six point two five that comes out to be point seven nine two okay. So this is how we can calculate the required performance parameters. So you can notice that first we have written drawn the systems schematic then we have drawn the cycle and T-s diagram because here T-s diagram is more useful then uh from the given information. We have obtained the state points properties at all other state points. And once you have the property set at all the state points all that you have to do is apply proper mass and energy balance equations across each component or across the system and find out the required parameters okay.

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Okay, now the second part of the problem is we have to compare the performance of this system with the system which does not have regenerative heat exchanger okay. That means the simple system. So simple system I will just show the T-s diagram.

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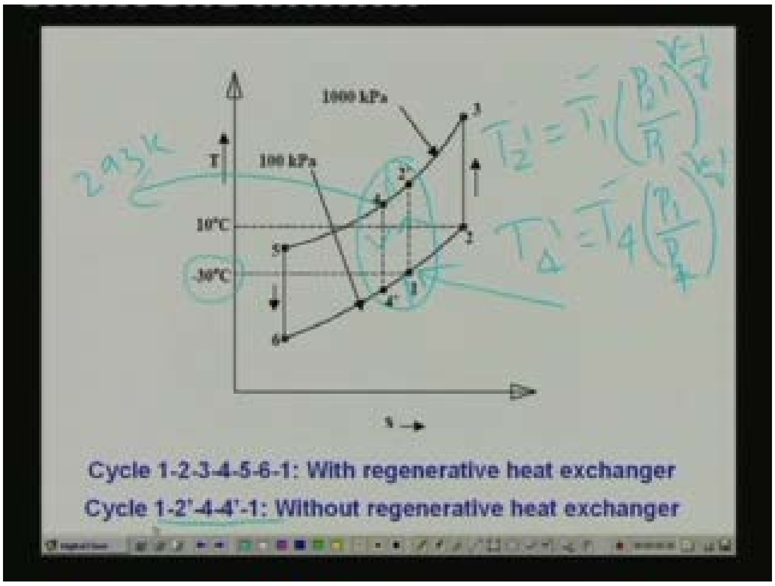

You can see that in a simple system cycle is given by this is the simple system okay, one two dash four four dash okay. So again you have isentropic compression isentropic expansion and isobaric heat rejection isobaric heat extraction. Since you do not have any regenerative heat exchanger there is no heat exchange between hot and cold streams okay. And in we know from the given input information that this temperature is minus thirty degree centigrade and this temperature T four is two ninety-three Kelvin okay. So these two temperatures are given we have to find out the remaining temperatures and since the pressures are same hundred kilo Pascal here and thousand kilo Pascal. We can find out T two dash is nothing but T one into P two dash divided by P one to the power of gamma minus one by gamma. Similarly T four dash is T four into T one by P one by P four to the power of gamma minus one by gamma. All the pressures are known T one and T four are known. So you can find out T two dash and T four dash okay. So that is what is done.

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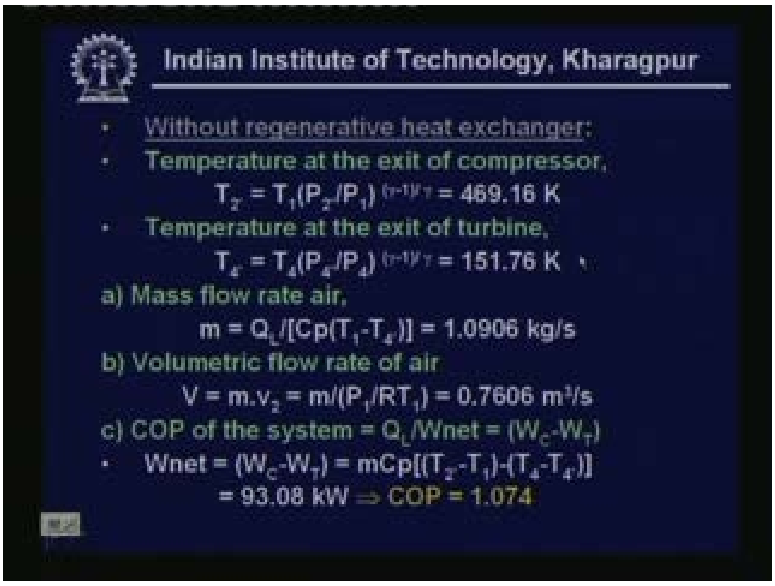

So from that you find that the temperature at the exit of compressor is four six nine point one six Kelvin temperature at the exit of the turbine is one fifty-one point seven six Kelvin. And mass flow rate of air again from energy balance across the low temperature heat exchanger is one point zero nine zero six kilogram per second and volumetric flow rate is point seven six zero six. And finally COP of the system we find out the net work input which turns out to be ninety-three point zero eight kilo watt and COP is found to be one point zero seven four okay. So this is the performance without any regenerative heat exchanger. Now we can quickly compare.

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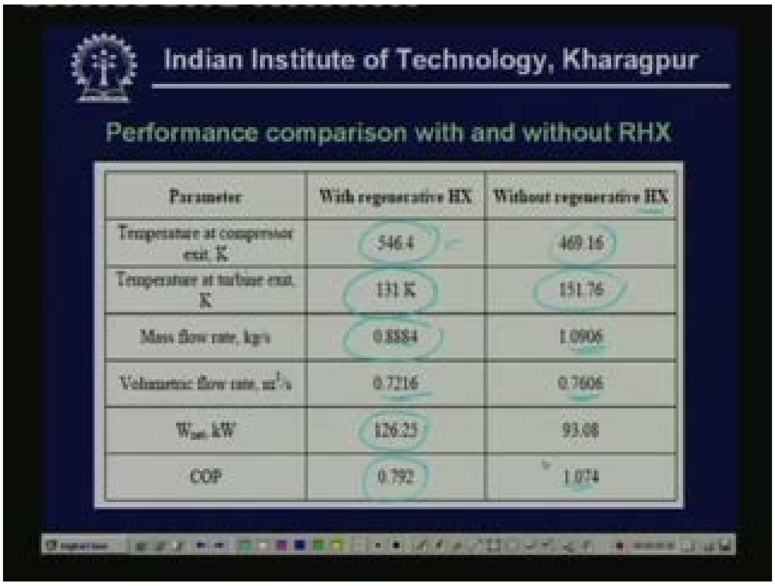

Parameter	With regenerative HX	Without regenerative HX
Temperature at compressor exit, K	546.4	469.16
Temperature at turbine exit, K	131 K	151.76
Mass flow rate, kg/s	0.8884	1.0906
Volumetric flow rate, m^3/s	0.7216	0.7606
W_{net}, kW	126.25	93.08
COP	0.792	1.074

The performance with and without regenerative heat exchangers you can see that when you are using regenerative heat exchanger temperature at the exit of compressor is much higher compared to this okay. This is the drawback actually but what is the advantage of using regenerative heat exchanger temperature at the exit to the turbine is much less compared to the one without regenerative heat exchanger. This is one thirty-one versus one fifty-one as a result of this refrigeration effect increases since refrigeration effect increases required mass flow rate reduces when you are using a regenerative heat exchanger. That is what you can see okay. And the required volumetric flow rate also reduces that means basically you will be handling less amount of air okay.

Of course the penalty you will be paying is in the form of higher net work input because of the higher temperature at the compressor exit okay. You can see that net work input is much higher compared to the system without regenerative heat exchanger. As a result the COP of the system with regenerative heat exchanger is less compared to the system without regenerative heat exchanger. So basically you have to make a trade of between the mass flow rate volumetric flow rate and COP okay and justify the use of regenerative heat exchanger right. So this is the way to solve the typical problems in refrigeration and air conditioning okay. So based on this problem i will give you an home work problem you work out work it out.

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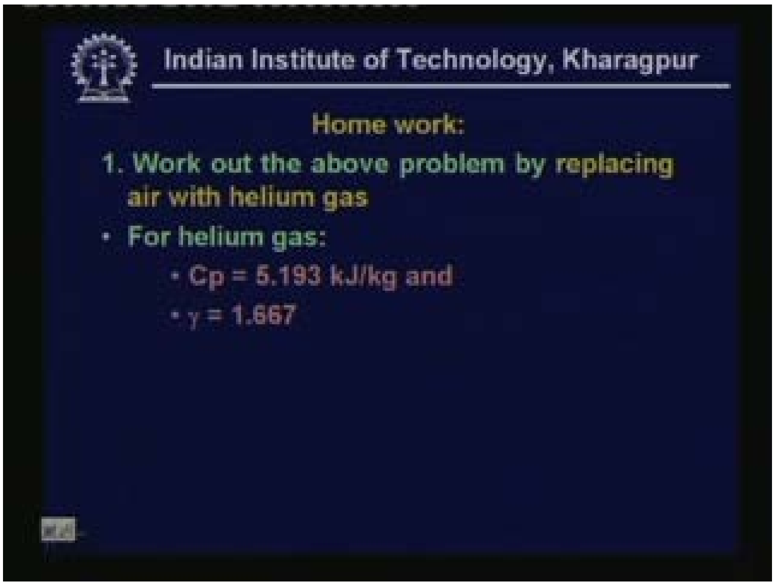

Okay, the home work problem is like this you work out the above problem just by replacing air with helium gas okay. So rest of the data remains same all that you have to do is you have to replace the working fluid with helium gas okay. And for helium gas the properties are like this the specific heat Cp is given as one point one nine three kilo joule per kg Kelvin and specific heat ratio is one point six six seven. Okay, I will give you the answers in the next class for this problem.

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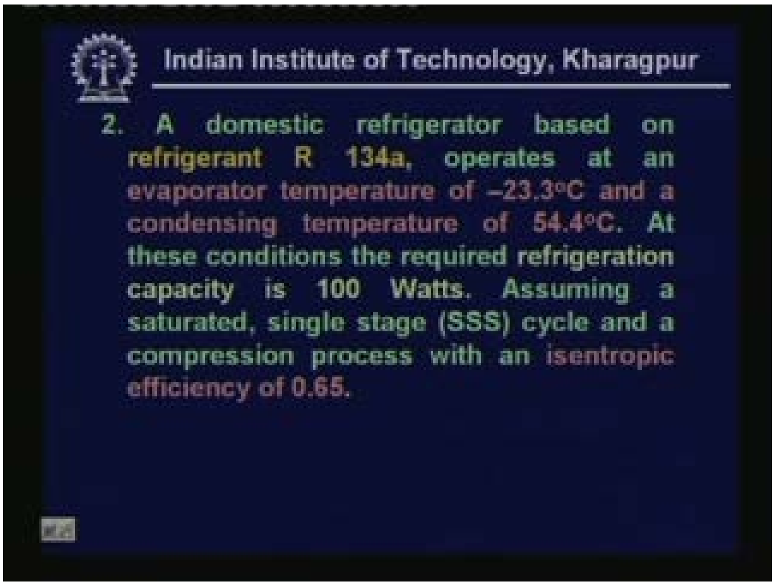

So the second problem is like this is a vapour compression refrigeration system problem on vapour compression refrigeration system problem statement is like this a domestic refrigerator based on refrigerant R one thirty-four a operates at an evaporator temperature of minus twenty-three point three degree centigrade and a condensing temperature of fifty-four point four degree centigrade. At these conditions the required refrigeration capacity is hundred watts assuming a saturated single stage cycle. And a compression processes with an isentropic efficiency of point six five. So this is the, in information given refrigerant is specified temperatures are specified capacity is specified. And the efficiency of the compressor is also given.

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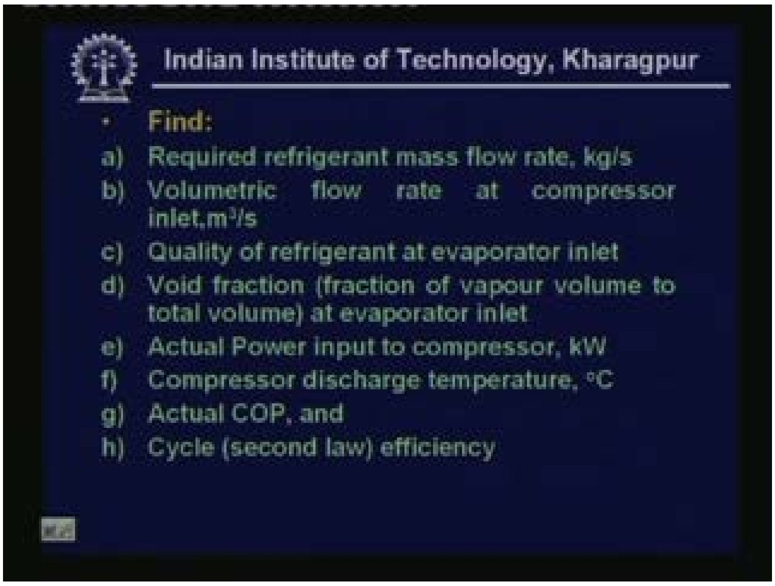

From these information we have to find out a required refrigerant mass flow rate in kg per second volumetric flow rate at compressor inlet in meter cube per second quality of refrigerant at evaporator inlet void fraction at evaporator inlet actual power input to compressor in kilowatts compressor discharge temperature actual COP and finally the cycle or second law efficiency.

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So this is the list the information given information given is like this refrigerant is R on thirty-four a refrigerant capacity is hundred watts or point one kilo watts and evaporator temperature is minus twenty-three point three degree centigrade. And condensing temperature is fifty-four point four degree centigrade and the isentropic efficiency of the compressor is point six five. And it is mentioned that it is a standard single stage saturated cycle okay.

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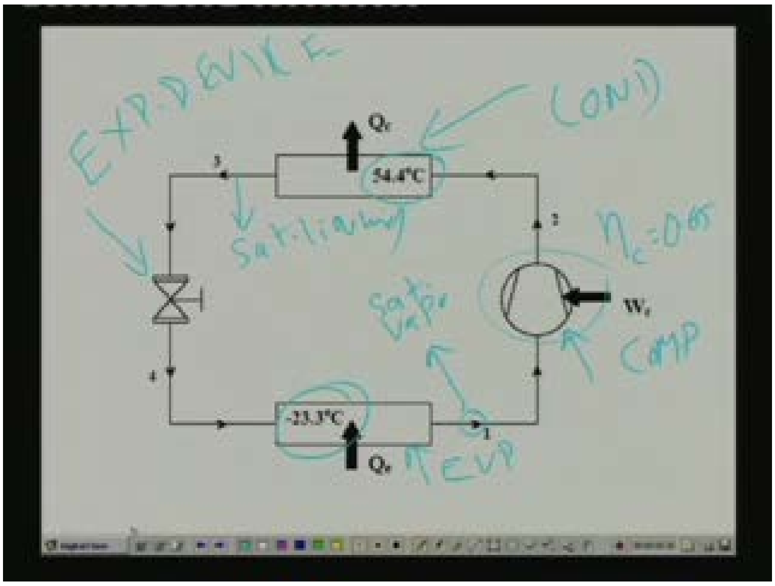

That means you have the four basic components inside the standard cycle. You have the evaporator compressor. This is the condenser and this as you know is expansion device and this temperature is specified evaporator temperature minus twenty-three point three degree centigrade. And this temperature condensing temperature is specified fifty-four point four degree centigrade and it says saturated cycle. So the exit condition this is saturated vapour and this condition that is at the exit of the condenser is saturated liquid okay. So this is the information given and this compression is not ideal. So you have an efficiency for the compressor which is given by point six five okay.

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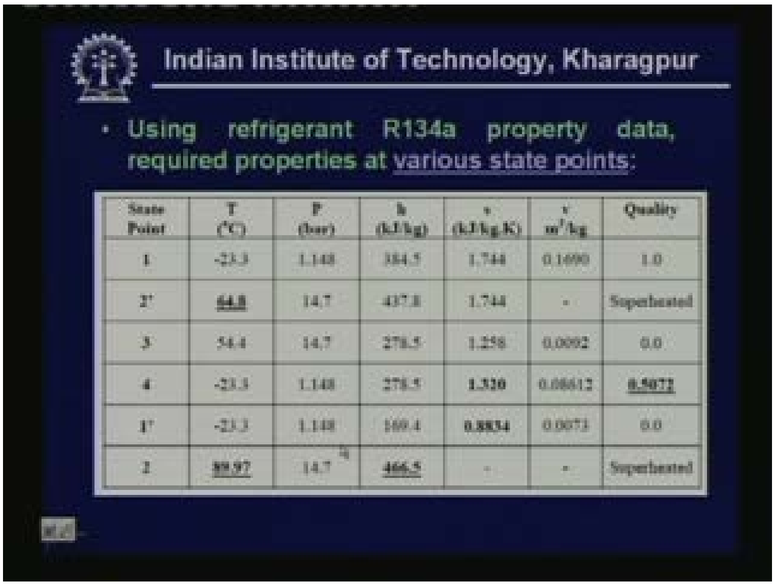

So now using refrigerant property data let us find out the required properties at various state points let me quickly explain how to find out the properties.

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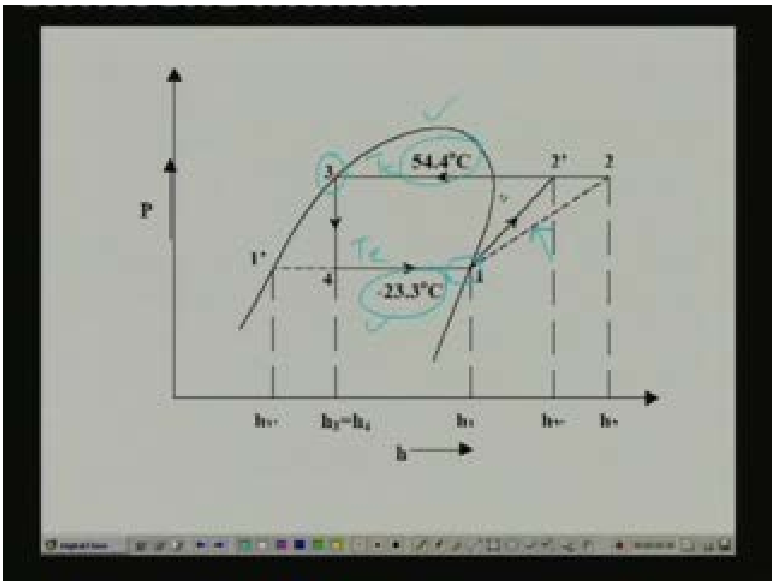

Okay, what is that we know and how do you find the rest of the properties all that we know is we know that the evaporator temperature okay. Te is minus twenty-three point three degree centigrade this is given to us and the condensing temperature Tc is fifty-four point four degrees this is also given to us. And we also know that the exit of the evaporator that is point one is saturated vapour and exit of the condenser point three is saturated liquid. So this the information given to us and it is also mentioned that the isentropic efficiency of the compressor is point six five okay, what do you mean by isentropic efficiency of the compressor point six five. That means the actual compressor process one to two is a non isentropic whereas one to two dash is isentropic and from the definition of isentropic efficiency of the compressor.

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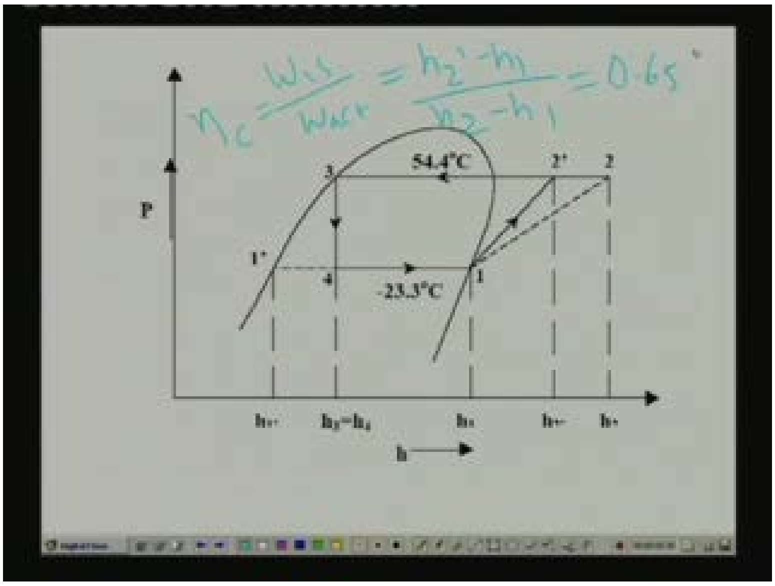

You can write the isentropic efficiency as isentropic work input divided by the actual work input. So from energy balance this is nothing but h two dash minus h one divided by h two minus h one this is given to be point six five okay. So this is the information that we have right.

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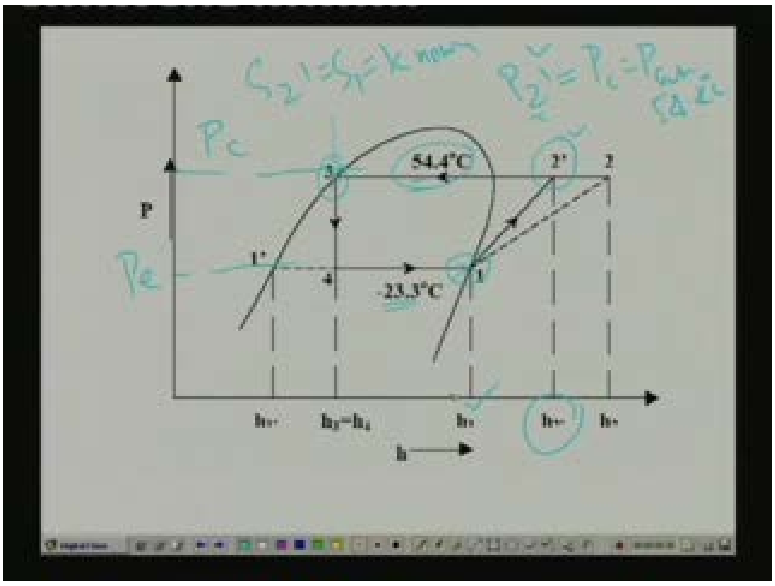

So from this information how do you find the state properties vary enthalpies temperatures at various points. So let us begin with the saturation line that means point one and point three okay. This point is already fixed because we know the temperatures and we also mentioned that this is saturated condition. So on the saturated line uh specifying any one parameter is enough okay. So once you say that it is saturated vapour and temperature is specified we can immediately locate the point and find out what is the enthalpy h one and what is the specific volume what is the entropy and all the properties can be obtained at this point okay. Similarly all the properties at point three can be obtained just from this temperature and the quality because it is a saturated liquid okay.

So this properties also can be obtained directly from the refrigerant database or if you have a P-h chart you can directly locate these points okay. And from the P-h chart you can find out what is the condensing temperature and what is the evaporation temperature. Once you know the condensing and evaporating temperatures okay. So we know the pressures and we know the properties at point one and three. Now how do you find property at point two dash point two dash lies in the super heated region?
So if you want to find the properties you have to specify two independent properties okay. So what are the properties? We know the pressure at this point okay. We know P two dash okay. P two dash is nothing but condenser pressure which is the pressure at saturated pressure at fifty-four point four degree centigrade this is known to us okay. So at this point we know the pressure. What else we know? We know that process one to two dash is isentropic process. That means the entropy at point two dash is same as entropy at point one dash. That means we also know the entropy at this point because we know the entropy at point one. That means S two dash is equal to S one this is known okay. So at point two dash we know two independent properties that is pressure and entropy. So we can find out from these two independent properties rest of the properties such as temperature enthalpies and all that okay. So that is how you can find the properties of point two dash once you find the properties of point two dash.

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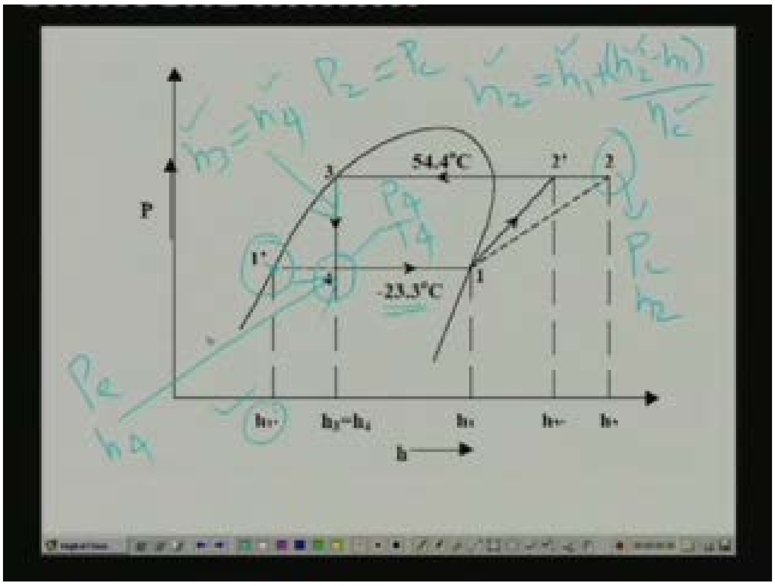

Properties at two can be obtained because at point two we know that P two is equal to Pc which is known to us and h two is the enthalpy at this point enthalpy at this point is nothing but from the expression of uh isentropic efficiency. It is an inlet enthalpy plus h two dash minus h one divided by isentropic efficiency of the compressor okay. So h one is known to us h two dashes is known to us also and this is given as input so we can also find out the enthalpy. So for this point use the pressure data and enthalpy data and find out the rest of the properties okay.

Now coming back to point one dash point one dash is nothing but the saturated liquid at evaporator temperature. So straight away you can locate this point because you know the temperature and you also know the pressure. And you know that it is, in saturated condition okay. That means you have to look at this point on the saturated liquid line. So you can find out enthalpy and all other properties. And finally coming back coming to the point four okay, point four is nothing but the inlet to the evaporator. And what do we know at this point? At this point we know what is the pressure and we also know the temperature. But can you find out from this pressure and temperature. What is the enthalpy and rest of the properties? You cannot because this is the two-phase region. So if you are fixing the pressure temperature is automatically fixed. That means pressure and temperature are not independent properties in the two-phase region okay.

So specifying both is meaningless okay. So you have to or useless, so you have to specify any one and another property what is that other property that property is enthalpy because we know that this process is a throttling process. So for this process h three is equal to h four okay. So h three is known to us that means h four is also known to us. That means at this point we know the pressure Pe and we know the enthalpy h four okay. So from these two properties you can find out the rest of the properties like entropy specific volume and all that okay. So that is how you have to find the properties at various points. So it is always useful to draw the cycle on P-s diagram and list what the points you know and have an idea of the process different processes okay. Then you can straight away read the missing data points okay.

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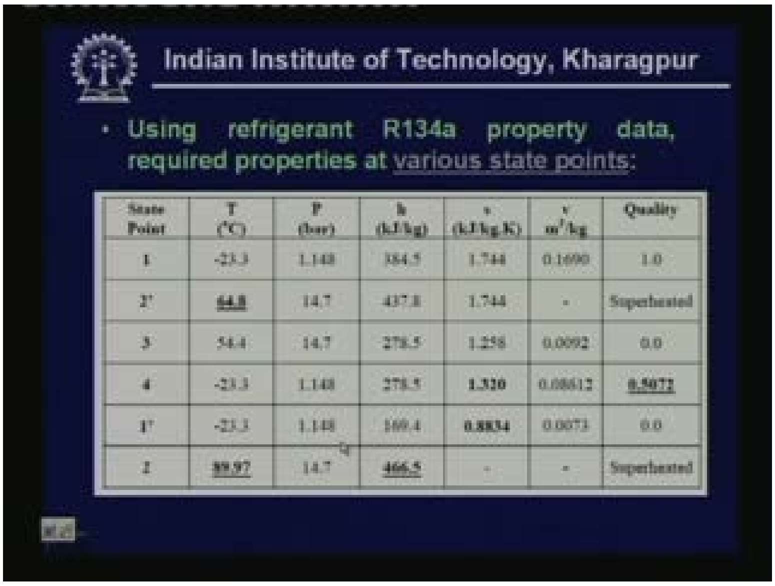

So using this procedure, this is the data obtained for various points state point one which is the outlet of the evaporator or inlet to the compressor temperature is minus twenty-three point three degree centigrade's specified. And pressure is nothing but the saturation pressure at this point is one point one four eight bar and we know that its saturated vapour. So quality is one which is known to us. So if you using this information from the P-h chart or from refrigerant property database. You find that enthalpy is three eighty-four point five entropy is one point seven four four and specific volume is point one six nine okay.

Similarly the data for other points at point two dash which is nothing but the exit of the isentropic compression process. We know the pressure to which is equal to fourteen point seven bar. And we also know the entropy which is same as entropy at point one that is one point seven four four. So from the pressure and entropy data we find the rest of the points that is the temperature and enthalpy okay. Point three is the exit of the compressor and inlet to the expansion device here we know the temperature which is equal to fifty-four point four. So the pressure is fourteen point seven which is the saturated pressure at this temperature and we also know that its saturated liquid.

So quality is known to us that is zero. So from the quality and the temperature find out the rest of the properties like enthalpy and entropy okay. And then comes point four which is the exit of the expansion device or inlet to the evaporator. So at this point as I have already told you we know the temperature and pressure. And we also know the enthalpy because enthalpy at point four is same as the enthalpy at point three okay. So using the pressure and enthalpy data we find the rest of the properties. That is entropy and specific volume and point one dash is the saturated liquid condition at evaporator temperature. So you find out the enthalpy and entropy and specific volume at these conditions and finally find out the actual temperature and enthalpy at the compression process okay at the exit of the compressor for the actual compression using the isentropic efficiency okay.

So this is how all the state points have been obtained. So using this state point data we will find the required performance parameters. One thing I would like to mention here is the enthalpy and entropy values may vary from database to database okay. Because if you remember enthalpy and entropy are generally defined with reference to a particular datum okay. If the datum is different these values can be different term okay, whereas the rest of the properties will be same for all the uh property databases or all types of P-h charts okay. So you need not worry if the enthalpy an entropy values are different from source to source okay. Because in our calculations ultimately we will be requiring the enthalpy difference or entropy difference okay. Since you will be using the differences the reference enthalpy and reference entropy really doesn’t affect the final answer okay.

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So now we know all the points. So we find out the mass flow rate of refrigerant apply the energy balance across the evaporator. From the energy balance we find that mass flow rate is equal to Qe divided by h one minus h four Qe is known to us this is point one kilo watt and h one and h four have been obtained from the refrigerant database okay. So this will give us mass flow rate as nine point four three four into ten to the power of minus four kg per second and volumetric flow rate at compressor inlet is nothing but mass flow rate into specific volume at compressor inlet which is known to us. So you find that volumetric flow rate is one point five nine four into ten to the power of minus four meter cube per second and then quality of refrigerant at evaporator inlet. So what do you mean by quality we have already defined the quality.

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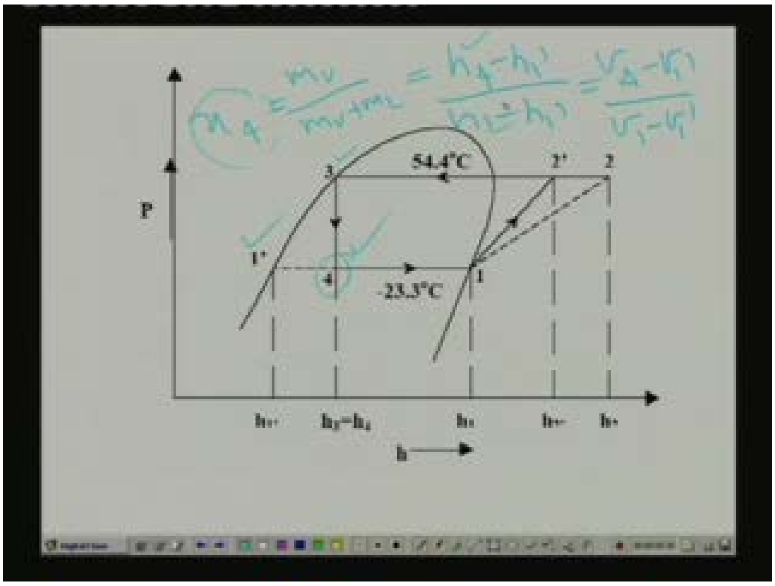

Okay, so quality is at evaporator inlet is at this point. So quality at this point is defined as mass of vapour divided by total mass that is mass of vapour plus mass of liquid okay. You can show that this is equal to h four minus h one dash divided by h one minus h one dash okay. This is also equal to you can write this in terms of, for example specific volume that means V four minus V one dash divided by V one minus V one dash. That means the quality can be expressed in terms of any intensive properties such as enthalpy or specific volume or entropy okay. That is what is required since we know the enthalpy. Let us write this in terms of enthalpies. We know the enthalpy at point four this is known because this is equal to h three and h one dash is known and h one also known okay.

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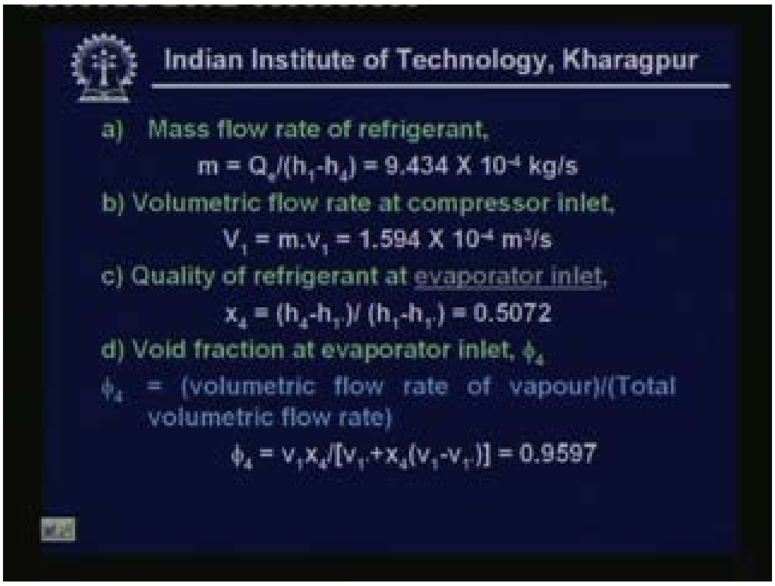

So we use that expression to find the quality. So quality is found to be X four is equal to h four minus h one dash divided by h one minus h one dash which is equal to point five zero seven two okay. Then void fraction void fraction is defined as the volumetric flow rate of vapour divided by the total volumetric flow rate. So the different between quality and void fraction should be clear quality is in terms of mass flow rates and void fraction is in terms of volumetric flow rates okay. So the volumetric flow rate can be expressed by multiplying the mass flow rates into specific volumes. So if you do that you find that the expression for void fraction is given like this phi four is equal to V one into X four divided by V one dash plus X four V one into V one dash and we know all these specific volume from properties. So you find that volumetric flow rate is point nine five nine seven. That means more than ninety five percent of the volume is occupied by the vapour.

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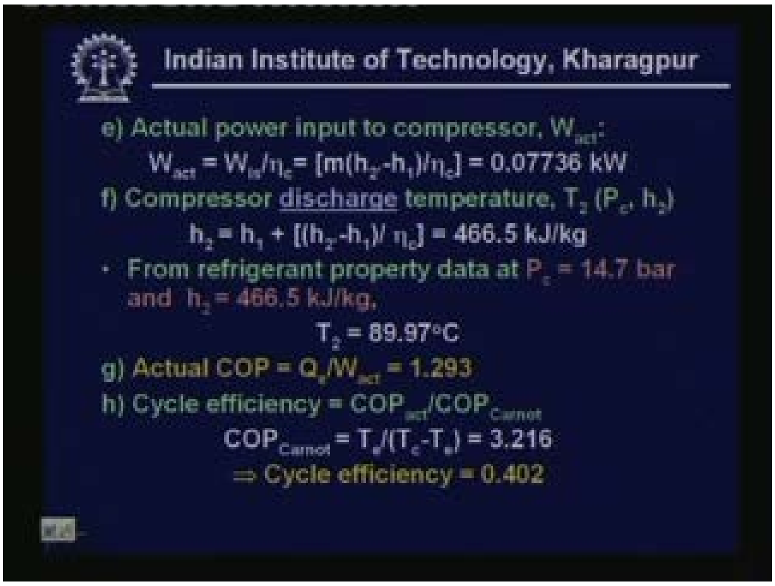

And actual power input to the compressor, as I have already explained is nothing but isentropic work input divided by the isentropic efficiency. We know the isentropic work input which is equal to mass flow rate into enthalpy difference for the isentropic process divided by the isentropic efficiency point six five. So if you substitute these values you find that the actual power input is point zero seven seven three six kilo watt or seventy-seven point three six watts okay. Compressor discharge temperature can be obtained because we know that at the compressor discharge the pressure and enthalpies are known to us. So using the pressure and enthalpy data we can find out the compression discharge temperature and this is found to be eighty-nine point nine seven degree centigrade okay.

So finally we have to find out actual COP actual COP is defined as Qe by W actual Qe is hundred watts and W actual is seventy-seven point three six watts. So you find out the actual COP is one point two nine three and the cycle efficiency is COP actual divided by COP Carnot. And COP Carnot is as you know is nothing but evaporator temperature divided by condenser temperature minus evaporator temperature. And all the temperature should be expressed in absolute scale that means in degrees Kelvin. So if you are writing this in degrees Kelvin you find that COP Carnot is three point two one six okay. So from this you find that the cycle efficiency is point four zero two okay. So this is the very simple problem and the whole idea of working out this problem is to show how properties various state points can be obtained and how the required performance parameters can be obtained by applying a proper energy balance equations okay.

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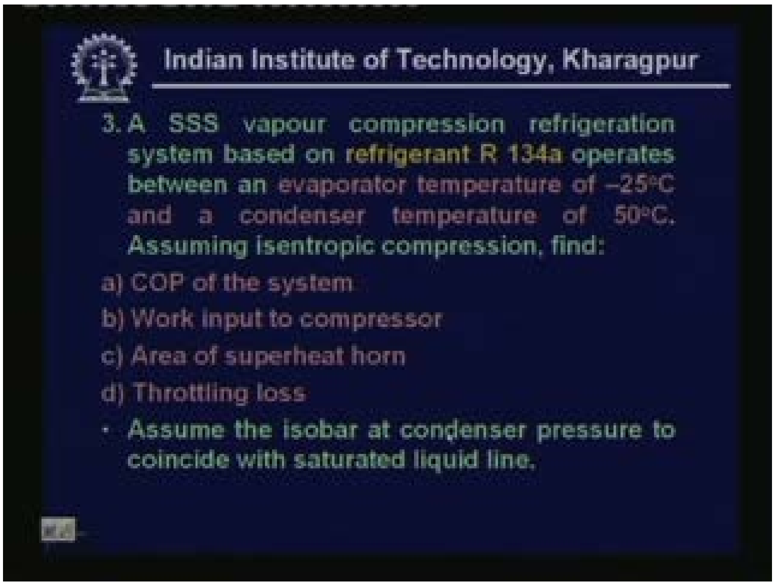

So let me explain the third problem the third problem is another simple problem. This is a saturated single state cycle and SSS vapour compression refrigeration system based on refrigerant R one thirty-four operates between an evaporator temperature of minus twenty-five degree centigrade and a condenser temperature of fifty degree centigrade. So evaporator condenser temperatures are specified and assuming isentropic compression we have to find COP of the system, find work input to compressor, find area of superheat horn and finally find the throttling losses okay. And assume that the isobar at condenser pressure to coincide with saturated liquid line. So this is the information given to us.

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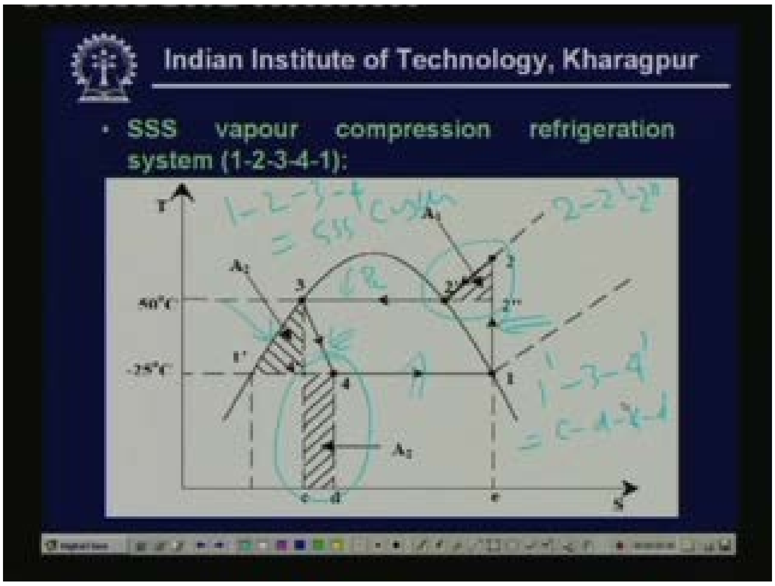

Okay, this is the standard vapour compression refrigeration system. Here it is convenient to represent this on T-s diagram. So you can see that on T-s diagram cycle one two three four is your SSS cycle okay. So one to two is your compression process two to three is heat rejection in the condenser three to four is throttling process and four to one is isobaric isothermal heat extraction okay. And if you remember from our earlier discussions the heat lost due to superheat horn is given by this okay. That means area two two dash two double dash this is the loss due to superheat horn and loss due to throttling is given by this area okay. And if you are assuming that this saturated liquid line coincides with the isobar at this that means it coincides with the isobar at Pc. Then this is also equal to throttling area okay. That means throttling area is either one dash three four dash which is equal to area C D four four dash okay. So we have to find out these two areas.

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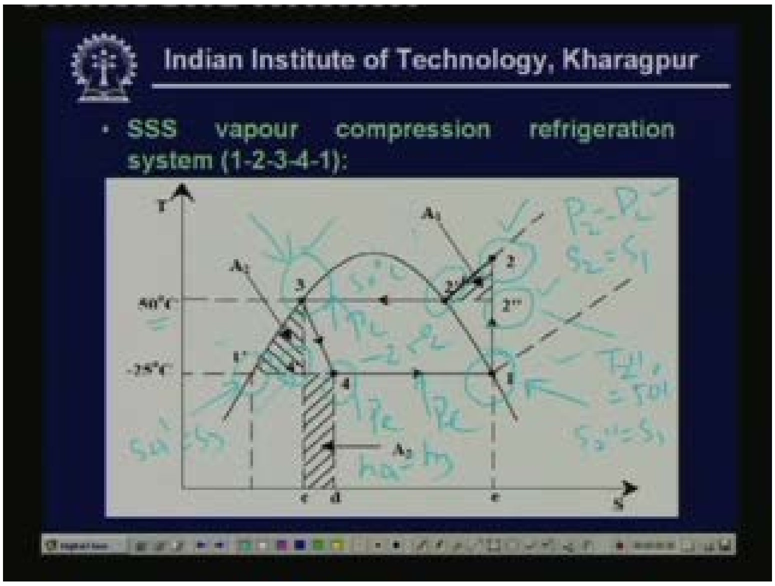

Before finding that we have to find out the state points at various location that means one two dash two etcetera. And we know this temperature to be minus twenty-five degree centigrade and this is to be fifty degree centigrade. So we can find out this evaporator pressure and condenser pressure Pc because they are the saturation pressures at these temperatures and we know that this is saturated cycle. So we can find out the data at point one which is the outlet of the evaporator and inlet to the compressor which is in saturated vapour state at evaporator temperature. Similarly you can find out the properties at point three which at the exit of the condenser which is in saturated liquid region.

So these two points we can easily obtain and point two at this point we know the pressure okay, pressure is equal to condenser pressure. So we can find out this and we also know that this is an isentropic process. So S two is equal to S one okay. So you can you know completely about point two. So you can find out rest of the properties and point two double dash point two double dash you can see that this has the temperature same as the condensing temperature. That means T two double dash is equal to fifty degree centigrade that is known and we also know that S two double dash is equal to S one. So we know again two properties. So we can find out rest of the properties and point two dash point two dash is nothing but saturated vapour at fifty degree centigrade. So you can easily find out the properties other properties and point one dash is the saturated liquid at minus twenty-five degree centigrade. So this point is uniquely fixed. So you can find out all other properties and point four at point four you know the pressure Pe and also you that it is an isenthalpic process.

So the enthalpy at point four is same as at point three. That means h four is equal to h three which is known. So you again know everything about point four. So you can find out rest of the properties point four dash as you can see from the drawing has same entropy as that of point three that means S four dash is equal to S three okay. So the, which is known to us and we also know the pressure at this point okay. That means from the given information you can find out the property data at all these points okay. So now let me show this property data.

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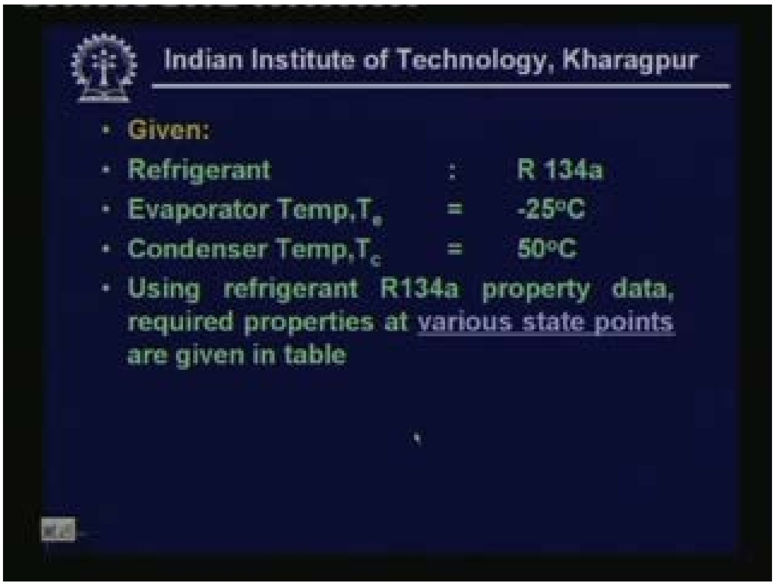

Before tha, this is the summary of the information given refrigerant is one thirty-four a evaporator temperature is minus twenty-five degree centigrade and condensing temperature is fifty degree centigrade okay.

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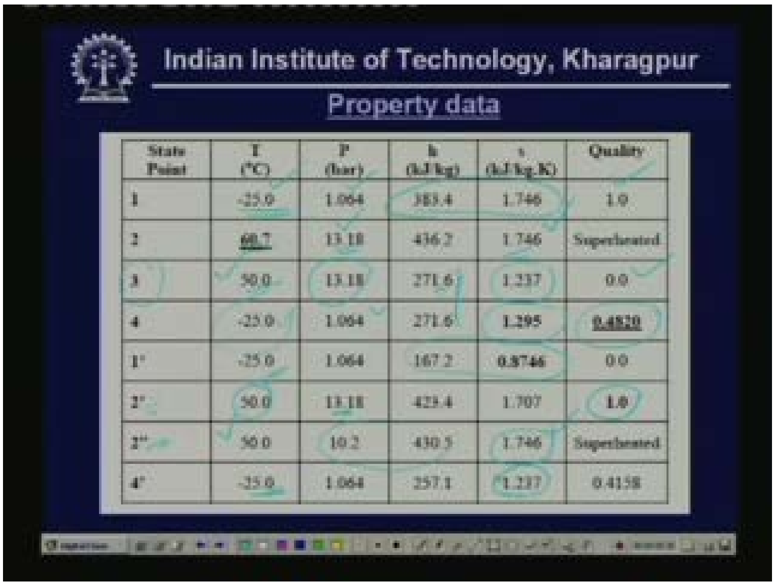

State Point	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kg.K)	Quality
1	-25.0	1.064	383.4	1.746	1.0
2	60.7	13.18	436.2	1.746	Superheated
3	50.0	13.18	271.6	1.237	0.0
4	-25.0	1.064	271.6	1.295	0.4820
1'	-25.0	1.064	167.2	0.8746	0.0
2'	50.0	13.18	423.4	1.707	1.0
2''	50.0	10.2	430.5	1.746	Superheated
4'	-25.0	1.064	257.1	1.237	0.4158

And the property, as I have already explained is like this is the exit of the evaporator or inlet to the compressor we know this temperature and quality. So we can find out the pressure saturation pressure and then we can find out the enthalpy and entropy from the P- H chart or from T-s chart or from any other data base. Next point two point two is isentropic compression. We know the pressure which is corresponding to fifty degree centigrade saturated pressure corresponding to fifty degree centigrade and we also know that it is a isentropic process. So the entropy is same so these two are known to us. So find the rest of the properties. Similarly point three point three is the exit of the condenser we know the temperature and we know the quality.

So find the pressure find the enthalpy and find the entropy point four okay it is the exit of the isenthalpic process. So we the enthalpies are same at point three and point four which is known to us and we know that the temperature is minus twenty-five which is same as evaporator pressure is also known to us. So from this we can find out what is the entropy okay. And you can also find out the exit quality from these enthalpies and point one dash is saturated liquid at evaporator temperature. So you can find out easily enthalpy and entropy point two dash is the saturated vapour at fifty degree centigrade. You can see that saturated vapour quality is one temperature is fifty degrees pressure is thirteen point one eight. So you can find out the rest of the properties point two dash two double dash. At this point we know the temperature which is equal to fifty degrees and we also know the entropy okay. Because this lies on the constant entropy line so this is known to us this is known to us. So rest of the things we can find out finally point four dash point point four dash. We know that the temperature is minus twenty-five and we know that at this point the entropy same as that of point three okay. So this is same as one point three seven. So we know the two properties. So we can find out the rest of the properties. So that this is how we found the properties at all the points.

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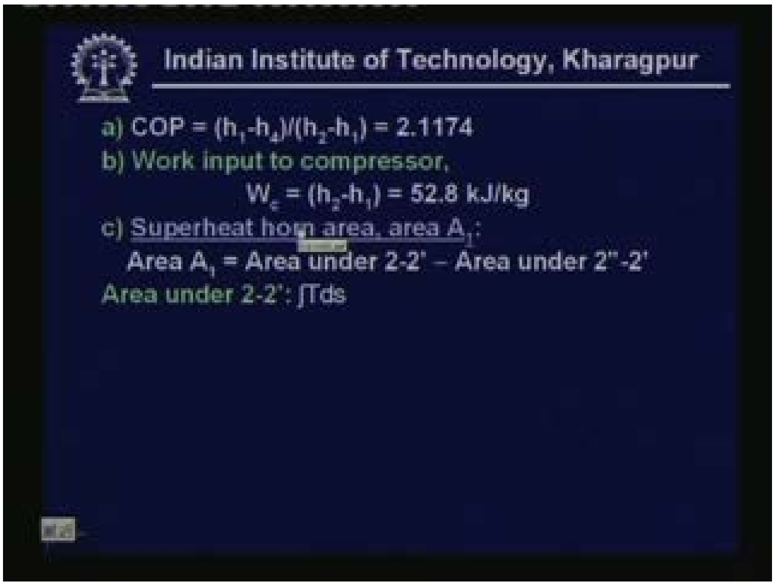

So once you find the properties at all the points you can easily calculate COP. COP is nothing but refrigeration effect h one minus h four divided by specific work of compression. That is h two minus h one which is found to be two point one one seven four. Then work input compressor is nothing but h two minus h one from energy balance across the compressor. So which is found to be fifty-two point eight kilo joule per kg. Then we have to find the superheat horn area okay. Superheat horn area is area A one and it is nothing but area under two two dash minus area under two two double dash to two dash okay. Let me explain this.

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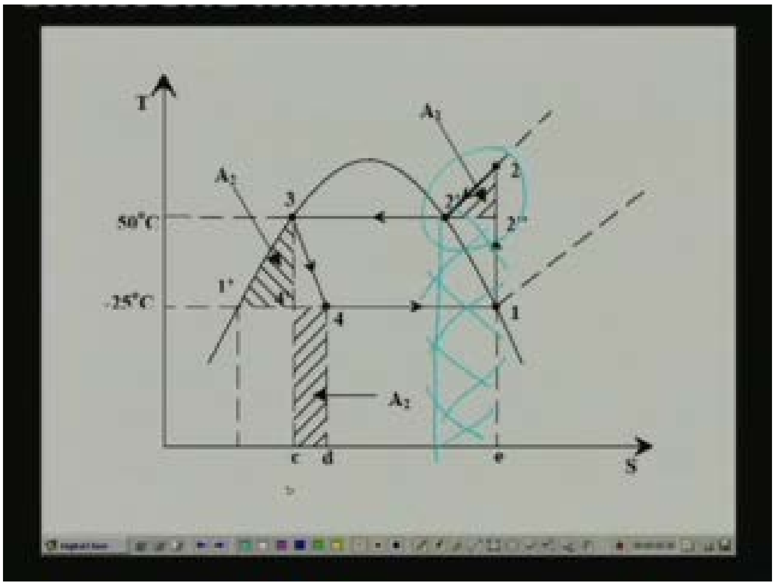

Okay, so this is the superheat horn area the hatched area hatched area is nothing but area under two two dash. That means the complete area this entire area minus area under two double dash to two dash. That means this area okay. So if you can uh find out the area under curve two to two dash and subtract the area under the curve two double dash to two dash you get the superheat horn area okay. And this is an isobaric process that means P two. So I will quickly explain how we can calculate this super heat horn area process two to three is an isobaric process.

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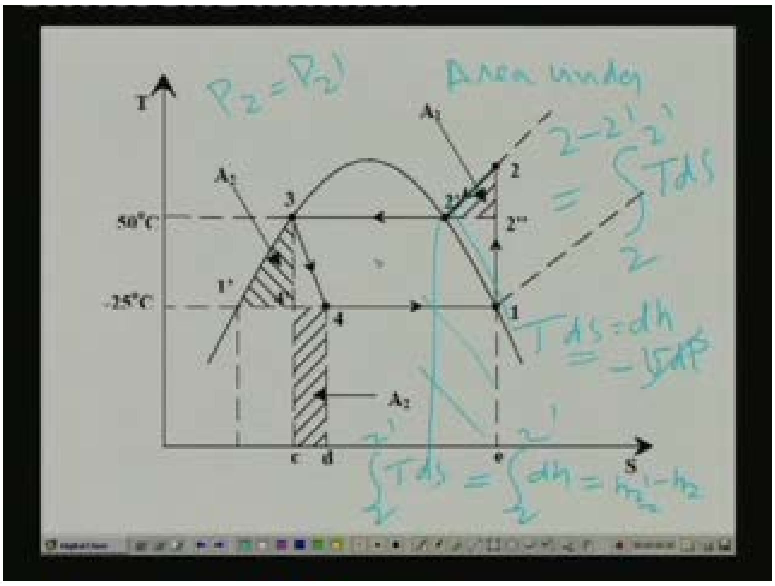

That means P two is equal to P two dash and remember that we know all the entropies and all the state properties are known to us. So area under the curve two two dash okay. Area under two two dash is nothing but integral Tds from two to two dash okay. And from thermo numeric property relations we know that Tds is equal to dh minus Vdp okay. So if you are applying this relation to this particular process two to two dash you find that Vdp is equal to Zero. Because the pressure does not change during this process this is an isobaric process. So finally you find that Tds is equal to dh. That means integral Tds from two to two dash is nothing but integral dh from two to two dash which is simply equal to h two dash minus h two okay it is as simple as that. So if since we know the enthalpies we can easily find out and this remember is nothing but the entire area okay.

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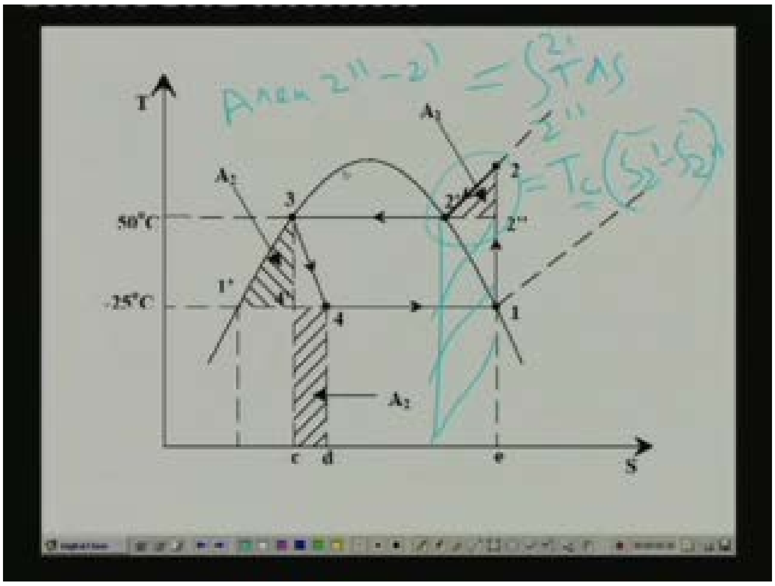

Under the curve and what is the area under curve two double dash to two dash area under two double dash to two dash is nothing but this rectangular area okay. So which is equal to again integral Tds from two double dash to two dash and this is an isothermal process. So temperature remains constant. So these simply equal to Tc into S two dash minus S two double dash okay. And we know the entropies at these points and Tc is known to us. So you can also easily find out this area okay. So it is very easy we just find out the area under two two dash and area under this one. And subtract these two areas you will get the super heat horn area okay. Now how do you find the throttling area okay. Throttling area can be obtained in by two ways.

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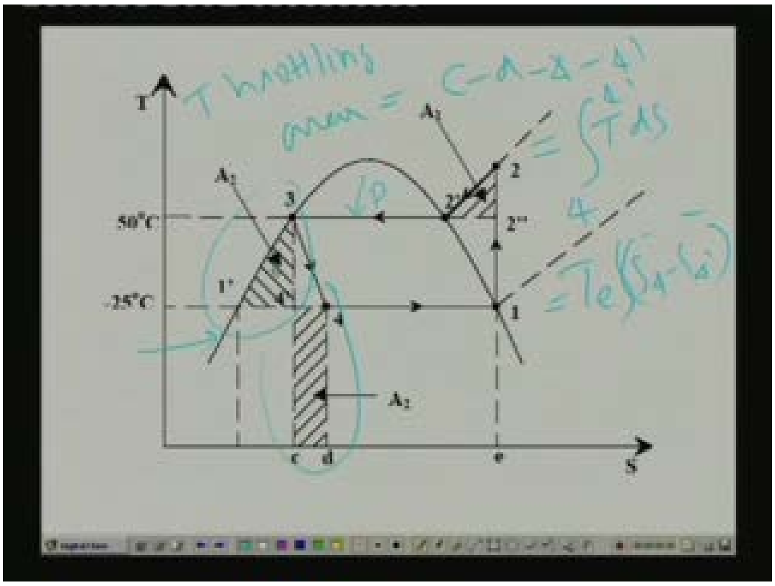

Okay the first way is if you are finding the proper throttling area is this is nothing but okay, throttling area from this expression is nothing but c d four four dash or nothing but the rectangular area. And this is equal to again if you are applying integral Tds temperature remains constant integral Tds from four to four dash. So this is simply equal to Te into S four minus S four dash. Again we know all the entropies you we can easily find out the throttling area using this expression you can also use the find out the throttling area from this side okay. Because if you are assuming this line to coincide with isobar at Pc this also happens to be a throttling area and if this is the throttling area.

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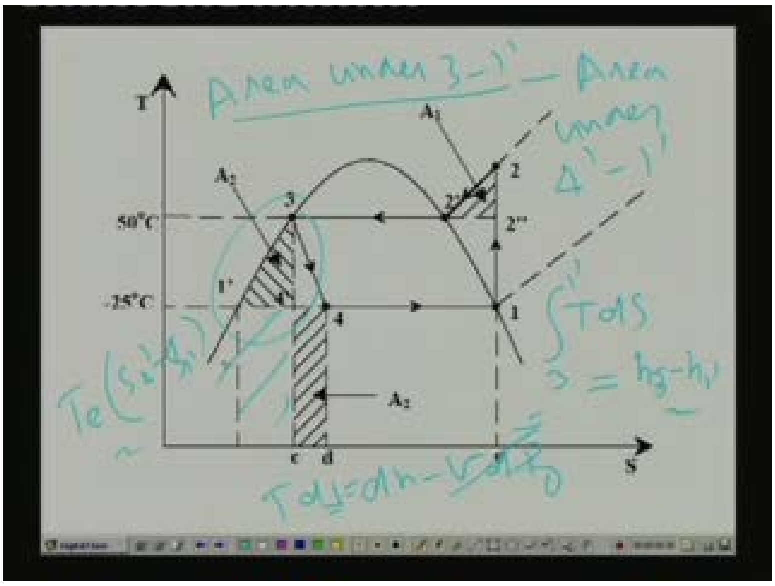

Okay, if you are calculating it from this side this is nothing but area under three to one dash. Area under three to one dash minus area under four area under four dash to one dash four dash to one dash that is this area okay. And area under three to one dash you can see that for this again area under three to one dash is integral Tds from three to one dash which is equal to again you can use the expression dh minus Vdp Tds is Vh minus d. And since we are assuming that this line is an isobaric line Vdp is zero. So this simply becomes Tds becomes equal to dh. So finally this is nothing but h three minus h one dash okay. So we can easily find out and this rectangular area that is area under four dash one dash is nothing but Te into S four dash minus S one dash okay. So that is how once you have the cycle diagram you can easily find out the required areas okay. So that is what is done.

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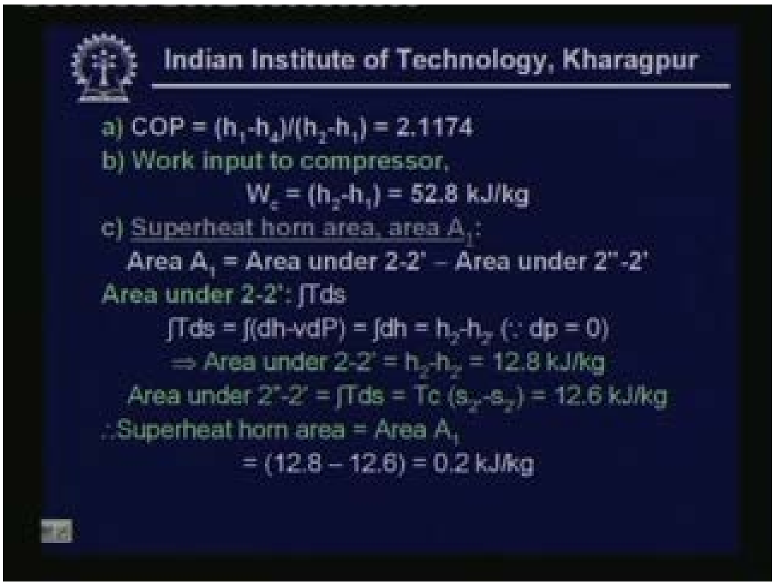

Here, okay, so I have explained this procedure. All this is shown to you and if you are substituting the values you find that area under two two dash is found to be twelve point eight kilo joule per kg. And area under two double dash to two dash is nothing but the rectangular area is found to be twelve point eight kilo joule per kg. So from these two we find that the superheat horn area is equal to twelve point eight minus twelve point six. That is point two kilo joule per kg okay.

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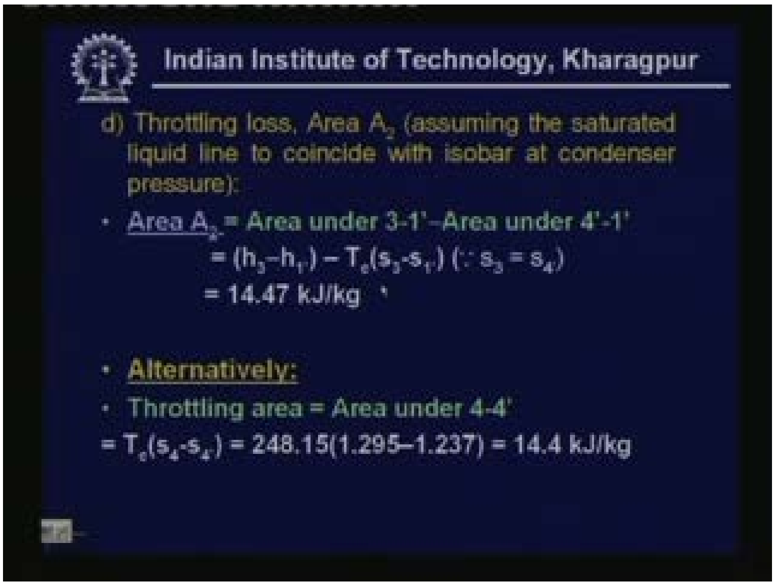

Now let us find out the throttling area. So I, as I have already explained how to find the throttling area if you are assuming that the saturated liquid line is coinciding with the isobar at condenser pressure. Then it is the area under three to one dash minus area under four dash one dash okay. So this is the expression area under three to one dash is nothing but h three minus h one dash. And area under four dash to one dash is nothing but Te into s three minus s one dash because s four dash is equal to s three okay.

So since we know all these values you substitute these values you find that the throttling area is fourteen point four seven kilo joule per kilogram. If you are finding in the actual throttling area without making this assumption then that is given by area under four to four dash which is equal to Te into s four minus s four dash. And this works out to be fourteen point four kilo joule per kilogram you can see that the assumption that the isobar coincides with the saturated liquid line is reasonably good. Because this two values are perfectly matching okay.

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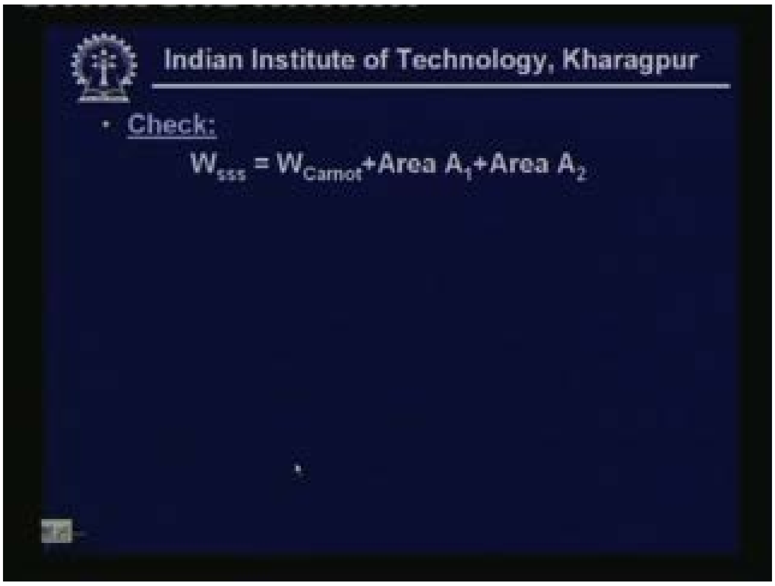

Now you can also check the your results because we know that for the single stage saturated cycle the work input is equal to work input of a Carnot cycle plus area A one plus area A two okay.

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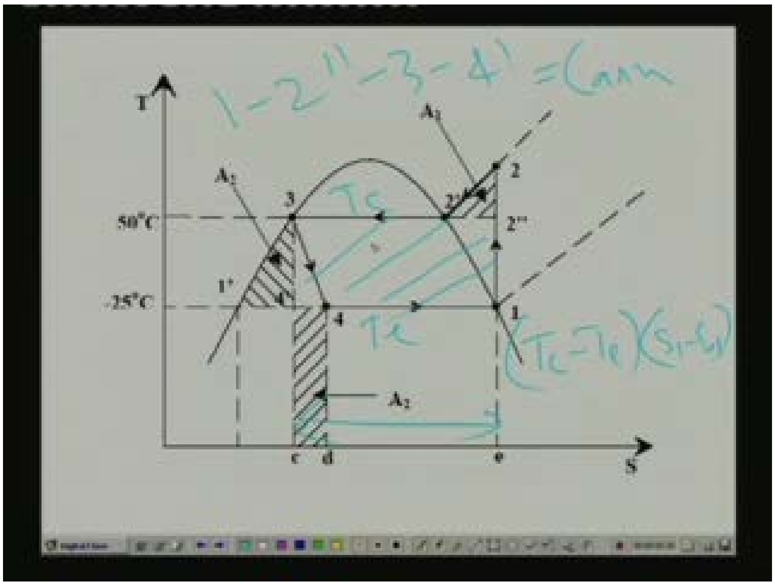

And what is the Carnot cycle Carnot cycle here is an equivalent Carnot cycle is one two dash three four dash. So this is your Carnot cycle. So find out what is the work done during this Carnot cycle work done during this Carnot cycle is nothing but this okay. Which is equal to Tc this is Te this is equal to the rectangular area that is Tc minus Te into this entropy difference okay. That means s one minus s four dash you know all these things. You can easily calculate the work input to the Carnot cycle and work input to the actual cycle is work input to the Carnot cycle plus this area plus this area okay. So you can check your result.

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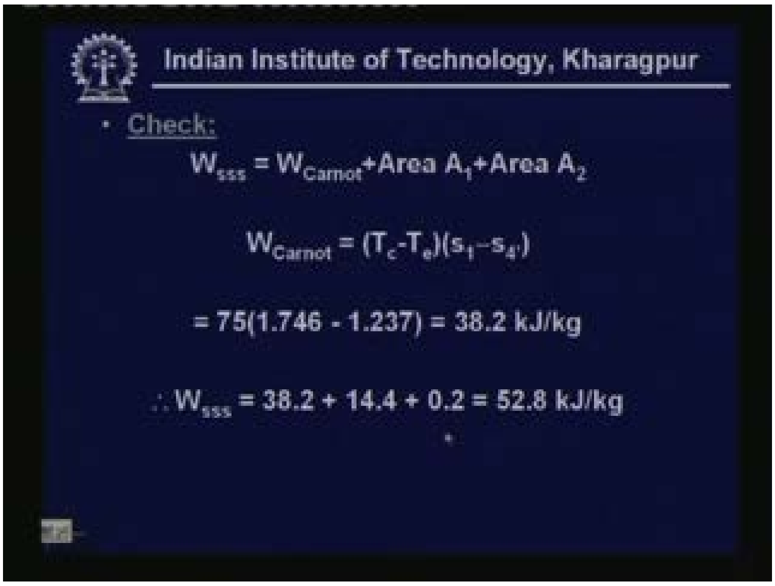

So if you are doing that work input to the Carnot cycle is found to be thirty-eight point two kilo joule per kg. And work input to the standard cycle from this expression is thirty-eight point two plus fourteen point four plus point two which is working out to be fifty-two point eight kilo joule per kg which matches exactly with the data of obtained earlier okay.

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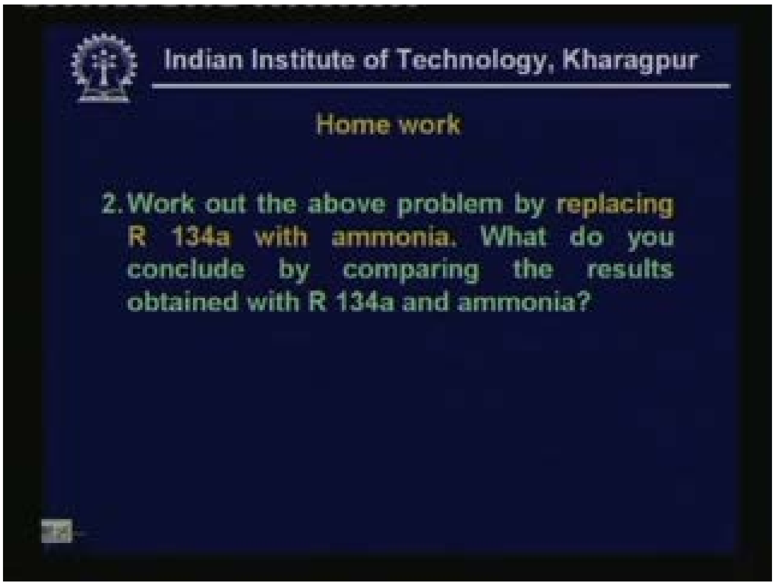

Now you repeat this problem the homework is like this repeat the problem by replacing R one thirty-four a with ammonia and you compare the performance and you conclude by comparing the results obtained with R one thirty-four a and ammonia okay. So there will be some differences because ammonia has a different TS shape okay, vapour dome shape is different on TS plane for ammonia and one thirty-four a okay. So this is the home work right. Now let me quickly give some objective types problems for your homework okay. So objective problems are like this.

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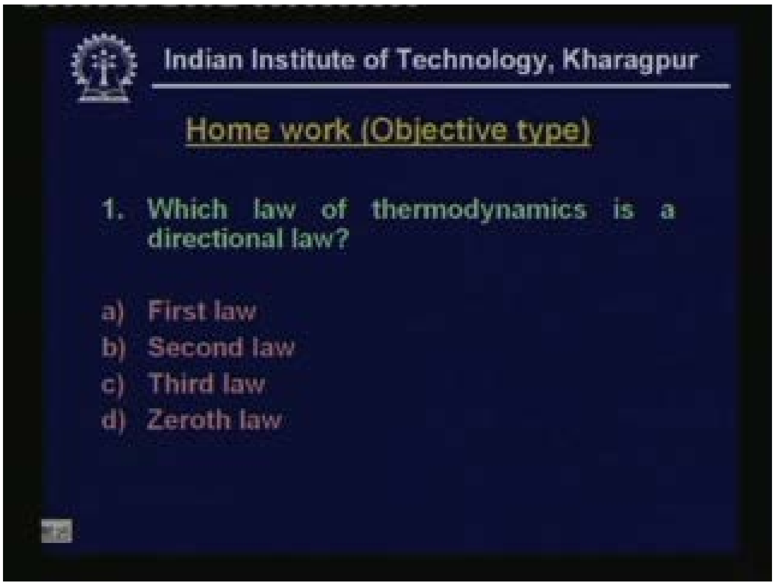

First problem is which law of thermodynamics is a directional law the answers are a is first law b second law c third law four zeroth law okay.

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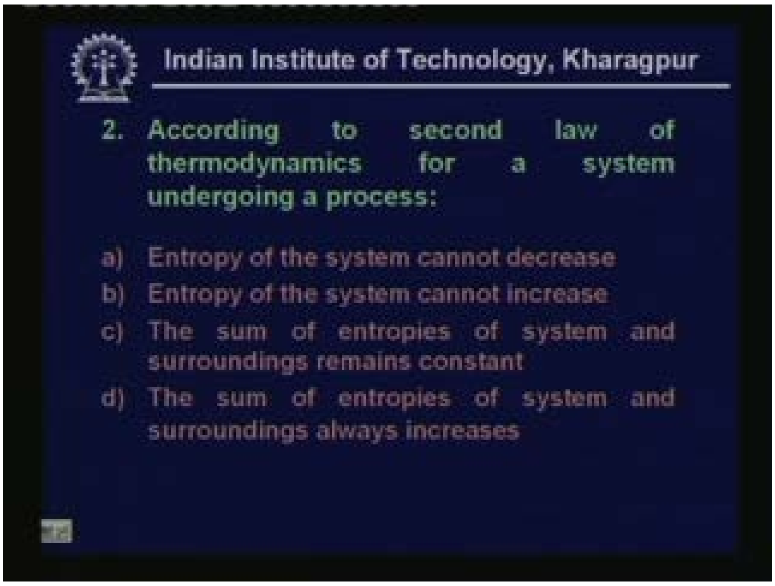

The second question is according to second law of thermodynamics for a system undergoing a process entropy of the system cannot decrease. That is a and b is entropy of the system cannot increase c is the sum of entropies of system and surroundings remains constant and d the sum of entropies of system and surroundings always increases.

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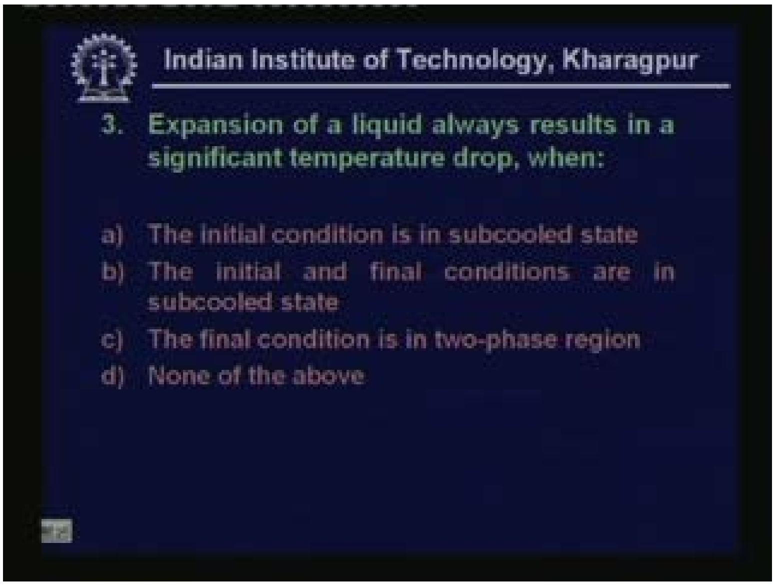

And third question is expansion of liquid always results in a significant temperature drop. When the initial condition is in sub cooled state the initial and final conditions are in sub cooled state the final condition is in two-phase region and none of the above.

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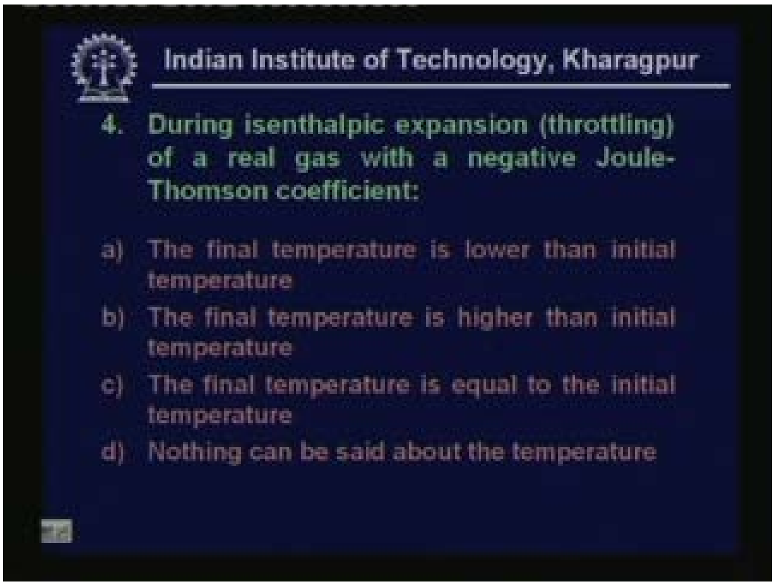

And fourth problem is during isenthalpic expansion of a real gas with negative Joule-Thomson coefficient. The final temperature is lower that initial temperature, the final temperature is higher than initial temperature, the final temperature is equal to the initial temperature and finally nothing can be said about the temperature.

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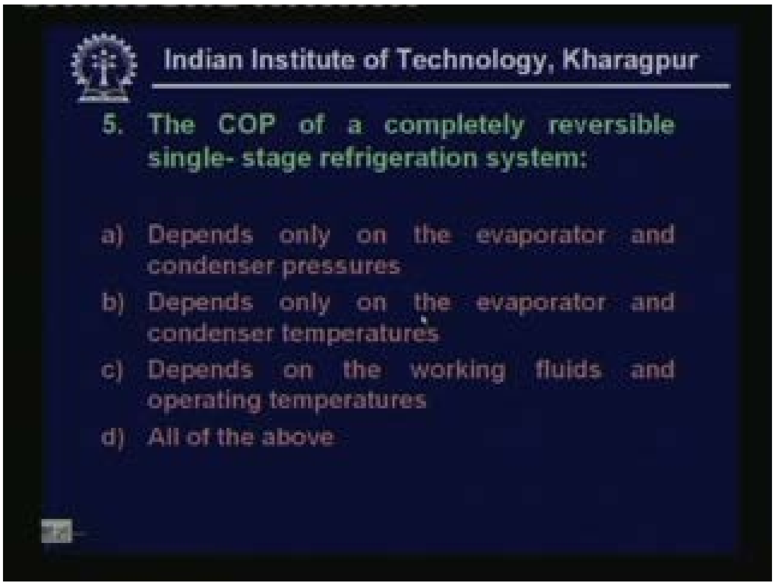

And problem number five the COP of a completely reversible single-stage refrigeration system depends only on the evaporator and condenser pressures depends only on the evaporator and condenser temperatures depends on the working fluids and operating temperatures and all of the above okay. I will give the answers to these problems in the next class and I will also work out one or two problems on vapour absorption systems in the next class.

Thank you.

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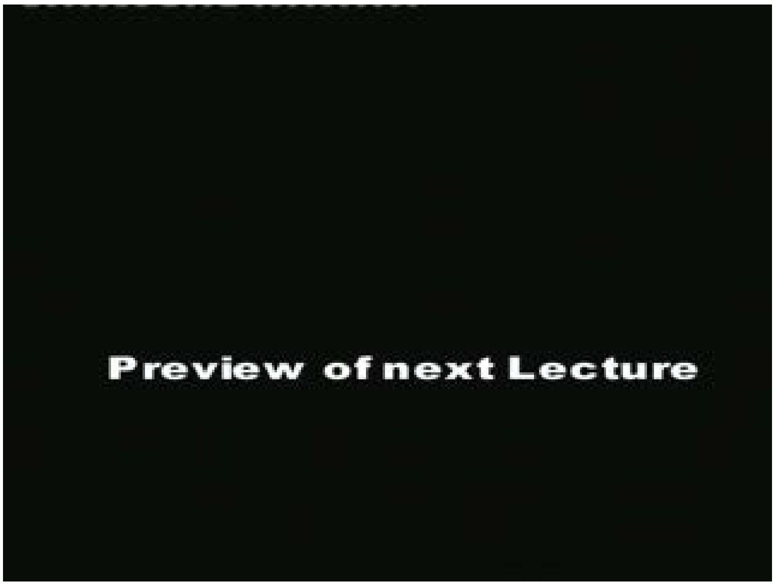

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Welcome back, in this lecture I will work out few more example problems and I will also give answers to the questions given in the last lecture. So the first let us go to the first problem the first problem is like this.

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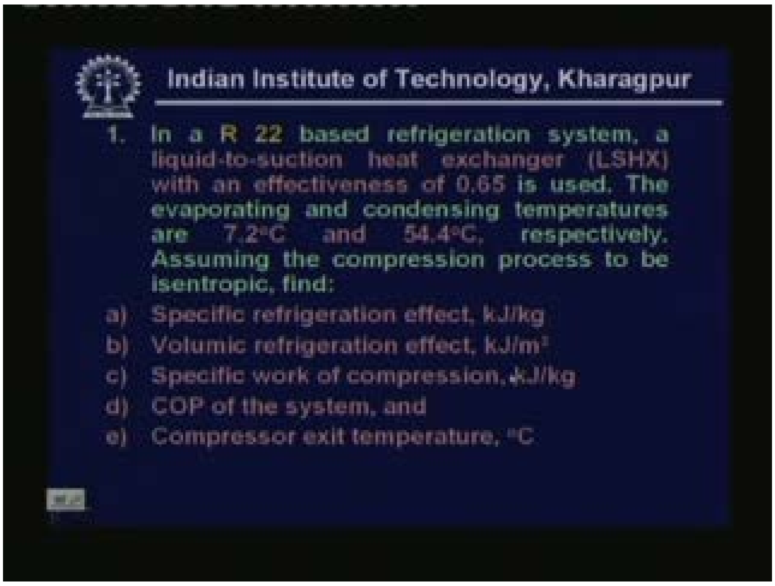

In a R twenty-two based refrigeration system a liquid to suction heat exchanger with an effectiveness of point six five is used the evaporating and condensing temperatures are seven point two degree centigrade and fifty-four point four degree centigrade respectively. Assuming the compression process to be isentropic find specific refrigeration effect volumetric refrigeration effect specific work of compression COP of the system and finally compressor exit temperature.

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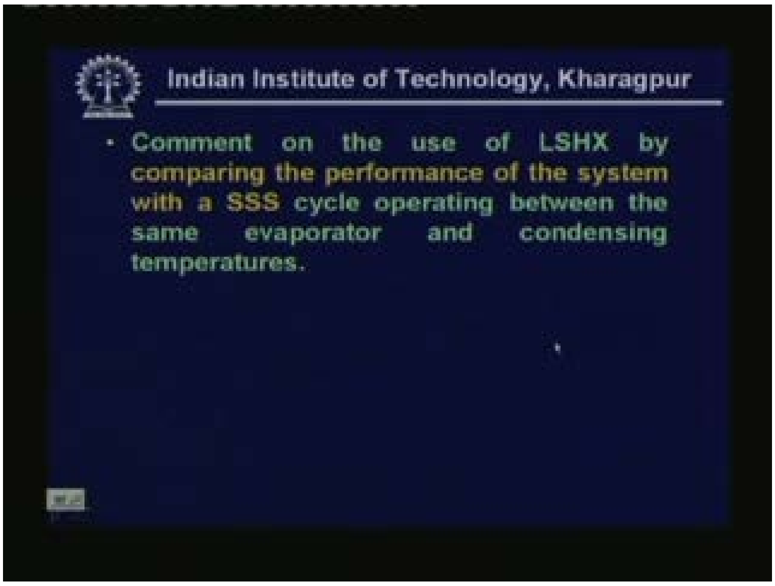

And comment on the use of liquid suction heat exchanger by comparing the performance of the system with a SSS cycle operating between the same evaporator and condensing temperatures. That means basically it is a single stage system. We have to make performance comparison between a system with liquid suction heat exchanger and the system without liquid suction heat exchanger. Both of them are operating between the same evaporator and condensing temperatures.

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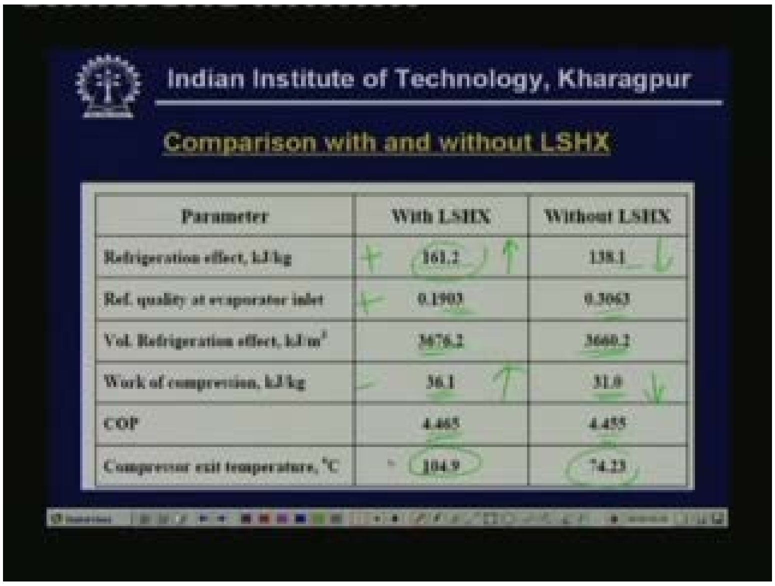

Parameter	With LSHX	Without LSHX
Refrigeration effect, kJ/kg	161.2	138.1
Ref. quality at evaporator inlet	0.1903	0.3063
Vol. Refrigeration effect, kJ/m^3	3676.2	3660.2
Work of compression, kJ/kg	36.1	31.0
COP	4.465	4.455
Compressor exit temperature, °C	104.9	74.23

Now let us see how then work of compression work of compression obviously with liquid suction heat exchanger work of compression has increased. Because the isentropes in super heated region are flatter compared to the isentropes closer to the vapour dome. So this is thirty-six point one this is thirty-one. So this is actually a negative this thing and COP you can see that is almost same okay. It is four point four six five with liquid suction heat exchanger and its four point four five five without liquid suction heat exchanger okay. This is because COP as you know is the ratio of refrigeration effect divided by work of compression. So when you are using liquid suction heat exchanger refrigeration effect is increasing work of compression is also increasing okay. And without liquid suction heat exchanger this is less at the same time work of compression is also less okay. As a result the net different between these two is not much okay. And one however one significant difference between the system with liquid suction heat exchanger and without liquid suction heat exchanger is in the discharge temperature okay.

You can see the with liquid suction heat exchanger discharge temperature is about one naught five degree centigrade whereas without liquid suction heat exchanger it is about seventy-four degree centigrade. That means almost more than thirty degrees increase okay. So this is definitely a negative point as far as the liquid suction heat exchanger is concerned okay. So you have when you are using liquid suction heat exchanger particularly for uh R twenty-two systems there are some benefits there are some disadvantages okay. So ultimately depending upon your requirement one has to decide whether liquid suction heat exchanger is required or not okay.