INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

NPTEL
NPTEL ONLINE CERTIFICATION COURSE

Refrigeration and Air-conditioning

Lecture-12
Compound Compression with Intercooling-1

with
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I welcome you all in the course of refrigeration in air conditioning and today we will discuss on compound compression with intercooling in a refrigeration system, now in a refrigeration system the major part of energy consumption is in the compressor. If I draw on a pressure enthalpy diagram then in a compressor and one so we get refrigerating effect in process four to one at the expense of the energy during process one to two and that is how we calculate the COP how much refrigerating effect we are getting h1 - h4 and how much energy we are spending to get this the refrigerating effect.

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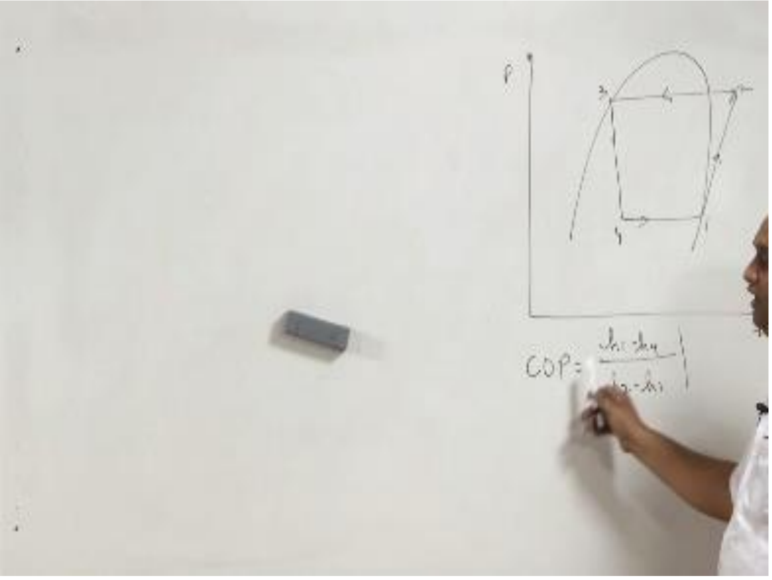

Now if any how if we can reduce the energy consumption during compressor process, if we are able to reduce the energy consumption in this process automatically the value of coefficient of performance will increase. In a reciprocating compressor if I take a simple reciprocating compressor that is 1, 2, 3, 4 the energy consumed is the area of this diagram right, now instead of compressing from state 1to 2 because, what happens when we are compressing from state 1 to 2, the temperature of the refrigerant keeps on increasing.

When the temperature of the refrigerant keeps on increasing, the enthalpy of the refrigerant keeps on increasing right? Now what we can do, if we tap the refrigerant in the middle of this process 1 to 2 and cool it and again compress it so 2, 3 this is 4, 5 and 6, it means we trap the refrigerant in the middle of this process 1 to 2 cool it to initial temperature, so cool it that is known as perfect intercooling.

Perfect intercooling means that if the gas is trapped in the middle of the compression process and then it is cooled up to initial temperature t1, so t5 = t1, t1 so, instead of having two compressors if we is sorry instead of having one compressor if you use two compressor one compressor process to 1 to 4 and another compressor for process 5 to 6, instead of using one compressor is from state 1 to state 2 if you are using two compressors and one heat exchanger, we can save this much of energy.

So multi staging is done normally is done in the very in the refrigeration systems in order to reduce the power consumption in the compressors and they are certain a certain other benefits also and we will discuss those benefits in subsequent lectures. Now starting with the most basic process this is 1 to 2 3 4, now here now the point is at what pressure we should compress? what should be the value of p4? or what should be the value of P 4?

If we take the value of P 4 less in that case we will be consuming more energy here but, so in order to I find the pressure at P4 let us do one a short derivation that what that in process 1 to 4 is in a reciprocating compressor it is going to be equal to n/n-1(P4V4-P1V1) divided by sorry this is okay. So or n/n-1*P1V1{(P4/P1) $^{n/n-1}$ – 1}, is it clear so this is the process 1 to 4, now process 5 to 6 is again we can write n/n-1 index of compression is remaining same P5V5{(P2/P4) $^{n/n-1}$ – 1.

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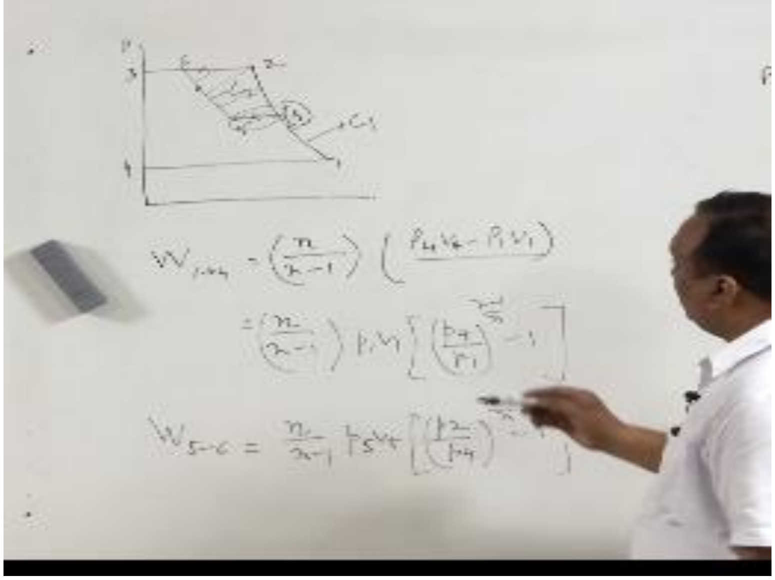

So work done in this process is this work done in this, process is this, now total work done but total work consumed during compression from state 1 to state 6 is $W_{1 \text{ to } 4}$ + $W_{5\text{to } 6}$ = W' or modified work. So now this W' Dash is equal to work in process 1 to 4 that is n/n-1*P1V1{(P4/P1)$^{n/n-1}$ – 1} + n/n-1 *P5V5{(P6/P4)$^{n/n-1}$ – 1, we can take n/n-1 here and since P 1 V 1 = P 5 V5, P 1 V 1 is equal to P 5 V5 because temperature at state 5 is equal to temperature of state 1 right.

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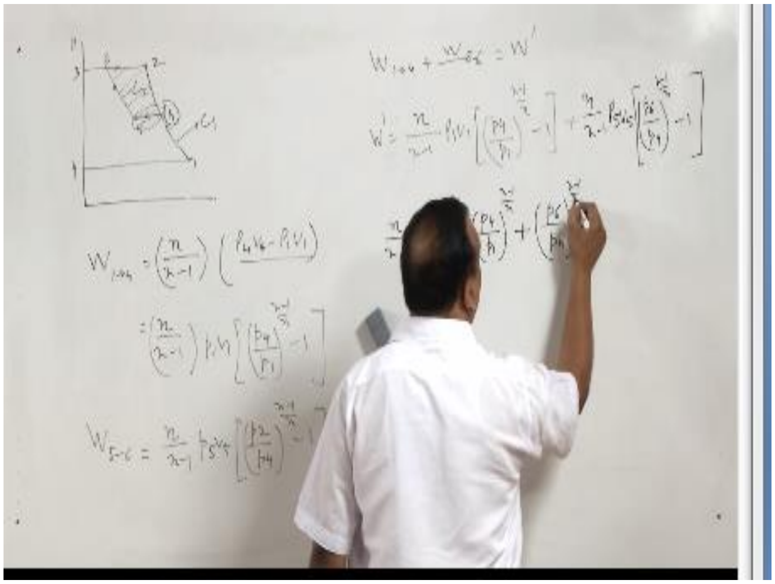

So we can always write P 1 V 1 = P 5 V5 so we will take here common P 1 V1 and inside the bracket will remain P 4/P 1 $^{n/n-1}$ + P 6/P 4 $^{n/n-1}$ -2, now again for W' n/n-1, we shall remain constant throughout the process. So n/n-1 can be taken as a, o n-1/n constant a can be taken as a constant a, and in that case W' is going to be equal to 1/a P1 V1* P4/ P 1^{a} + P 6/p4 or P 2/P 4 we can always write P $2/P4^{a}$ - 2 because P 6 =P2, so here we will replace P6/P 2 so, P 2/P 4.

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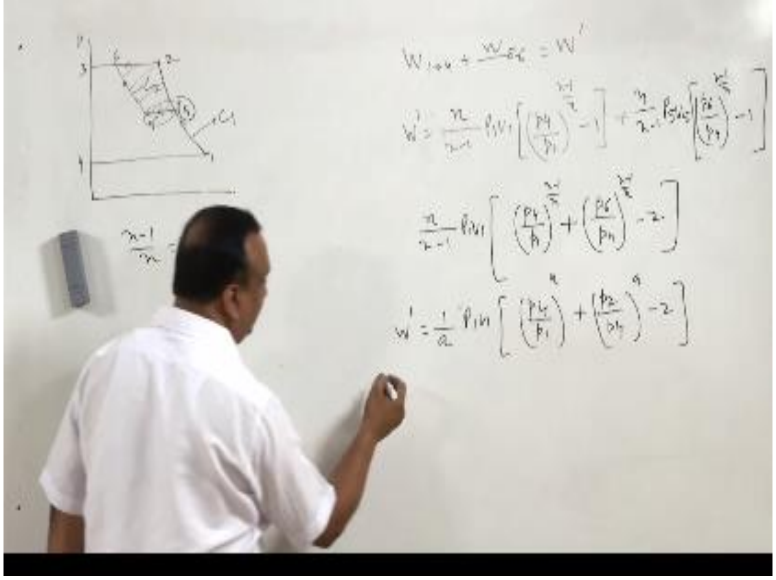

Again we can use same old technique that that is differentiate this dw’ with respect to P 4 and put it equal to 0, then in that case we will be getting is equal to 1/a P 1 V 1 a P 4^{a} -1 P 1^{-a} + P 4^{-a} - 1P 2^{a} and this will be 0. Now here what we have done we have this is constant P1 V 1 and a are constant we have differentiated the work with respect to P 4 so when we are differentiating it with respect to P4 then a X^{a} $X^{a-1,}$ P $4^{a-1 \text{ it}}$ will become P 1^{-a} ,when we'll go up it will become P 1^{-a} then P 4 here is in denominator then -a P 4^{a-1} P2^{a}.

We can further simplify it as a P 4^{a-1} P 1^{-a} - a P 4^{-a-1} P 2^{a} is = 0, because this is 0. If we want to find the value of the optimal value of P 4 now here a will be cancelled out and P 4^{a-1} P 1^{-a} =P 4^{-a-1}P2^{a} ,now this is going to be p$4^{a -1+a+1}$ = P 1^{a}P 2^{a} and this will be cancelled out so P 4^{2a} =P 1^{a}P 2^{a} or we can write P 4 = P 1 P 2 under root because this will give you P 4^{2} =P 1 P 2 from here we will get this and from this we can write, P 4 under root P 1 P 2.

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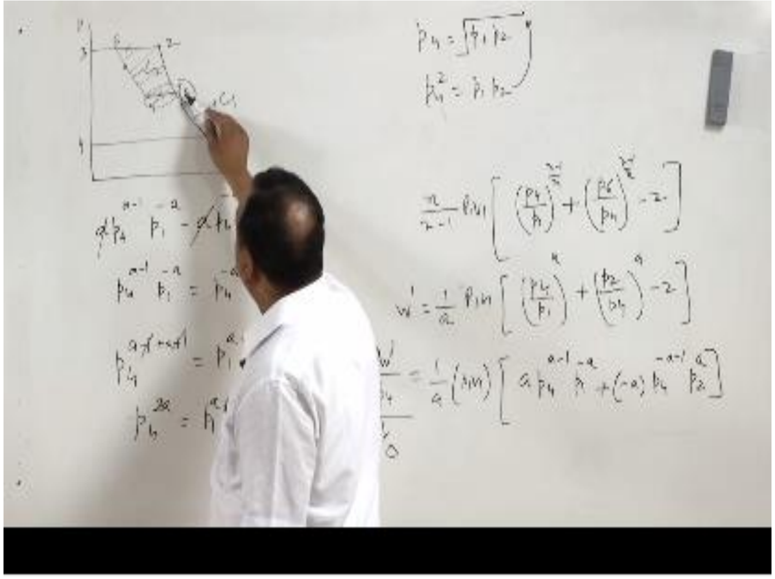

so if it is a two-stage compression the intermediate pressure will be under root of the product of lower pressure and higher pressure and this will give the minimum work input required or this in this case if we take the interpret intermediate pressure as P 4 SP under root P 1 and P 2 in this case the work done zoomed by the compressor will be minimum or work done on the compressor will be minimum, however because this sometimes we may get the odd value in case of suppose we are not taking under root P 1 P 2 but the value is close to P1 under root P 1 P 2 suppose the under root P 1 and P 2 is 5.1 6 so, instead of P 1 is 1.

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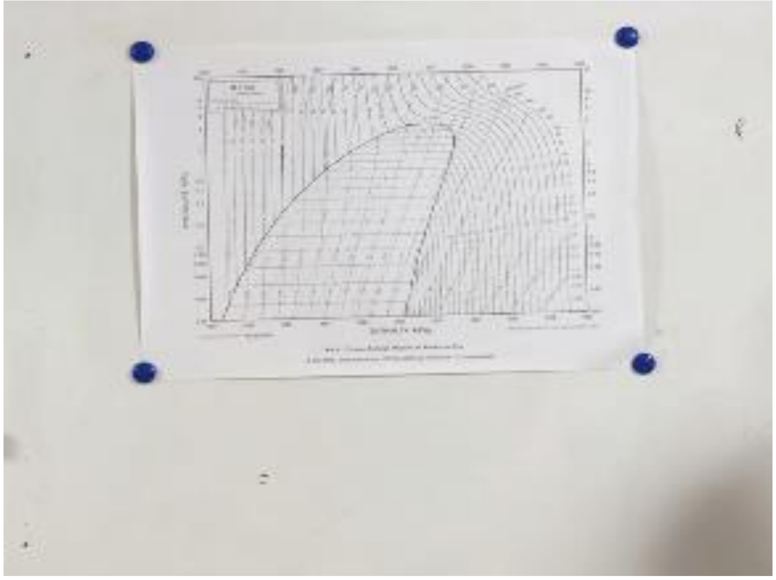

I will give you one example suppose P 1 is 1 and under root P 1 P 2 is 5.1 6 in that case p3 or p4 this intermediate pressure P 4 can be taken as 5. So if we are doing this much of deviation it is not going to affect much, it is not going to have much bearing on the power consumption by the compressor. Now I will take one live example at the application of this multistage compression in the case of refrigerant systems where we have taken 1 2 and suppose intermediate pressure optimum pressure is P 3 = under root P 1 and P 2 and then it is sub cool to 4 and P 4 we say that P 4 = t1.

Now in this case the t 4 = t1 is only in the case when there is perfect intercooling or after compression up to state 3 the initial state is initial temperature is restored in a heat exchanger so the gas after compression will go to the heat exchanger in heat exchanger heat exchange will take place and the initial temperature will is restored, however in the case of refrigerants, first of all this is not valid there is a deviation in this because the refrigerant is not an ideal gas so,ideally a gas equation we cannot apply to the refrigerants.

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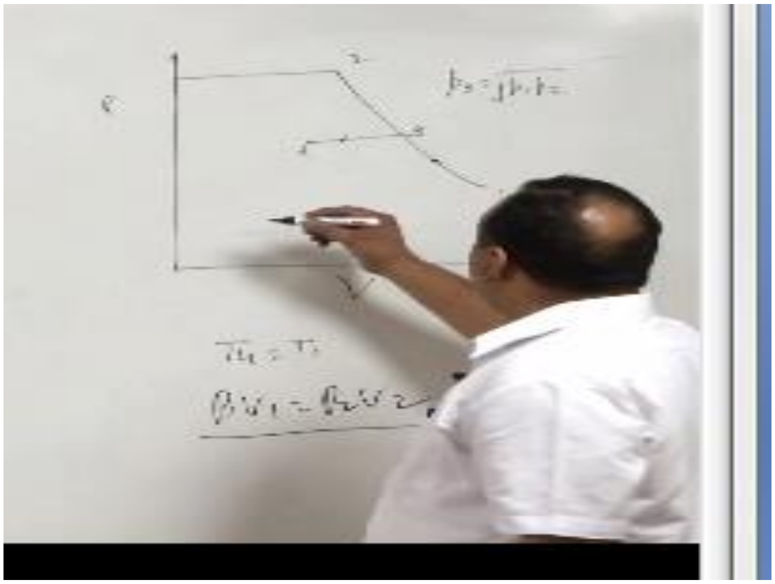

However if we use this concept we will be getting the P 3 very close to the optimum one, because the ideally if you look at that we will not be getting in if we take in the case of refrigerants if we take under root P 1 and P 2 we may not be getting exact value of P 3optimum value of P3 because, we have assumption that there is a perfect intercooling and for perfect intercooling we have used the relationp1 v1 =p2 v2.

But I have stated earlier if there is a slight deviation in the pressure at state 3 the total energy consumed by the compressor is not going to be substantial. So suppose we are getting pressure at 3.7 1 so we can always go for 4, ideally the energy consumed in both the states should be equal. But practically it is difficult to maintain, so if the initial in Inlet pressure is 1' so instead of designing it up to three point seven bar three point eight bar, so one we can design up to four bar so one bar to four bar and four bar to let us say 15 bar or sixteen bar so work consumed by the compressor in both the stages it will be different and we will be using two different compressors for these two processes in multi compression system.

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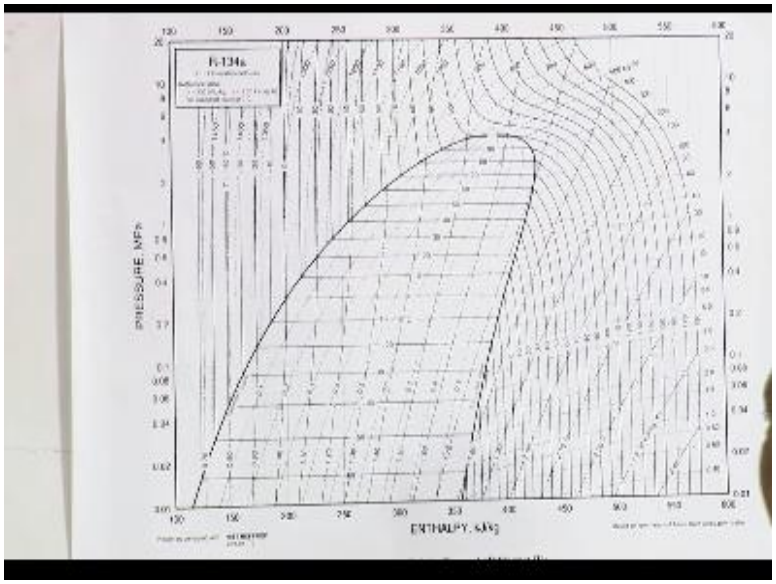

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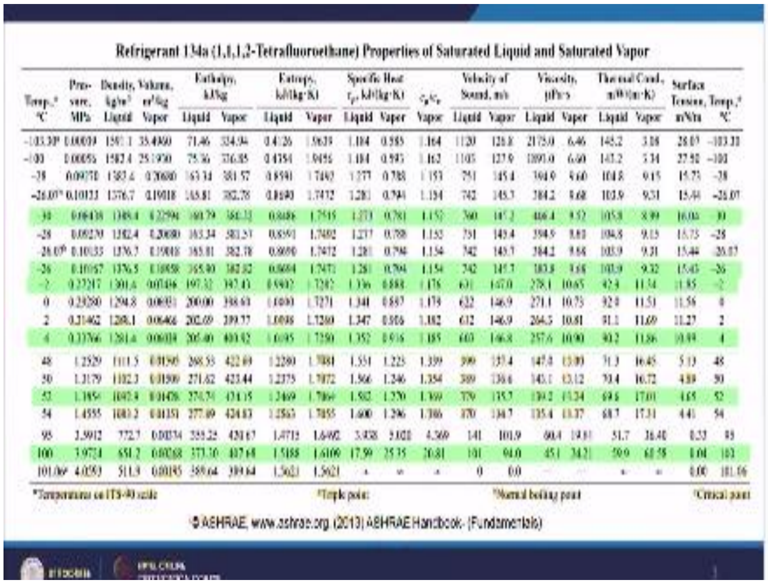

Refrigerant 134a (1,1,1,2-Tetrafluoroethane) Properties of Saturated Liquid and Saturated Vapor

Temp.,ᵃ °C	Pressure, MPa	Density, kg/m³ Liquid	Volume, m³/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	Specific Heat c_p, kJ/(kg·K) Liquid	Specific Heat c_p, kJ/(kg·K) Vapor	c_p/c_v Vapor	Velocity of Sound, m/s Liquid	Velocity of Sound, m/s Vapor	Viscosity, μPa·s Liquid	Viscosity, μPa·s Vapor	Thermal Cond., mW/(m·K) Liquid	Thermal Cond., mW/(m·K) Vapor	Surface Tension, mN/m	Temp.,ᵃ °C
−103.30ᵇ	0.00039	1591.1	35.4960	71.46	334.94	0.4126	1.9639	1.184	0.585	1.164	1120	126.8	2175.0	6.46	145.2	3.08	28.07	−103.30
−100	0.00056	1582.4	25.1930	75.36	336.85	0.4354	1.9456	1.184	0.593	1.162	1105	127.9	1893.0	6.60	143.2	3.34	27.50	−100
−28	0.09270	1382.4	0.20680	163.34	381.57	0.8591	1.7492	1.277	0.788	1.153	751	145.4	394.9	9.60	104.8	9.15	15.73	−28
−26.07ᶜ	0.10133	1376.7	0.19018	165.81	382.78	0.8690	1.7472	1.281	0.794	1.154	742	145.7	384.2	9.68	103.9	9.31	15.44	−26.07
−30	0.08438	1388.4	0.22594	160.79	380.32	0.8486	1.7515	1.273	0.781	1.152	760	145.2	406.4	9.52	105.8	8.99	16.06	−30
−28	0.09270	1382.4	0.20680	163.34	381.57	0.8591	1.7492	1.277	0.788	1.153	751	145.4	394.9	9.60	104.8	9.15	15.73	−28
−26.07ᶜ	0.10133	1376.7	0.19018	165.81	382.78	0.8690	1.7472	1.281	0.794	1.154	742	145.7	384.2	9.68	103.9	9.31	15.44	−26.07
−26	0.10167	1376.5	0.18958	165.90	382.82	0.8694	1.7471	1.281	0.794	1.154	742	145.7	383.8	9.68	103.9	9.32	15.43	−26
−2	0.27217	1301.6	0.07496	197.32	397.43	0.9902	1.7282	1.336	0.888	1.176	631	147.0	278.1	10.65	92.9	11.34	11.85	−2
0	0.29280	1294.8	0.06931	200.00	398.60	1.0000	1.7271	1.341	0.897	1.179	622	146.9	271.1	10.75	92.0	11.51	11.56	0
2	0.31462	1288.1	0.06466	202.69	399.77	1.0098	1.7260	1.347	0.906	1.182	612	146.9	264.5	10.81	91.1	11.69	11.27	2
4	0.33766	1281.4	0.06019	205.40	400.92	1.0195	1.7250	1.352	0.916	1.185	603	146.8	257.6	10.90	90.2	11.86	10.99	4
48	1.2529	1111.5	0.01590	268.55	422.69	1.2280	1.7081	1.551	1.225	1.339	399	137.4	147.0	13.00	71.3	16.45	5.13	48
50	1.3179	1102.3	0.01500	271.62	423.44	1.2375	1.7072	1.566	1.246	1.354	389	136.6	143.1	13.12	70.4	16.72	4.89	50
52	1.3854	1092.9	0.01416	274.74	424.15	1.2469	1.7064	1.582	1.270	1.369	379	135.7	139.2	13.24	69.6	17.01	4.65	52
54	1.4555	1083.2	0.01351	277.89	424.83	1.2563	1.7055	1.600	1.296	1.386	370	134.7	135.4	13.37	68.7	17.31	4.41	54
95	3.5912	772.7	0.00334	355.22	420.67	1.4715	1.6492	3.938	5.020	4.369	141	101.9	60.4	19.81	51.7	36.40	0.33	95
100	3.9724	651.2	0.00268	373.30	407.68	1.5188	1.6109	17.59	25.35	20.81	101	94.0	45.1	24.21	59.9	61.58	0.04	100
101.06ᵈ	4.0593	511.9	0.00195	389.64	389.64	1.5621	1.5621	∞	∞	∞	0	0.0	—	—	∞	∞	0.00	101.06

ᵃTemperatures on ITS-90 scale ᵇTriple point ᶜNormal boiling point ᵈCritical point

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Now let us take an example suppose we want to have multi compression starting from minus thirty to fifty the evaporator temperature is -30 and condenser temperature is 50 degree centigrade and the working fluid is 134a so if the temperature is difference is search between -30 and 50, now p1 = 0.8434bar and p2 is, p2 is 13.17 bar right, now p3 is going to be the under root of the product p1 and p2 and that is going to be equal to 0.8434x 13.179 and p3 so P 3 is equal to we will be getting 3.33bar.

Now instead of going for 3.33 bar if you because here it is 0.2 and then 0.0.4, we can comfortably take 0.3 bar or sorry 3bar as the intermediate pressure, so the vapor is compressed from this point to this point and this line will be close to the near parallel to the nearest isentropic line. So we will extend this call strain pressure line here and this line is parallel to this one so state 1 and then state 2, now this is not we will not take it straight to it is taken as state a andstate B also we state B is this one this is state B so state a state B.

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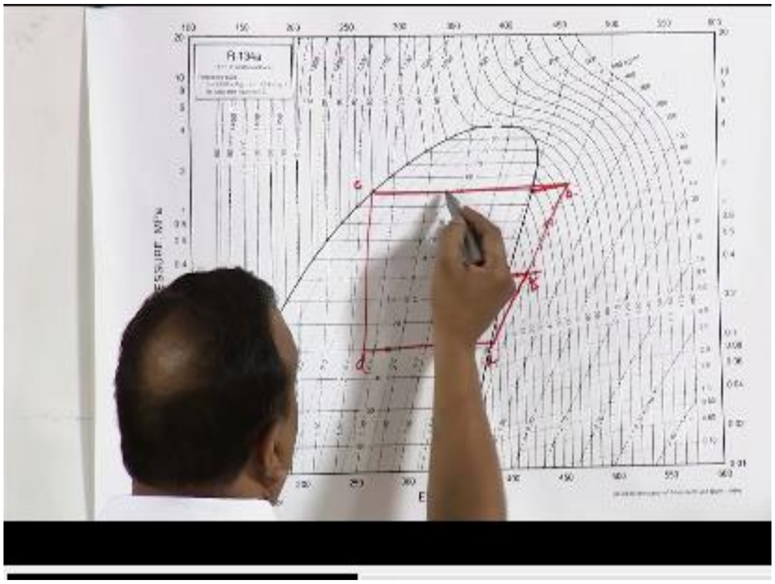

Now first of all draw the simple cycle state a state B then state C and -30 we will be getting here state D and state A this is the original cycle with without any multi compression or intercooling a b c d then we will take off the cycle with intercooling, so then it is heated then good up to the saturation state and then the vapor is again heated and this cycle is H F and G. Now I am explaining it again there is a original cycle which is operating between -30 degree centigrade and plus 50 degree centigrade, 50 degree centigrade is condenser temperature, evaporator temperature is -30 degree centigrade.

Single compression from going from A to B right, instead of doing that we have try to find we have tried to find some intermediate pressure for multi compression so we have taken under root of P 1 and P 2 that is P 2 this is 2 and this is 1, so we have taken and the root of P 1 and P 2 and we have got the value 3.33 bar. Now 3.33 bar instead of going for 3.33 bar because, this is for the ideal gas we have taken 3 bar, a 3 bar can be easily shown on the pH diagram here.

So the vapor is compressed from this pressure to up to three bar then it is cool to the saturation State and then again it is compressed in another compressor, so this is compression one and this is compression two, we will be saving this much of energy or we can say that the saving of energy can be taken as w1 - w2 work done in this process. So let us take process a b c d h a is equal to if you read, from here it will come around 380 kilo joules per kg, if you can look at the screen of this PPT you can get better idea about the values because, this diagram is clearer.

So now SC is equal to HD and that is equal to 271 approximately, 271 kilojoules per kg and HB is equal to for 445 kilo joules per kg. Now in this case the refrigerating effect is H M - HD so R =HM -HD and that is 380 -270 1 = 1 0 9 kilo joules per kg if the mass flow rate is 1 kg per second so it is going to be1 0 9 kilowatt. Now work in the process A to B is going to be 445 that is enthalpy at B - enthalpy at A that is 380, is it going to be 65 kilo joules per kg is the mass flow of refrigerant is again 1kg per second then it is going to be 65kilo watts and COP in this case is 1 0 9/ 65 that is going to be equal to 1.677.

Now let us take another case another case means when there is a multi compression so compression from A to F from F to G Cooling and then G to H. Now we have to get the two more values that is H F n H so H F is from this diagram itself you will get 410 kilo joules per kg and HH is going to be 428 kilojoules per carry we also need the value of H G and H G is 400 kilo joules per kg these values you can take from a pH diagram which is shown on the PPT so now with the help of these values we can get the work in the compressor that is HF- HA+HH - HG and work in the compressor here is going to be 410 – 380 that is HH and HA+ 428-HG 400e that is going to be equal to 30 +28 = 58.

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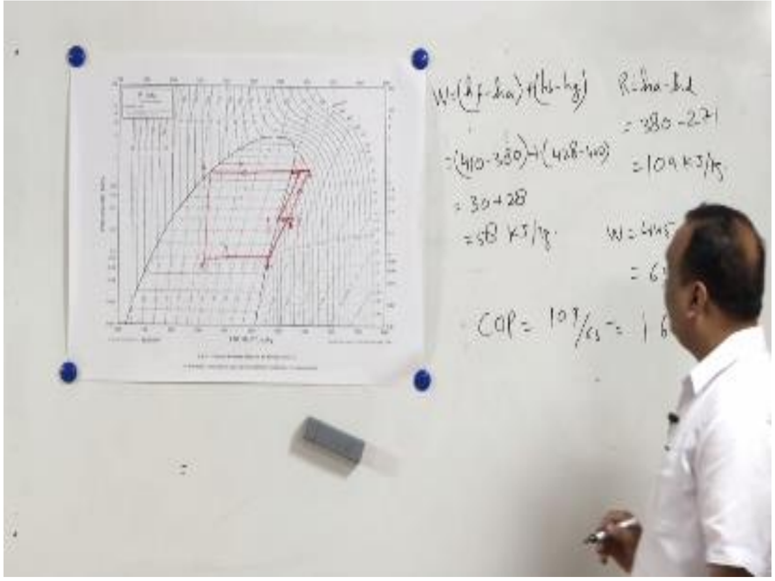

This is the work kilo joules per kg per kg of refrigerant now here in this case the work is 58 kilo joules per kg in this case it is 65 kilo joules per kg now if this modifies the co ps10 9divided by 58 and that is going to be equal to 1.879, now if we compare these two COP's this COP is higher than the previous COP by approximately 12% and were consumed here in this case 65 this is 58 and this is reduction the four consumed by approximately this is approximately a 10.8% and or we can say 11%, by simple intercooling we have improved the COP by 12% or reduce the work consumed by the compressor by 11%, they are much more better system or a smarter system which can provide these type of processes without any use of this intercooling heat exchanger. So all those processes we will discuss in the coming lecture thank you.

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