Cooling Technology: Why and How utilized in Food Processing and allied Industries

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Lecture 45

Reciprocating Compressor (Contd.)

Good afternoon, my dear students and friends. Perhaps, today it should be the last class for the compressor, because, we have still more, condenser, expansion device, and evaporator. So, hopefully, those will be covered in another week, and we will have with us 2 more weeks, where, we will do the application side, right, Including, the last class. I hope, I should take a very good, I mean, mouthwatering, ice cream, right, how refrigeration is also working with that, ok. So, coming back to the reciprocating type of compressor, no, maybe one more class before condenser, we will cover up with compressor, other type, like, that will be very compact, that, screw type, and this revolving one, which one, will be covering up, ok. Continuation of this reciprocating type of compressors, where we last left with, we start from there, and we had done in the last class, the mass flow rate of the refrigerant, right. $Pv^n = \text{constant}$

Now, what is the work input to the compressor with clearance volume? This is what, we are comparing from the no clearance in ideal, and another ideal with clearance, right which is, more logical or more towards the reality, right. So, here, if we assume that, both compression and expansion follow the same equation, that is, p v to the power n, that is, equal to constant, that is, the index of compression is equal to the index of expansion. Then, the extra work required to compress the vapour, that is left in the clearance volume, will be exactly equal to the work output obtained, during the re-expansion process, right. So, we can say, the clearance for this special case, does not impose any penalty on work input to the compressor, the total work input to the compressor, during the cycle will then be equal to, the area under A B C D A on the p v diagram, right.

$$w_{id} = \int_{Pe}^{Pc} v.dP = P_e v_e \left(\frac{n}{n-1}\right)\left[\left(\frac{Pc}{Pe}\right)^{\frac{n-1}{n}} - 1\right] \quad \ldots \ (25)$$

The specific work with and also without clearance, will be given by the same expression, as W id equal to integral of V dp between the limit pe to pc, and that is, equal to pe ve into n by n minus 1 into pc by pe to the power n minus 1 by n, minus 1. However, since the mass of refrigerant compressed during one cycle is different with and without clearance, right. Then we can write that, the power input to the compressor, will be different with and without clearance. The power input to the compressor and mean effective pressure, that is, MEP with clearance, that, those, can be given as W c equal to m dot W id, that is equal to yeeta v clearance into V dot sw over ve into W id, and MEP can be written as, yeeta volumetric clearance, v,cl into W id over ve. So, thus, the power input to the compressor and MEP, decreases with clearance, due to decrease in mass flow rate, with clearance.

$$W_c = \dot{m} w_{id} = \left(\eta_{V,cl} \frac{\dot{V}_{SW}}{v_e} \right) w_{id} \quad \ldots \text{ (26)}$$

$$mep = \eta_{V,cl} \frac{w_{id}}{v_e} \quad \ldots \text{ (27)}$$

Therefore, we can write that, if the process is reversible, and adiabatic, that is, n is equal to k, then the power input to the compressor with clearance, is given by, W c equal to yeeta v,cl into V dot sw over ve into hB minus hA, that is, yeeta v,cl into V dot sw over ve into delta hcs, where delta hcs is the isentropic work of compression, in kilo Joules per kg. Now, performance of reciprocating compressors, if we look at the specific objectives of this part is that, to discuss the performance aspects of ideal reciprocating compressor with clearance, specifically, effect of evaporator temperature on system performance at a fixed condenser temperature, and effect of condenser temperature on system performance at a fixed evaporator temperature, which we have shown earlier also in other way, in other classes. Effects of pressure ratio, and type of refrigerants, on compressor discharge temperature. Now, other part is, to discuss the performance aspects of actual compressor of actual compression process by considering effect of heat transfer in the suction line and compressor and effects of pressure drops in the suction and discharge line and across suction and discharge valves of the compressor. Effect of refrigerant leakage, then, describe various methods of capacity control and discuss the methods of compressor lubrication, right.

$$W_c = = \left(\eta_{V,cl} \frac{\dot{V}_{SW}}{v_e} \right) (h_B - h_A) = \left(\eta_{V,cl} \frac{\dot{V}_{SW}}{v_e} \right) \Delta h_{c,s} \quad \ldots \text{ (28)}$$

At the end of this, we can come to this, that you should be able to describe qualitatively, the effects of evaporator and condenser temperatures on performance of reciprocating compressor. Discuss the effects of heat transfer, pressure drops, and refrigerant leakage on performance of actual compressor. Explain, various methods of refrigerating capacity, or regulating the capacity of reciprocating compressors, and to discuss aspects of compressor lubrication. Now, ideal compression with clearance, the effect of evaporator temperature on performance of the system is obtained, by keeping the condenser temperature, or pressure and compressor displacement rate and clearance ratio fixed. To simplify the discussion, it is further assumed that, the refrigeration cycle, as in say, SSS, cycle, right.

$$\eta_{V,cl} = 1+\varepsilon-\varepsilon\left(\frac{P_c}{P_e}\right)^{1/n} = 1-\varepsilon\left[r_p^{1/n}-1\right] \qquad \ldots(29)$$

SSS means, we have done it earlier. On volumetric efficiency and refrigerant mass flow rate, the volumetric efficiency of the compressor with clearance, that can be given by yeeta volumetric clearance, equal to 1 plus epsilon minus epsilon into P c over P e to the power 1 by n, equals to 1 minus epsilon R p to the power 1 by n minus, 1. This we have given, right, earlier. Now, if from here, what we can see that, this is a PV diagram, for different evaporator pressures, and a fixed condenser pressure, right. Different evaporator pressure and fixed compressor pressure.

So, for that compressor displacement remains same if the compressor displacement remains same the clearance volume efficiency decreases as evaporator temperature decreases. So, we can say as we have already explained at a limiting pressure ratio the volumetric efficiency that becomes equal to 0. At the mass flow rate of the refrigerant that can be given as m dot equals to yeeta v,cl into v dot S w over v e right. As the evaporator temperature decreases the clearance volume efficiency decreases and the specific volume of refrigerant at compressor inlet, right, is negative, rather inlet, that is v e increases. As a result of these two effects the mass flow rate of refrigerant through the compressor decreases rapidly, as it is, as the evaporator temperature decreases, right. This is shown in this figure also, that how it is behaving.

So, we already we had shown earlier. So, let us, we had shown earlier, in the sense that, yeeta volumetric clearance versus evaporator temperature and versus the mass flow rate right. So, yeeta volumetric clearance is increasing with mass flow rate, if you look at, like this, and this is, the mass flow rate is increasing with the volumetric clearance. So, that for a given Te, we can see both the things, right. Now on refrigeration effect and refrigeration capacity, if we straight away go to the ph diagram, right, we straight away go to the ph diagram because, time is going out.

$$\dot{m} = \eta_{V,cl} \frac{\dot{V}_{SW}}{v_e} \qquad \ldots(30)$$

The refrigeration capacity of the compressor Q e, that can be given as Q e is equal to m dot into Q e, right. This is effect of evaporator temperature on refrigeration effect in a ph diagram, right. So, this is ph diagram, how the refrigeration effect on evaporator temperature is affecting, that we are showing it here. Now, since, mass flow rate of refrigerant capacity, since, mass flow rate of refrigerant increases rapidly, and refrigerant effect also increases, though marginally, with increase in evaporator temperature, the refrigeration capacity increases sharply, with increase in evaporator temperature, as it is shown here right. This is like that, temperature of evaporator and the refrigeration effect Q e at constant temperature right.

$$Q_e = \dot{m}.q_e \qquad \ldots(31)$$

This is Q e for different, this thing, and small q e, and this is capital Q e, that is, this is per unit mass, this is the whole, which, we have said earlier also. Now, on work of compression and power requirement, we have seen that, the power input to the compressor, that is given by W c equal to m dot into delta h c right, where, if it is effect of evaporator temperature on the work of compression, that is delta h c, and power input to the compressor W c for a given condenser temperature, right. So, that is how it is behaving. Now, if we look at, if we look at so, this part we can, we can skip, otherwise, we will not be able to complete.

Δ h_c (= h_2-h_1)

$$W_c = \dot{m}.\Delta h_c \qquad \ldots(32)$$

Now, on COP and volumetric flow rate per unit capacity. The COP of the system, that can be defined as, COP is equal to q e over w c, that is, small q e over delta h c right. So, as the evaporator temperature increases, the refrigeration effect q e increases marginally, and the work of compression, that is, delta h c e reduces sharply. As a result, the COP of the system increases rapidly, as the evaporator temperature increases and this can be seen from this figure, as it is shown, ok. Before that, the volume flow rate per unit capacity, that is, V, is, that can be given as V equal to yeeta V cl into V sw over Q e, that is, V e over Q e right. And as we said that, effect of evaporator temperature on COP, it varies like this right.

So, with the volume flow rate per unit capacity, v, right. So, this is v, and this is COP, with v meter cube per kilo watt per second, is like that, and under constant condenser temperature right. So, effect of condenser temperature, it is also similar. Obviously, not the same, as that of the evaporator. So, we only look at the figures, and it is showing that, the condenser temperature yeeta, volumetric efficiency, this is, the mass flow rate, this is the yeeta, volumetric efficiency under constant evaporator temperature, right. So, we can skip it, otherwise we shall not be able to talk on refrigeration effect and refrigeration capacity, right, that can be seen from here, that, refrigeration effect and refrigeration capacity, that, this is the refrigeration effect and capacity, ok.

$$COP = \frac{Q_e}{W_c} = \frac{q_e}{\Delta h_c} \qquad \ldots(33)$$

That Q e, as we have seen, that is, whole mass and small q is the part mass, and this is the constant, and this is the condenser temperature under constant evaporator temperature, right. So, on work compression and power requirement, that also we can see, this is how it is behaving, it is following right. Now, on COP and volume flow rate per unit capacity, that also is seen from, here is that, this is the COP, this is the volume flow rate and COP versus volume flow rate, the volume flow rate is increased like that, COP is decreasing like that, for T with T c against a constant evaporator temperature. Now, compressor discharge temperature. So, compressor discharge temperature, if you look at from the PV gamma, is equal to constant, and PV is equal to RT. We can then, say that, the discharge temperature Td can be given as, Td is equal to Te into E PC over P to the power gamma minus 1 by gamma right.

$$V = \frac{\eta_{V,cl} . \dot{V}_{SW}}{Q_e} = \frac{v_e}{q_e} \qquad \ldots(34)$$

$$Pv^{\gamma} = cons\tan t \quad and \quad Pv = RT \quad \ldots(35)$$

So, for a given compressor inlet temperature, Te, the discharge temperature Td increases as the pressure ratio Pc over Pe, that is, Rp and specific heat ratio gamma, increases. Even though refrigerant vapour may not exactly behave as a perfect gas, the trends remain same right. So, in this figure, we see, this is for different refrigerant, for ammonia, for R 22, for R 11, that PC over Pe versus Td, how it is behaving? right. Obviously, they are linear. So, we can see the effect of Pc over Pe on Td right.

Then, actual compression process. This is deviated from the ideal compression process due to heat transfer between the refrigerant and surroundings during compression and expansion, which makes these process, non adiabatic. Frictional pressure drops in connection, in connecting lines, and across suction and discharge valves, and losses due to leakage right. And effect of heat transfer is, let us see whether there is any such ok. Obviously, the effect of heat transfer will be very very high, and we can say that isentropic efficiency yeeta is for compressor and can be defined as yeeta is, isentropic, is equal to delta hc, is over delta hc actual right. Now we can, delta hc is the isentropic work of compression and delta hc actual is the actual work of compression.

This is observed that for a given compressor the isentropic efficiency of the compressor, is mainly a function of the pressure ratio. Similarly, it is the function of that, the function varies from compressor to compressor and is obtained by conducting experimental studies on compressors. The actual work of the compression and actual power input can be obtained if the isentropic efficiency of the compressor is known as the isentropic work of compression, can be calculated from the operating temperatures right. Effect of pressure drops in actual reciprocating compressors pressure drop takes place due to resistance to the flow of the fluid. Pressure drop across the suction valve is called the wire drawing.

This pressure drop can have adverse effect on the compressor performance, as the suction pressure at the inlet to the compressor, that is, Ps, will be lower than the evaporator pressure, right. And this is also seen in this picture, that is, effects of suction and discharge side pressure drops on PV diagram of a reciprocating compressor, right. So, this part so, this is Pe, and this is Pc, right. So, effect is this much, and the suction side is this much. So, discharge side, it is this much, and suction side this is this much, right.

So, that you have to look at from the PV diagram, right. Now we come to the last part, that is the effect of lubrication, that is, one of the prime importance. Effect of lubrication, that is, leakage. So, in actual compressors refrigerant leakage, losses take place, between the cylinder walls, and piston, across the suction and discharge valves, and across oil seal in open type of compressors. The magnitude of these losses depends on the design of the compressor valves, pressure ratio, and compressor speed, and the life and condition of the compressor. Leakage losses increases as the pressure ratio increases, compressor speed decreases, and the life of compressor increases.

$$T_d = T_e \left(\frac{P_c}{P_e} \right)^{\frac{\gamma - 1}{\gamma}} \qquad \ldots(36)$$

Due to the leakage, some amount of refrigerant flows out of the suction valves, as the beginning of the compression stroke and some amount of refrigerant enters the cylinder through the discharge valve at the beginning of the suction stroke. The net effect is to reduce the mass flow rate of refrigerant, even though it is possibly, to minimize refrigerant leakage across cylinder valves. Eliminating leakages across valves is not possible as it is not possible to close the valves completely, during the running of the compressor. So, yeeta v actual, we can say, to be equal to, actual volumetric flow rate over compressor displacement rate and that is, equal to actual mass flow rate over maximum possible mass flow rate right. So, by general, we can say yeeta v actual is yeeta v e theoretical into T s over T sc minus xi L, right, and we can say that, yeeta v T h is the theoretical volumetric efficiency obtained from PV diagram.

T s is temperature of vapour at suction flange in Kelvin, T sc is temperature of vapour at the beginning of compression in Kelvin, and xi L is the leakage loss, the distraction in percentage. Then yeeta volume or yeeta v actual, we can say, it will be equal to A minus B into R p to the power c, right. Now, the very last one, we go into that, ok, v optimum versus, rather, divided by root over m is 420 meter per second, where, v optimum is the optimum velocity of the refrigerant through the valve port in meter per second, and m is the molecular weight of the refrigerant in kg per kg mole. This relation suggests that the higher the molecular rate of the refrigerant lower is the optimum refrigerant velocity. Let us come to lubrication, there can be reciprocating compressors required lubrication to reduce wire between several parts which rub against each other.

$$\eta_{is} = \frac{\Delta h_{c,is}}{\Delta h_{c,act}} \quad \ldots(37)$$

During the operation, normally, lubricating oil is used to lubricate the compressors. The lubricating oil usually comes in contact with the refrigerant and mixes with it. Hence, it is essential to select suitable oil in refrigerant compressors. The important properties that must be considered, while selecting lubricating oil in refrigerant compressors are chemical stability, then chemical stability, then pour and or flock points, dielectric strength and viscosity. So, by this, we complete the compressor reciprocating, right.

$$\eta_{V,act} = \frac{actual \quad volumetric \quad flow \quad rate}{Compressor \quad displacement \quad rate} = \frac{actual \quad mass \quad flow \quad rate}{\max imum \quad possible \quad mass \quad flow \quad rate}$$

$$\eta_{V,act} = \eta_{V,th} \frac{T_s}{T_{sc}} - \xi_L \quad \ldots(38)$$

$$\eta_{V,act} = A - B(r_p)^C \quad \ldots(39)$$

Perhaps, we can show in this class, thank you. There are so many right. So, we complete because, our time is over, and whatever is left, with reciprocating, if there be a little. So, I have shown you the slides you can just look at if possible. I hope you know how to do that and please look into at next, we will go for the other compressors, right and then condenser, expansion device, and evaporator. Of course, the evaporator and condenser both are heat exchangers. So, though they are not same, but as much as we can cover, we will look into it. Thank you so much.

$$V_{opt} / \sqrt{M} \approx 420 \quad m/s \quad \ldots(40)$$