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

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Module No 07
Lecture 34
Pure Substance as Refrigerant

Good afternoon my dear boys and girls and friends. So, we were with the ideal situations, that is, Carnot Refrigeration Cycle. Now, we have to come out of that, we have to come to the real one, and we start with pure substance, as a refrigerant right. Till now, in the Carnot, we have said repeatedly, that, it is irrespective of the substance taken, but in reality, when we are in the actual cycle, then, we see that, the refrigerant plays an important role right. So, we are now doing that, what the refrigeration cycle will behave, when we are considering pure substance, as the refrigerant. Now, that pure substance, as refrigerant, and in the wet compression cycle, if gas is used, as a working substance, isothermal heat transfer are not possible right.

So, that an isothermal heat transfer meaning what? Say, you are having a heat transferred through this, but, the thing has to be isothermal, that is, constant temperature right. So, it is very difficult to maintain such kind of thing, and is not possible without a compressor or an expander. So, isothermal heat transfer means, the refrigerant condenses, during heat rejection, and boils during heat absorption. This means, the heat transfer processes involve latent heat transfer only, no sensible heat.

I hope, you know, what is the sensible, and what is the latent heat. Latent heat is that, where, phase is getting transferred, and sensible heat is that, where, there is no phase change. Phase change, I mean, it is solid to liquid to gas, anywhere, any phase change, solid to liquid, one phase change, liquid to gas is another phase change. So, everywhere, the latent heat is used, but, the heat transfer process involves, in this case, is the latent heat transfer only, and the process is also reversible right. So, this is this cycle, or this system can be said as reversed Carnot refrigeration system, with wet vapour compression.

So, we have said in the Carnot, what is the difficulty of wet vapour compression. So, here, as the pure substance, let us take first, wet vapour compression. That means, as we can figure out that, we will have a T-S diagram, where the dome is like this, say. So, here, 1, here 2, here 3, here 4. So, this kind of T-S diagram, we will be having right, in which we will have one compressor, from point 1 to point 2, then one condenser, under, Tc, that is, isothermal condition, it will reject heat, right, to the ambient, and it will come to point 3, then, under turbine expansion, it will go to the point 4, where it will enter the evaporator, at constant temperature, Te, right. And heat will be given to this, equivalent to Qe, right, and this was Qc.

So, if we have this, then, we can say that, the process involves 1 to 2, that is, isentropic compression, carried out at an isentropic compressor, then 2 to 3, is isothermal heat rejection, by condensation, carried out in an heat exchanger, and that is called condenser. Then, process 3 to 4, is isentropic expansion, carried out in a turbine, or in an expansion device, and process 4 to 1, that is, isothermal heat absorption, by boiling, carried out in a heat exchanger, called evaporator. So, all the inlet of point 2, and exit of point 3, the state of the refrigerant is saturated vapour and liquid. So, this we can see, perhaps, from a TS diagram. So, this is that TS diagram, where we are first considering wet compression right, and by this, we can say that, both wet compression and expansion has practical difficulties, which we have said, repeatedly, in the Carnot, and here also, since we have started with the wet compression, that, it has practical difficulties and disadvantages.

So, step 1 to 2, this is that step, 1 to 2, is called wet compression, since whole of the process occurs in the mixture region, where, liquid droplets of refrigerant are also present. So, this is a TS diagram of reverse Carnot refrigeration cycle, with wet vapour right. So, we can say that, a typical high reciprocating compressor, a high speed reciprocating compressor, has a rpm of say, around 1440. This is a typical number, it could be 1400 or 1500, like that, and due to the high rpm, the compression strokes, takes place, in less than 0.02 seconds. So, it is taking place in less than 0.02 seconds, which is less than half of one cycle. So, what do you mean by cycle, that we started from 0.1 to 0.2 to 0.3 to 0.4 and back to 0.1, the time taken is the cycle time, right. So, we can say that, the high speed compressor, reciprocating, having high rpm around 1440 or 1500, and the time required for stroke of a compression is 0.02 second, and is less than half of one cycle. So, that means, by one stroke, it will be completing half of the cycle, like this, sorry, half of the cycle like this, right.

So, what about the whole cycle? So, that will be required more time. So, this small time is not sufficient for all liquids to evaporate. In the T-S diagram, then, state of compression is shown to be a saturated state right. Let us go back to that, this was that ok. This is that saturated state, sorry, this is that saturated state, this one, this is under that saturation line.

So, is the saturated state. Now, this small time is not sufficient for all liquids to evaporate and in the T-S diagram, then state of compression is shown to be in saturated state, which, may be on the average, a mixture of some superheated vapour and some left over liquid droplets. The average piston velocity is, 2 to 3 meter per second, average piston velocity is 2 to 3 meter per second, and the outlet valve passage area may be one-sixth of the cross sectional area of a cylinder, of the cylinder. Whereas, the refrigerant outlet velocity will be around 12 to 18 meter per second. It is very high, right 12 to 18 meter per second. The liquid refrigerant droplets coming out of such a high velocity, hit the compressor valves, like bullet, and damage it. This, we have also said earlier, if you remember correctly, then, we had also said the same thing earlier, right.

So, this is true for vapour compression, wherever it be, whatever, be the cycle. So, moreover, the liquid refrigerant has more solubility for the lubricant, another negative point for the Carnot cycle. Carnot refrigeration system, that, the liquid carries with it the lubricant used for the compressor, right. So, the solubility of the refrigerant being high for the lubricant oil, then it is also carried out by the liquid refrigerant, right, than the vapour refrigerant of course, so the liquid refrigerant droplets will dissolve more lubricating oil present in the walls of the cylinder. This will certainly increase, the wear and tear of the compressor, this also we have said earlier.

In the older models of compressors, the RPM used to be around 100 to 400, which gives sufficient time for heat transfer to occur to evaporate the liquid refrigerant present at the inlet. So, the wet compression cycle is primarily of academic interest. So, wet compression cycle is primarily of academic interest. The moral of this discussion is that, we have to use dry compression with high speed reciprocating compressors, right. So, we started with wet compression, and we saw that, not feasible, as it was also same with the Carnot system, right. So, we have shown it, then we come to standard reversed Carnot cycle, right.

So, there we see that, compressor inlet state is, saturated vapour, what we have shown here is that, this is the T s diagram, right. So, we have this vapour dome, right and we started with the point 1, here, which, is the saturated vapour state. Then, we went vertical, that is, isentropic, this is, T s, and then an isothermal, and from there, to the point, and then from that point, to this, and from here back to the point 1. So, this is point 1, this is point 2, this is point 3, and if this is point 2 and this is point 2 prime, point 3, and this is point 4, back to 1 ok. This is what is reflecting here right.

So, we are getting 1 to 2 being an isentropic compression process, that occurs in superheated state, this one, right, that occurs in superheated state. This is the T s diagram of reversed Carnot cycle, with saturated vapour right. Then, we can now see, the other, that step 2 to 2a, right step 2 to a actually, this should have been 2, and this should have been ‘a’ ok. So, step 2 to ‘a’ is isothermal heat rejection. However, just like the gas cycle, the pressure, during the part 2-a increases, that is, Pa equal to Pc, is greater than P2, and this therefore, so, it is therefore, it requires an isothermal compressor, and ‘a’ to 3 is isothermal heat rejection, 3 to 4 is isentropic expansion, carried out in a turbine, or in an expansion device and process 4 to 1 is isothermal heat absorption by evaporation, carried out in an evaporator.

So, this is the standard reversed Carnot refrigeration cycle right. So, we can say, now, that, if we analyze, the cycle, then, applying the first law of thermodynamics, we can say, to the components used, that is, all components individually, assuming a steady state, we can say that, in the step 1, that is, process 1 to 2, is isentropic compression. So, assuming, there is no change in kinetic and potential energies, that is, delta Ke and delta Pe is 0, or negligible. The process being isentropic, it means that the process is adiabatic, and reversible, and hence, Q is equal to 0. If W isentropic is the work, W, isentropic is the suffix, if, W isentropic is the work input to the isentropic compressor, then, the first law of thermodynamics reduces to minus W isentropic, is equal to m dot into h 2 minus h 1.

The specific work input in terms of per unit mass flow rate is minus w isentropic, is equal to h 2 minus h 1. Here it was capital W, for the entire mass, here it is small w, per unit mass, right. This, we have been saying repeatedly. The negative sign indicates that the work is done on the system, since the right hand side of the positive, here, since the right hand side is positive, we can write that w isentropic, within the domain, right, is equal to h 2 minus h 1 right. Now, we can say, now, that, step 2 is the process, 2 to 'a', isothermal compression. So, if it is, isothermal compression, then work done on the isothermal compressor, is W iso, and heat rejected by the compressor, is Q reverse, and both of which are negative.

Then, the first law of thermodynamics says, that Q iso minus W iso is equal to m dot h a minus h 2, and this process is considered to be reversible therefore, Q reversible is also T d s, which, we have seen earlier, right. So, we can write that, Q isentropic is equal to m dot T c into s 2 minus s a and that is, m dot, area 2 a c d 2, if we go back, if we go back to that, we can say 2 a c d 2, is the, sorry, so, this is the s, and not here, the previous one here, this is 2- a, right. So, 2 a, then 3 b d, if I am not mistaken, let us look into that, we have to change it. So, let us look into that, it was 2 a c d 2, right.

So, the same thing we have said, 2 a, this is 2 a, then 2 a c, this part, right. So, this is 2, this is a, this is c, this is d, and back to 2. So, this part is the area, that m dot area 2 a c d 2, right. Now, if we come to rewriting. So, minus W iso is T c into s 2 minus s a minus, H 2 minus H a, and integrating, T d s equal to d h minus V d p, along the process 2 to a, this result can also be obtained only if minus V d p is W is used for an open system.

Therefore, W isentropic is minus between 0.22 a V d p is equal to integral of T 2 to a T d s and minus integral of 2 to a d h. So, this is T c into S a minus S 2 minus H a minus H 2 right. So, we can say that, since, it is the work done on the system, therefore, it is negative, we also said many times, that, if work is done on the system, then it is negative, and if work is done by the system, then it is positive, this we have said many times, right. So, we can then say that step 3 is process a to 3, right, and process to a to 3, if you remember, it was like this, that, this was a and this is 3, right.

So, process a to 3 in that T s diagram is this, and considering, there is no kinetic and potential energy, and this is equal to 0, since, there is no work involved in this process, W is equal to 0. Therefore, first law reduces to, first law reduces to Q is equal to rather, minus Q c is equal to m dot h a minus h 3 minus m dot T c into s a minus s 3. Since, a to 3 is isothermal, and isobaric process, and using T d s, is d h minus V d p. So, we can write, then d H is equal to T d s because d p is 0, there is no pressure difference between a to 3. So, integrating along a to 3, we can write, from T s diagram, that h a minus h 3 is equal to between a 3 to an integral T c d s and that means, T c into s a minus s 3, that means, area under 3 b c a 3, we will just show this, and then obviously, time is up we will go to the next for step 4.

Now, if you remember, what we said, we said, it is area 3 b c a 3, right area 3 b c a 3. So, back to 3 right. So, 3 is this area, b is this c is this, a is this, and back to 3. So, this area we are referring to for the process 3. Our time is up for today. So, I thank you all for attending this class. I will continue in the next class for this, ok. Thank you.

Analysis of the cycle:-
Applying first law of thermodynamics to all the components individually assuming a steady state:
Step 1:- Process 1 – 2 : Isentropic Compression:- Assuming changes in kinetic and potential energies, i.e., Δ KE and Δ PE are negligible, the process being isentropic, it means the process is adiabatic and reversible, and hence, q = 0. If Wisen is the work input to the isentropic compressor, the first law of thermodynamics reduces to . The specific work input in terms of per unit mass flow rate is
The negative sign indicates that the work is done on the system. Since, the right hand side is positive, we can write,

$| w_{isen} | = h_2 - h_1$.

Step 2: Process 2 – a : Isothermal compressor:-

Work done on the isothermal compressor is W_{iso}, and heat rejected by the compressor is Q_{rev}, both of which are negative (-ve). Then the first law of thermodynamics reduces to .

This process is considered to be reversible and hence, Q_{rev} = T ds.

$$\therefore -\dot{Q}_{iso} = \dot{m} T_c \left(s_2 - s_a\right) = \dot{m}\left(area\, 2 - a - c - d - 2\right)$$

$$or,\ -W_{iso} = T_c\left(s_2 - s_a\right) - \left(h_2 - h_a\right)$$

Integrating T ds = dh – v dp along the process 2 – a, the above result can also be obtained only if w = - v dp is used for an open system.

$$\therefore w_{iso} = -\int_2^a v\,dp = \int_2^a T\,ds - \int_2^a dh = T_c\left(s_a - s_2\right) - \left(h_a - h_2\right)$$

Since, it is the work done on the system and hence –ve*

Step 3: Process a - 3 : Condensation:- Δ KE and

□ Δ ΔPE = 0. Since, there is no work is involved in this process, W = 0. Hence, first law reduces to

Since, a – 3 is isothermal and isobaric process and using T ds = dh – v dp, we can write dh = T ds because dp = 0. Integrating along a – 3, we can write, from T-s diagram

$$h_a - h_3 = \int_3^a T_c\,ds = T_c\left(s_a - s_3\right) = area\, 3 - b - c - a - 3$$

Step 4: process 3 – 4 : expansion turbine:- ΔKE and ΔPE = 0

For isentropic process, q = 0. Assuming w_T is the specific turbine work out put, first law reduces to : $w_T = h_3 - h_4$