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

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Module No 06

Lecture 29
Carnot Refrigeration Cycles

Good afternoon my dear friends and students. We have finished, Carnot cycle with heat engine. Now, we will go to another new one, that is called, Carnot refrigeration cycles, right. So, this is the first class, obviously, it will also take some classes. It is not that; in one class it will be over. So Carnot refrigeration cycles, we will start with, we have done with, Carnot heat engines. For refrigeration cycles we need to know some of the things, right.

Again, let us take it back to this side. Otherwise, it will be difficult. So, Carnot refrigeration cycle is a completely reversible cycle. Hence, it is used as a model of performance, or perfection for a refrigeration cycle, operating between constant temperature heat source and heat sink. It is used as reference, against which, the real cycles are always compared to, right.

$$\int \partial q = \int \partial w \qquad \int \partial q = q_{4-1} - q_{2-3} = q_e - q_c$$

$$\int \partial w = w_{3-4} - w_{1-2} = w_T - w_C = -w_{net} \quad (1)$$

$$\Rightarrow (q_c - q_e) = w_{net}$$

So one figure, like figure 1 A, and B, it will show the schematic of a Carnot vapor compression refrigeration system, and the operating cycle on T-S diagram. Already S, we have defined, S is the entropy obviously, T is the temperature. So temperature entropy diagram, if we see the figure. So, it is figure A, as it is seen from here, it is figure A. We have a heat source, Q e, we have a heat sink, that is, Q c, we have one compressor, we have one turbine right. So, these are the 4 units, that is, compressor, condenser, turbine expansion and evaporator.

These are the 4 units of the Carnot refrigeration cycle. Now, if we look at the other one, and this is figure 1 A, because, please remember that, this is the point 1, this is the point 1, this is point 2, that is before the compressor, 1, after the compressor, 2, then, before the expansion device, 3, and before the evaporator, it is 4. So, the cycle will be 1 to 2 to 3 to

4 back to 1 right. So, that will show in a pictorial view, just this. I am repeating, because, you keep in mind, all the time, it may not be possible, we will be going to and fro. So, the next one is 1 B, and that is under the T S diagram.

So, this is temperature versus entropy, right and as you see, this is the dome, right. This is the dome, someday, I told that, I will show you how these domes are easily created through software, nowadays available, but yeah, these are to be, of course, obtained, or bought from the market. So, a T S diagram, where this is the, sorry, this is the state point, 1, this is state point, 2, this is state point, 3 and this is state point, 4. So Q e quantity of heat is supplied, W 1 - 2 quantity of work is done on the system, Q c quantity of heat is rejected to the ambient, or environment and W 3 - 4 is obtained as work, right. So, this is the cycle and also some more things, which you require very much, that is, the temp, pressure is P e at the point 1, and pressure is P c at the point 2, right, and these are those pressure lines, right and this, we will describe, we will say more in detail.

$$q_c = -q_{2-3} = -\int_2^3 T.ds = T_c(s_2 - s_3) \quad \dots (2)$$

$$q_e = q_{4-1} = \int_4^1 T.ds = T_e(s_1 - s_4) \quad \dots (3)$$

So, the two diagrams, we have shown, one is T S diagram and another is the one, diagram for the Carnot refrigeration system right. So, if we go back, if we go back, this was the schematic diagram. So, if we are going back to the original, where, we said that figures 1 A and 1 B show the schematic of Carnot vapor compression refrigeration system, and operating cycle, on a T S diagram. So, as it is shown in 1 A, the basic Carnot refrigeration system for pure vapor, that consists of 4 components, number 1, compressor, number 2, condenser, number 3, turbine and number 4, is the evaporator. Refrigeration effect, that is Q 4 – 1, equivalent to Q e, is obtained at the evaporator, as the refrigerant undergoes the process.

This process is vaporization of the substance, that is, this process 4 – 1, and, extracts the latent heat, from the low temperature heat source. The low temperature, low pressure vapor is then, compressed isentropically, right isentropically means, entropy is constant. In the compressor, to the heat sink temperature, that is, T c. The refrigerant pressure increases from P e to P c, which, I have shown during the compression process, that is, process 1 – 2, and the exit vapor is saturated. Next, the high pressure, high temperature saturated refrigerant undergoes the process of condensation, in the condenser, that is, process 2 – 3, as it rejects, the heat of condensation, that is, Q c or Q 2 - 3 is equal to Q c. So, it is rejected to an external heat sink at temperature T c.

The heat, rather, the high pressure, that is, saturated liquid, then follows through the, or rather, it flows through the turbine and undergoes isentropic expansion, that is, process 3 -4. And during this process, the pressure and temperature fall, from P c T c to P e T e, that is, P c, corresponds to pressure at the condenser, T c corresponds to temperature at the condenser, and P e corresponds to pressure at the evaporator, and T e corresponds to temperature at the evaporator. Since, saturated liquid is expanded in the turbine, some amount of liquid flashes out, and it forms into vapor, and the exit condition lies in the two phase, right. So, this two phase region, exit condition, it should be as low as possible, because two phase, it is very difficult to analyze right. So, for the simplicity, we are saying that, at this very moment, that two phase, are minimum, or minimal two phases.

$$s_1 = s_2 \quad and \quad s_3 = s_4 \; ... \; (4)$$

So that, it can be overlooked, or it can be neglected. However, that this, as it is seen, from the T s diagram, the cycle involves, two isothermal heat transfer processes, that is, process 4 – 1, and process 2 – 3, and two isentropic work transfer processes, that is, process 1 – 2, and process 3 - 4. Heat is extracted isothermally at evaporator temperature, that is, T e during the process 4 – 1, and heat is rejected isothermally, at constant temperature, that is, T c during process 2 - 3. Work is supplied to the compressor during the isentropic compression, that is, from state point 1 to 2 of the refrigerant. Vapor from or refrigerant vapor, rather, from evaporator pressure, P e to the compressor pressure, P c, and work is produced by the system, as refrigerant liquid expands isentropically, in the turbine from the condenser pressure, P c to the evaporator pressure, P e.

All the processes are both, internally as well as externally reversible. This is a must, that is, net entropy generation for the system and the environment is 0. As, we have shown, during entropy definition, that entropy, the moment it is increasing is showing that, the system is undergoing chaotic condition. So, when it is 0, that means, system is stable, that net entropy generation for the system and environment is 0. Now, applying first and second law of thermodynamics to the Carnot refrigeration cycle, we can write, we can say, that, del Q is equal to Q 1 4 2 1, minus Q 2 2 2 2 3. So, it is Q e minus Q c, and del W, integral of dQ, was Q 4 2 1 minus Q 2 2 3, and is equal to Q e minus Q c, and del W, integral of del W, is W 3 - 4 minus W 1 – 2, which is W turbine, W t minus W c, that is, equal to W net.

Therefore, we can say, W net is equal to Q c minus Q e. This we keep in mind that, W net is equal to Q c minus Q e, right and this was our schematic, which I said, and this is, our T-S diagram right. Now, for the reversible isothermal heat transfer process 2 -, 3 and 4 – 1, we can write that Q c minus Q 2 – 3, Q c, equal to Q minus Q 2 – 3, is equal to minus, is equal to minus 2 – 3, integral T dS, and that is, equal to T c into S 2 minus S 3, right. This we have given, a number of equation number 2, and if we remember, what was that equation number 1, is this, that is, W net is W t minus W c, that was W minus W net, right, that was said to be equation number 1, that is W net is W t minus W c right. W t was the work of turbine and W c is the work of compressor. So, equation number 2, has become that, Q c is minus Q 2 - 3 is equal to integral of minus 2 to 3 T dS, and that is, T c into S 2 minus S 3 equivalent to equation number 2, right, and Q e is Q 4 – 1, that we can write, integral between 4 – 1, T dS, and is equal to T e into S 1 minus S 4, is the equation number 3.

Obviously, the T e and T c are the evaporator and condenser temperatures, respectively. Now, since, this is isentropic, so, S 1 is equal to S 2. This was our point 2, and this was our point 1, right this was our point 2, and this was our point 1, right. So, it is isentropic, so, S 1 is equal to S 2, and this is 2, this is 3, this is 4, this is 1 back. So, this is 4, this is 3. So, again this 3 to 4 is isentropic because it is under T S diagram right this was T and this is S right.

So, this is isentropic, this is isentropic, this is isothermal, this is isothermal. So, between point 3 – 4, it is isentropic so, that is why, S 3 is equal to S 4. The coefficient of performance or COP, that can be written, as COP Carnot is equal to refrigeration effect over net work out input. So, how much you are giving and how much you are getting, that is the efficiency. So, COP is expressed, that, the refrigeration or refrigeration effect obtained over the net work input, how much work you have given, and how much refrigeration effect you have obtained. The ratio of this two of the refrigeration effect obtained over the work input, you have given, that is the COP right.

$$COP_{Carnot} = \frac{refrigeration \quad effect}{net \quad work \quad input} = \frac{q_e}{w_{net}} = \frac{T_e(s_1 - s_4)}{T_c(s_2 - s_3) - T_e(s_1 - s_4)} = \left(\frac{T_e}{T_c - T_e}\right) \quad \ldots (5)$$

Then we can write that COP of Carnot is equal to refrigeration effect given or obtained over the net work input right, and this can be written as Q e over W net right. So, that is equal to T e into S 1 minus S 4 S 1 minus S 4 over T c into S 1 minus S, S 2 minus S 3, minus T e into S 1 minus S 4 right. So, this can be written as, this T e into S 1 minus S 4, if you remember that, from here this is equal to Q e right, and T c into S 2 minus S 3, this one is Q c, right. So, it is Q, it is Q e over Q c minus Q e right. So, this is what exactly we have. Therefore, we can say that the COP of Carnot refrigeration cycle is equal to T e into S 1 minus S 4 over T c into S 2 minus S 3 minus T e into S 1 minus S 4 and that is equal to T e over T c minus T e that is, T e over T c minus T e, T e over T c minus T e because, S 1 minus S 4, S 2 minus S 3 and S 1 minus S 4, we have said S 1 is equal to S 2 right.,

So, that means, it becomes S 2 minus S 4 and S 3 is equal to S 4, S 1 is S 2, and S 3 is equal to S 4. So, we can write it to be S 1 minus S 4, right and this is also S 1 minus S 4. So, if you take common S 1 minus S 4 we have in the denominator T c minus T e, and numerator we have S 1 minus S 4. So, it cancels out. It is, T e by Q c minus T e by T c minus T L, right this is T e by T c minus T L, that is the COP of the Carnot Refrigeration cycle, right. So, we have established, what is the Carnot Refrigeration cycle, right.

Now, we can say that the COP of Carnot Refrigeration cycle is a function of evaporator and condenser temperatures only, and condenser temperatures only, and it is independent of the nature of the working substance. The Carnot COP sets up, or sets an upper limit for refrigeration systems operating between two constant temperature thermal reservoirs that is heat source and heat sink. From Carnot's theorem, for the same heat source and heat sink temperatures. No irreversible cycle can have COP higher than that of the Carnot COP right. So, our time is almost over. So, let us just have a recapitulation that, we started with, in the T-S diagram, because, this is what, subsequently, we will be doing that in the T-S diagram, this is the dome we have 0.1, we have 0.2, we have 0.3, we have 0.4. This is isentropic, this is also isentropic, this is isothermal and this is isothermal. So, two isentropic and two isothermal processes, we had right, and the temperatures are one is T e, that is, evaporator temperature, one is T e that is, evaporator temperature and another is T c, that is condenser temperature, right and pressures are P e and P c right. And since, it is isentropic, we said S 1 is equal to S 2, and S 3 is equal to S 4, and that is the reason, why this, if we keep this in mind, that S 1 is equal to S 2 and S 3 is equal to S 4, we have found out that, this one S 1, is S 2 and S 3 is equal to S 4, this we found out. So, we defined COP as the refrigeration effect to that, the work input and this was Q e over W net, and this was T e into S 1 minus S 4 over T c into S 2 minus S 3 and minus T e into S 1 minus S 4, that came out to be T e over T c minus T e, and this is the Carnot COP, and for reversible refrigeration cycle Carnot COP is the maximum, and is taken as the datum, or as the, as the, not datum as the one, which may be achieved, which is to be achieved right.

So, we have come to the end of this period. So, I am thankful to you for your listening. Thank you all.