Thermodynamics
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Lecture 88
Thermodynamics cycles: Vapor compression refrigeration cycle

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Figure 1.

Let's study the refrigeration cycle, also known as the vapour compression refrigeration system cycle (VCRS).

Figure 1 shows the back of a household refrigerator which implements the VCRS cycle. The system here consists of 4 components: a compressor, a condenser, an expansion valve and evaporator.
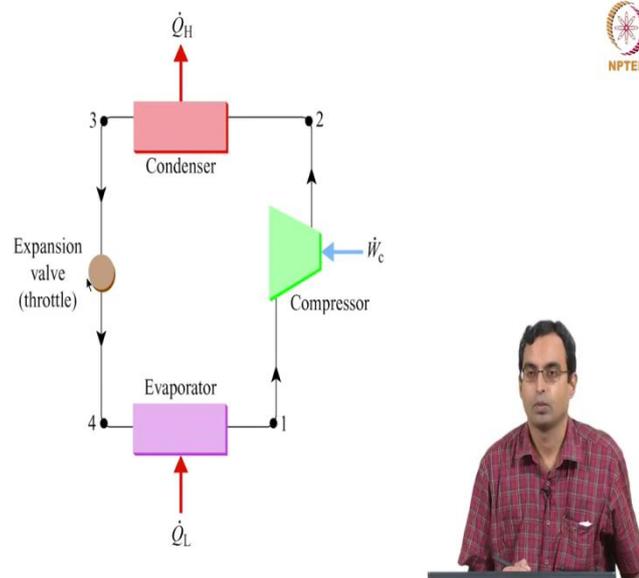
Figure 2.

Figure 2 shows the schematic of the components of the VCRS cycle.

The compressor takes in a refrigerant, compresses it and gives out high pressure high temperature refrigerant. Ideally, this compression process is isentropic. The refrigerant then enters the condenser, rejects heat and becomes liquid. The heat rejection process is a constant pressure process. Then, the refrigerant enters the expansion valve (or a throttle valve). The pressure as well as the temperature of the liquid refrigerant drop significantly in the expansion valve. We are left with the mixture of liquid refrigerant and its vapour at the exit of the expansion valve. This low pressure low temperature mixture, then, enters the evaporator, where it absorbs heat from the substances inside the refrigerator which we want to cool, and becomes saturated vapour. This saturated vapour enters the compressor and the cycle continues.
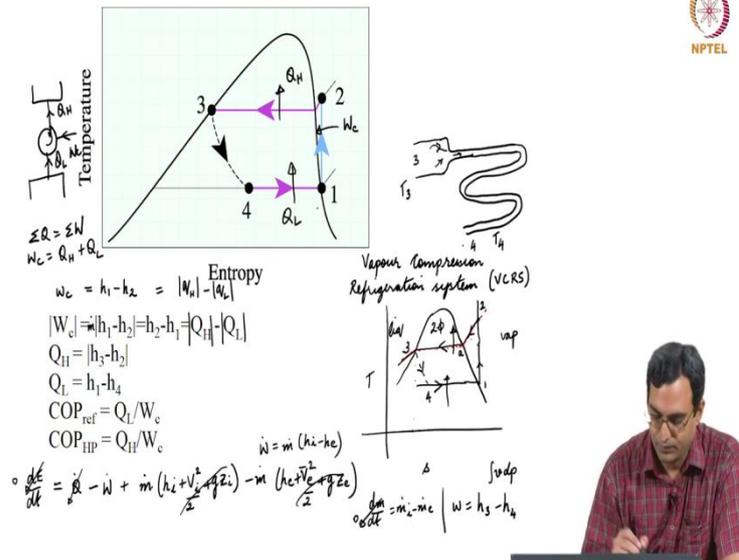
Figure 3.

Figure 3 shows the processes discussed above on the T-S diagram. The process1-2 happens inside the compressor. The process 2-3 happens inside the condenser. The process 3-4 happens inside the expansion valve (or a throttle valve). The process 4-1 happens inside the evaporator. The compressor needs the work input. Heat is rejected in the condenser, whereas heat is absorbed in the evaporator. The throttling process in the expansion valve is highly irreversible. There is no work interaction associated with it. Ideally, the throttling process is adiabatic (we discussed this before).

Ideally, we would like to have a reverse Carnot's engine (refrigerator) so that we have the maximum COP possible between the given heat source and heat sink. As discussed before, we cannot have isothermal heat transfer when we are dealing with a single phase of a substance. Hence, the processes where heat transfer takes place, processes 2-3 and 4-1, should be inside the liquid vapour dome of the refrigerant used, where the working substance is a mixture of liquid and vapour, and isothermal heat transfer is possible. Also, as pointed out before, a compressor cannot compress a mixture of liquid and vapour without getting damaged. Hence, the compression process 1-2 lies outside the liquid-vapor dome on the vapor side (Fig. 3). Ideally, the compression is isentropic. The compression happens till the state 2. The entire heat rejection process 2-3 cannot happen isothermally as some part of it lies in the single phase region on the vapor side of the dome (Fig. 3). As said before, it is

difficult to have isothermal heat transfer with a single phase of a substance. However, isobaric heat transfer is possible with a single phase of a substance. Hence, the states 2 and 3 lie on an isobar, and we have isobaric heat rejection in the process 2-3. The temperature at state 2 is higher than the temperature at state 3. The process 3-4 is an expansion process. We could have done this expansion in a turbine and get some work output. However, as mentioned before, a turbine cannot work with a mixture of liquid and vapor without getting damaged. Even then, if we decide to employ a turbine for this expansion process, the work output we get will be significantly small. The process 3-4 is quite close the saturated liquid line. Hence, the specific volume of the liquid-vapor mixture which is going to expand in the turbine is small. If we consider isentropic expansion in the turbine, the magnitude of the work output through expansion from the condenser pressure to the evaporator pressure is given by $|\int vdp|$. Since the specific volume is small for the process 3-4, the work output is also small. Also, the turbine is a costly device. This will increase the cost of a refrigerator significantly even though the work output is very small. Hence, instead of a turbine, the expansion process happens through a throttling valve or a throttling tube. This tube is small in diameter and quite long. There is a large pressure drop as the refrigerant passes through the tube because of viscosity (friction). If the refrigerant flows through the tube fast, the process can be assumed to be adiabatic. We had also concluded that the throttling process is an isenthalpic process based on some assumptions. If the conditions are properly chosen, then along with pressure, the temperature of the refrigerant also drops significantly. The process 3-4 is an irreversible process which is represented by a dotted line on the T-S diagram in Fig. 3. The process 4-1 happens inside the evaporator where the refrigerant takes in heat, evaporates and enters the compressor as saturated vapor. In this way, the VCRS cycle continues. It runs in an anticlockwise direction on the T-S diagram unlike the Rankine cycle.

The main processes of the VCRS cycle shown on the T-S diagram in Fig. 3 are mentioned below:

1. Process 1-2: isentropic compression of the refrigerant in the compressor

2. Process 2-3: constant pressure heat rejection by the refrigerant in the condenser

3. Process 3-4: irreversible expansion of the refrigerant in the throttling valve (or tube)

4. Process 4-1: constant pressure heat addition to the refrigerant in the evaporator

Let's call the heat rejected Q_H, heat added Q_L and the work input to the compressor W_c. There is no work interaction associated with the expansion valve. Applying the first law to the cycle, $\oint \delta W = \oint \delta Q \rightarrow W_c = Q_H + Q_L \rightarrow |W_c| = |Q_H| - |Q_L|$. We also know that the work input to the compressor on a unit mass basis is given by $w_c = h_1 - h_2$. Hence, $w_c = h_1 - h_2 = -q_H + q_L$ (q_H leaves the system and q_L enters the system [the four components of the VCRS cycle and the refrigerant inside form the system)]. The expression $w_c = h_1 - h_2$ can be obtained using the first law for a control volume. We have discussed this before.

If we apply the first law for a control volume to the condenser (heat exchanger) and make assumptions as discussed in the previous lectures, we get,

$q_H = h_3 - h_2 \ or \ |q_H| = |h_3 - h_2|$

Similarly, for the evaporator (heat exchanger),

$q_L = h_1 - h_4$

The coefficient of performance, COP, for the refrigerator is $COP_R = \frac{Q_L}{W_C} = \frac{q_L}{w_c}$, whereas the COP for the heat pump is $COP_{HP} = \frac{Q_H}{W_C} = \frac{q_H}{w_c}$.