Indian Institute Of Technology - Gandhinagar

Project-1

Thermodynamics

ES 211

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Contents

1 Introduction

We have chosen CO_2 as a pure substance. Carbon-dioxide operates in a transcritical process in the thermodynamic cycle for the heat pump. We have made a model depicting the relation of Pressure(P), Temperature (T), and the specific volume(v) of CO_2, known as the P-v-T surfaces. Additive manufacturing techniques were used to make our model. The 3D model has been made by *ultimaker* 3D printer.

We have studied about the thermodynamic states along which the carbon-dioxide gas moves in order to complete the cycle of heat pump or refrigerator. The state of the CO_2 gas at each stage of the cycle has been analysed, followed by the entire process graphed on the P-v-T surface through its sectioning so as to get a pictorial insight of our analysis. We have further studied about various types of design of Heat pumps and the thermodynamic aspect of the refrigeration cycle. We have also studied about the technology used in compressor.

2 P-v-T-Model Overview

We had chosen CO_2 as the pure substance for this project. To get the values of Pressure for different values of Temperature and specific-volume we had used CANTERA, a toolbox available in MATLAB. However, with CANTERA we cannot get the values for solid phase of the pure substance.

We plotted the graph for the saturated liquid-vapor mixture state of the pure substance. We set the minimum temperature to be 273.15 K. We take 100 points on both the halves of the critical point. And by iterating over each temperature, we calculated the corresponding values of specific volume and temperature. The values were stored in a matrix of P, v and T, and then used the *surf* function of MATLAB, on the matrices to get the surface.The surface created from the Matrix of P-v-T, is shown in the figure below :

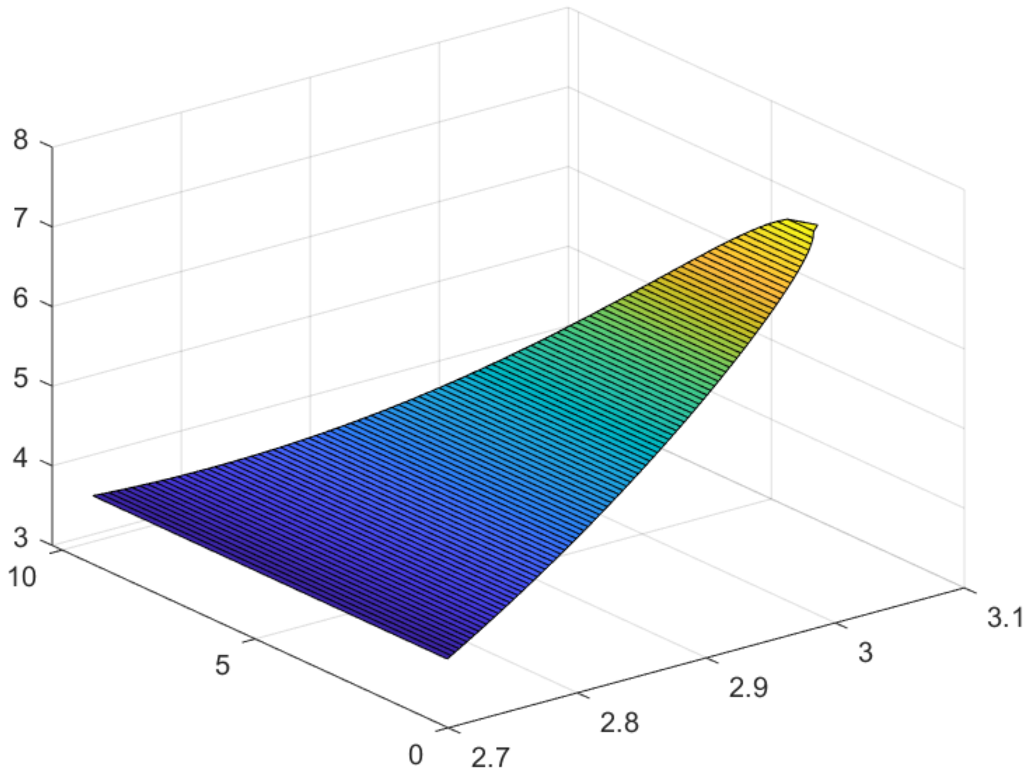


Figure 1: Surface for Liquid-Vapor Mixture

Then, by using the *surf2solid* function of MATLAB, we converted the surface into a solid model, showing the relation of P-v-T for the saturated liquid-vapor mixture.

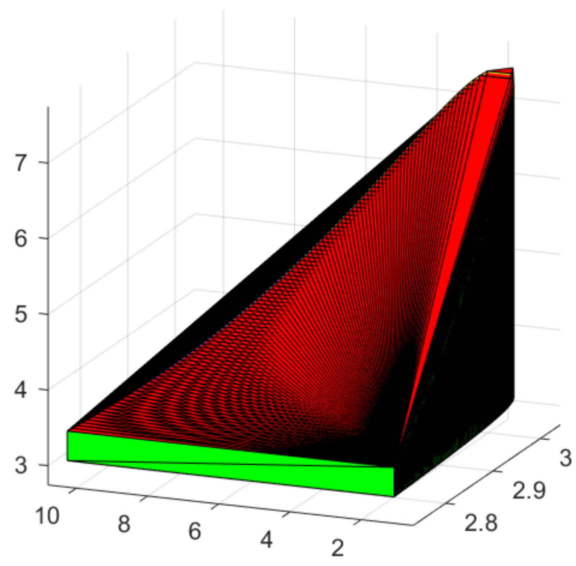


Figure 2: Solid Model for Liquid-Vapor Mixture

To get the complete surface of CO_2 we have used a function that was available online in a paper[1].This function provides us with the stl file when appropriate matrices are given as input. The solid model was converted into a *stl* file by using the function *stlwrite*. The surface diagram and the solid model for the CO_2, that we get from this function is shown below :

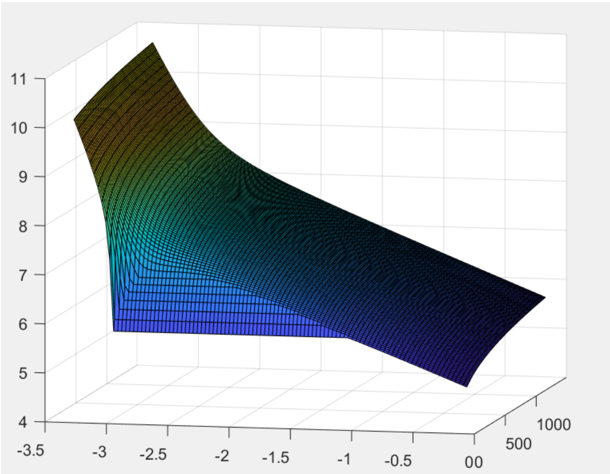


Figure 3: Surface diagram of CO_2

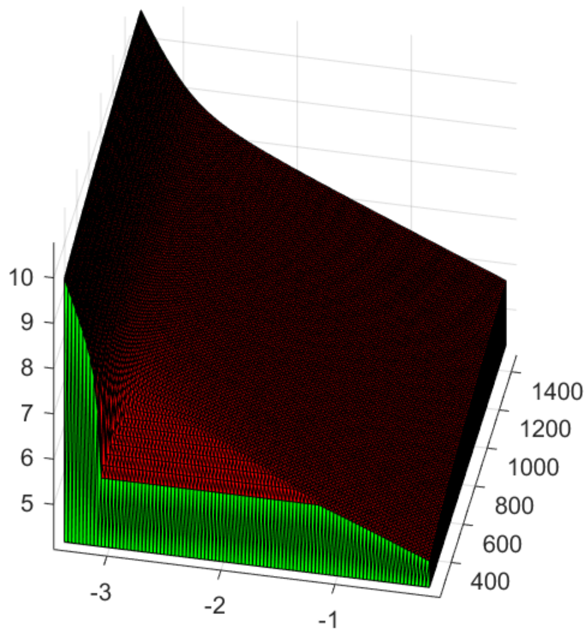


Figure 4: Solid Model of CO_2

However, we were not able to convert this MATLAB model, into a file that can be used by 3D-printer. Se, we tried to make the model in AutoCAD and the image of the model is shown below :

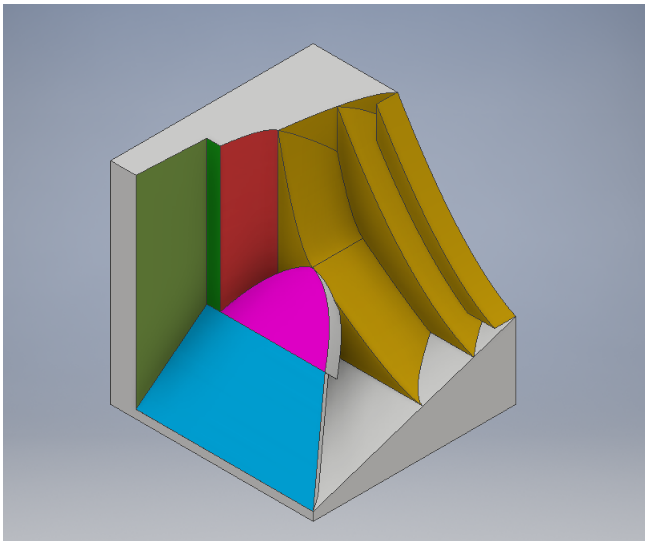


Figure 5: Solid CAD Model of CO_2

3 Applications of CO_2

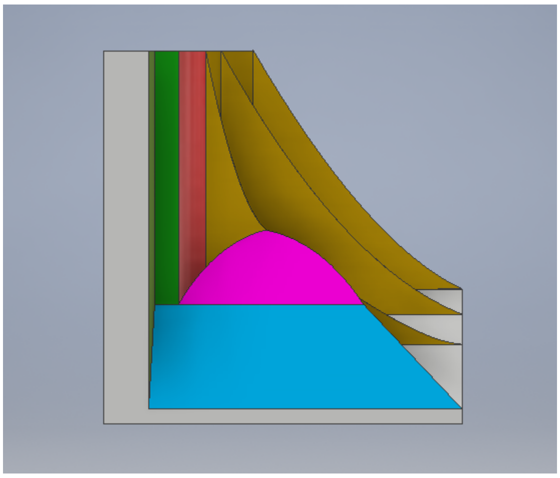
Carbon dioxide has large applications in chemical and petroleum industries. It also has applications in the electronic industries to clean the surfaces in the circuit board assembly and in the manufacturing of semiconductor devices. It is also used as working fluid in refrigerators and heat-pumps which run in thermodynamic cycles[2].

The use of CO_2 as a refrigerant is becoming popular, because of the adverse effects of harmful refrigerants like HFC (Hydro Fluoro Carbon), Hydrocarbons[3]. There is an increasing trend in shifting from the traditional refrigerants towards naturally available refrigerants such as CO_2,NH_3 and propane. However, due to high flammability of propane and toxicity of NH_3, CO_2 is more preferable. CO_2 has higher thermal conductivity, larger density, higher latent heat and specific heat capacity, and lower dynamic viscosity in comparison to other hydro-fluorocarbons (HFCs).

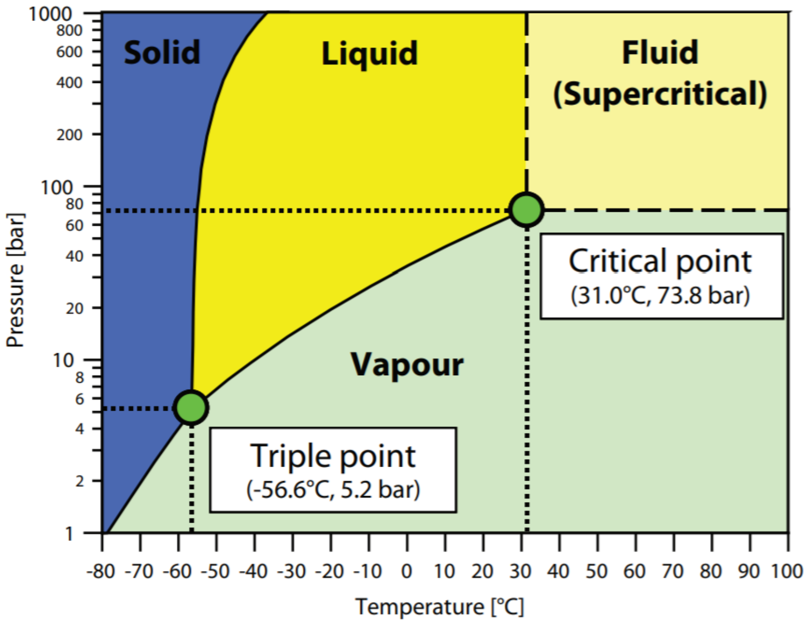
The Global Warming Potential (GWP) is the index of heat trapped by a greenhouse gas present in the atmosphere up to a specific time, relative to carbon dioxide[4].The traditional refrigerants have high GWPs, whereas carbon-dioxide has GWP of unity, which makes it an environmentally friendly refrigerant. The disadvantage of CO_2 as refrigerant is that in refrigeration cycle, it has lower coefficient of performance (COP) when compared to other HFCs.

4 Thermodynamic Analysis[5]

R-744 is the chemical reference of CO_2 as a refrigerant. The critical temperature of carbon-dioxide is $T_c = 31.0°C$ and the critical pressure is $P_c = 7.39MPa$. The triple line value of CO_2 is $T = -56.6°C$ and pressure of $P = 518kPa$. The point above the purple region is the critical point and the points in the intersection of purple (liquid-vapour) and the blue(solid-Vapor) region are the triple point.



The projection of Pressure(P) verses Temperature (T) is shown below[5] :



At the boundaries, the two phases co-exist in equilibrium and temperature and pressure won't be independent intensive properties anymore. The diagram shows the two crucial points, i.e. the triple point of carbon dioxide and the critical point of carbon dioxide.

The triple point denoted the position where all the three phases co-exist in equilibrium. At temperatures less than the triple point, the liquid state of any substance cannot exist. Triple point, thus provides the lower temperature limit for all heat transfers which are based on evaporation or condensation[5].

The critical point is the point on the top of the saturated liquid-vapor dome. The critical point like Triple Point provides the upper limit for all the heat transfer processes which are based on evaporation or condensation. At pressure and temperature higher than critical point, the liquefaction of a pure substance is not possible[5].

CO_2 operates in a transcritical cycle. The transcritical cycle is a thermodynamic cycle that passes through the states of both sub-critical and supercritical regions.

The commonly used refrigerant R134a has the critical temperature equal to $101.1°C$. Thus it denotes that for R-134a, heat rejection by condensation can be done at temperatures till $101.1°C$, the critical temperature. For many refrigeration applications, this temperature is more than enough to reject heat to the atmosphere.

For R-744(carbon dioxide)the critical temperature is $31.0°C$. Thus it denotes that for R-744, heat rejection by condensation can be done at temperatures till $31.0°C$, the critical temperature. This temperature is comparatively lower than the required temperature(as seen in R134a) so that heat can be rejected to the atmosphere for many of the applications of refrigeration. However, this does not mean that CO_2 will not be used as a refrigerant. Carbon dioxide can definitely be used as a refrigerant for many applications(like R134a) but the process by which heat is rejected for carbon dioxide should differ from condensation.

The Pressure verses Specific Enthalpy curves for sub-critical and trans crtical cycles is shown below.
The process from $1 \longrightarrow 2$ involves the compression in both the cycles. The path $2 \longrightarrow 3$ involves condensation in the sub-critical cycle and gas-cooling in the transcritical cycle. The gas condenses until it turns into its super-cooled liquid state in

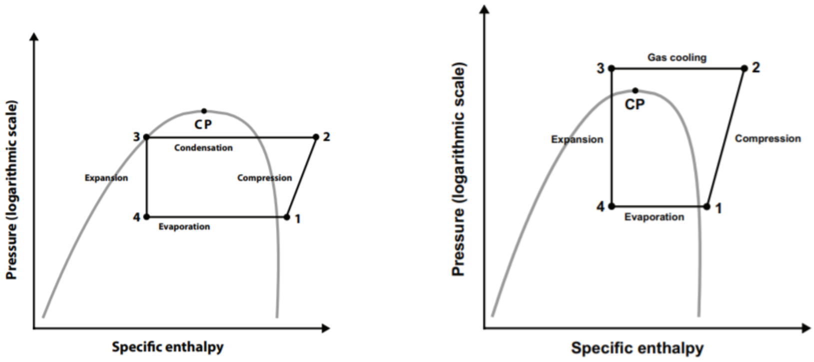


Figure 6: Sub critical and Trans critical cycles

the sub-critical process. After condensation, the gas is expanded in the path 3⟶4 where the gas enters inside the dome for the trans-critical cycle. Finally in the path 4⟶1, the gas gets evaporated to the vapor phase.

Following are the steps involved in CO_2 refrigeration cycle (Necessary thermodynamic values for a typical refrigeration mentioned along with)[6]:

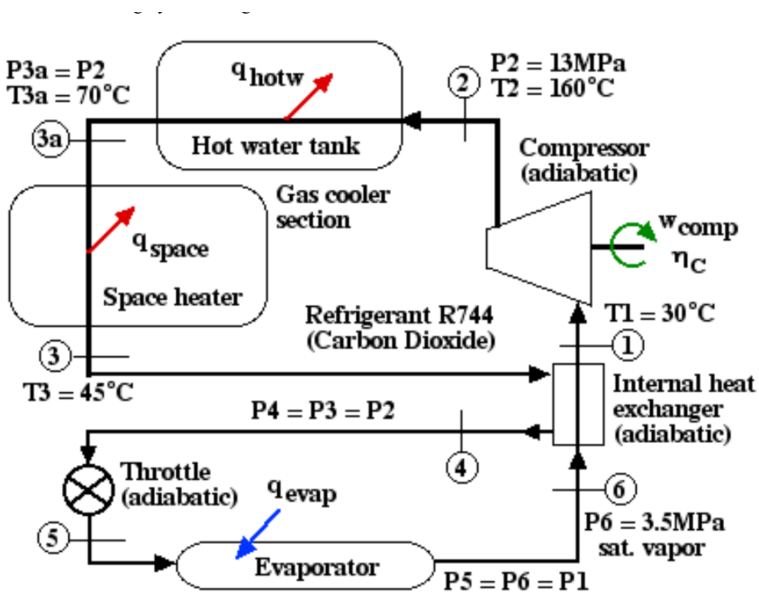


Figure 7: Values of trans-critical cycle of CO_2

1. The evaporator takes up heat from the low-temperature source and supplies

it to the refrigerant. Hence, the liquid-vapor mixture of CO_2 is converted to saturated vapor state.

2. The refrigerant CO2 enters the compressor inlet as saturated vapor at temperature $T_1 = 30°C$ and pressure $P_1 = 3.5MPa$ and exits the compressor outlet at pressure $P_2 = 13MPa$ and temperature $T_1 = 160°C$, well above the critical pressure and the state in the super-critical region.
3. Unlike the condenser in the traditional refrigerants with refrigerant as a HFC where heat rejection to the surroundings implies condensation of the working fluid, there is a high-pressure gas cooler where heat rejection to the surrounding implies the cooling of the gas at a constant pressure above the critical pressure. Here, the CO_2 is cooled to temperature $T_3 = 45°C$.
4. Then CO_2 passes to an internal heat ex-changer, where its temperature reduces below the critical temperature.
5. In the throttler, the gas undergoes iso-enthalpic process, reducing the pressure from $P_4 = 13MPa$ to $P_5 = 3.5MPa$ and also, temperature of the gas reduces to room temperature.

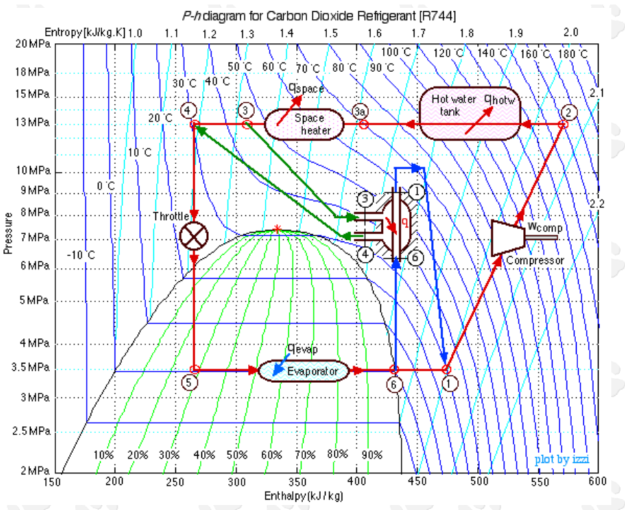


Figure 8: Pressure versus enthalpy for CO_2

5 Design and Engineering of Heat Pump

Heat Pumps are thermodynamic devices which transfers heat from a low temperature medium to a high temperature medium with some work input. Heat pump can be used to maintain the refrigerated place at low temperature by removing heat from it.

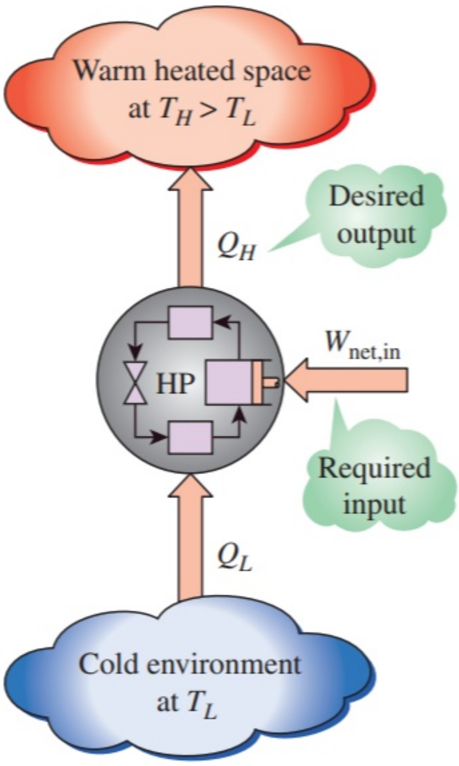


Figure 9: A Schematic diagram of Heat Pump.

The heat pump absorbs heat from a low temperature reservoir like a well or cold air, and supplies this absorbed heat to a high temperature source like a room. To absorb heat from a colder reservoir some necessarily minimal amount of work has to be done on the heat pump.

COP_{HP}, called the Coefficient of Performance ,is used to measure the performance of heat pump
COP_{HP} is defined as

$$COP_{HP} = \frac{\text{Desired Output}}{\text{Required Input}} = \frac{Q_H}{W_{net,in}}$$

$$\therefore COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

Designing of a Transcritical CO_2 system[5]

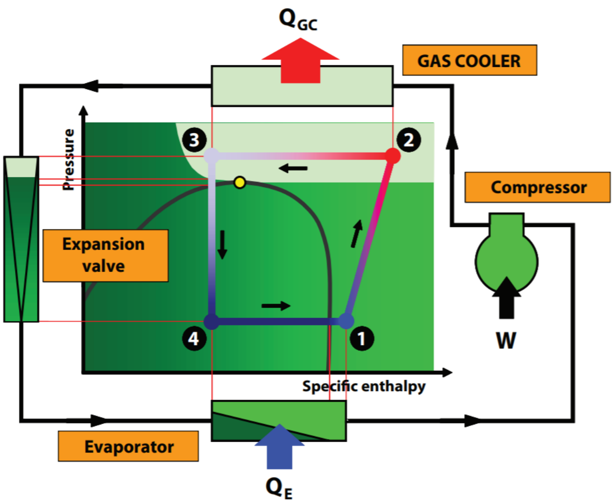


Figure 10: A Schematic diagram of transcritical CO_2 system

There are four main components involved in the trans-critical cycle, i.e., compressor, gas cooler, expansion valve, and evaporator. The gas releases heat Q_{GC}, during the gas cooling process and the power consumption of compressor is W. Q_E is the heat required for the vaporization of the saturated liquid-vapor mixture.Specifying the operating conditions of a transcritical refrigeration cycle is different than those of the subcritical cycle processes. Applying the First Law of Thermodynamics :

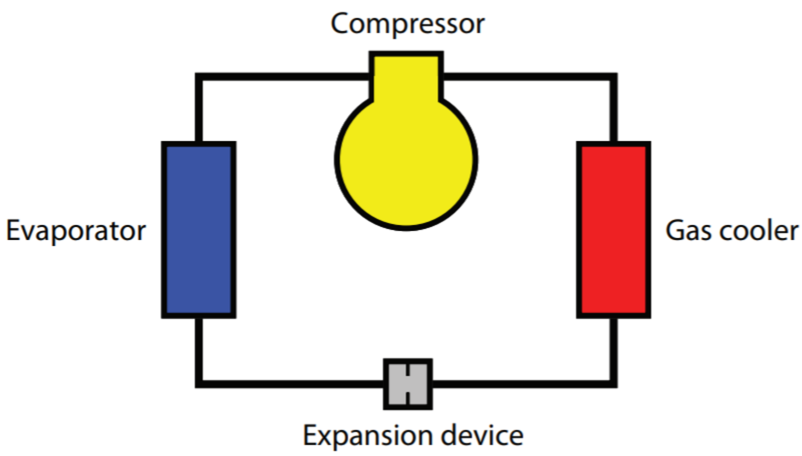
$$\dot{E_{\text{in}}} - \dot{E_{\text{out}}} = \frac{\Delta E_{\text{sys}}}{\Delta t}$$

The system is in a steady state $\implies \frac{\Delta E_{\text{sys}}}{\Delta t} = 0$

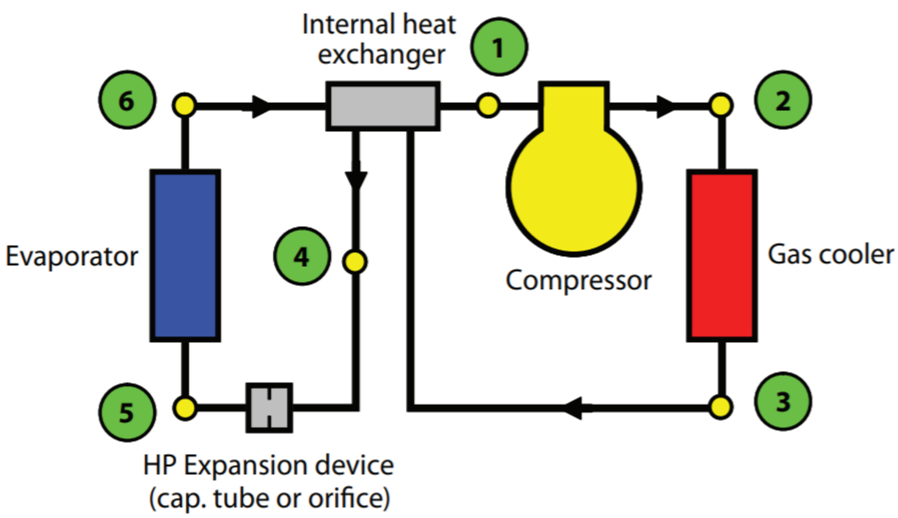
$$\therefore W + Q_E - Q_{\text{GC}} = 0$$

$$\therefore Q_{\text{GC}} = Q_E + W$$

The design of simple refrigeration system for transcritical operation is shown.

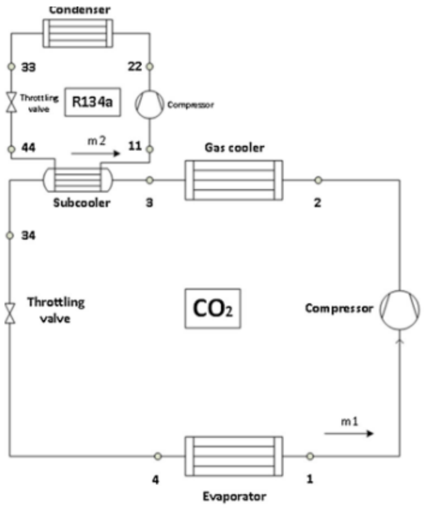


The performance of the simple system can be enhanced by using an internal heat exchanger between the suction line (the part before evaporation) and the gas cooler.



The design shown in the above figure can be used for a system that operates with medium variations in the ambient temperature (generally 25°C), but with requirements for capacity or efficiency at only one fixed rating point.

Another type of design is shown below[8]



The sub-cooler is used to condense the exit CO2 gas from the gas cooler and it is then passed through throttling valve.

Design of Components in Heat Pump :

1. **Compressor**[7]

   Compressor is one of the most important component in Heat Pump. It compresses the refrigerant(here, carbon dioxide) having low pressure and temperature to extreme high temperature and pressure.

   Heat Pump having carbon dioxide as the refrigerant uses "Single Rotary Compressor". In this compressor, the refrigerant is compressed by rotating the piston of the cylinder in compressor and a blade is thrust adjacent to the surface of the piston such that the space in the cylinder is divided into Suction and Pressure. Since carbon dioxide is the refrigerant, the valves and structures are made more rigid and thick, so the compressor can withstand high temperature and pressure.

   Second Law of Thermodynamics states that, heat flow happens from Higher Temperature thermal reservoir to Lower Temperature thermal reservoir. In heat pumps, we make the heat flow from low temperature thermal reservoir to high temperature thermal reservoir. Thus, we provide external work, in the form of electric power. Thus, the compressor makes the refrigerant to absorb heat from low temperature reservoir to high temperature reservoir.

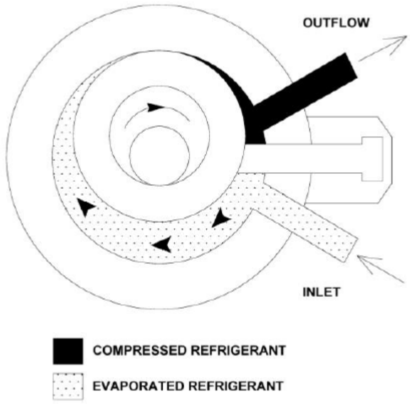


Figure 11: Rotary Compressor

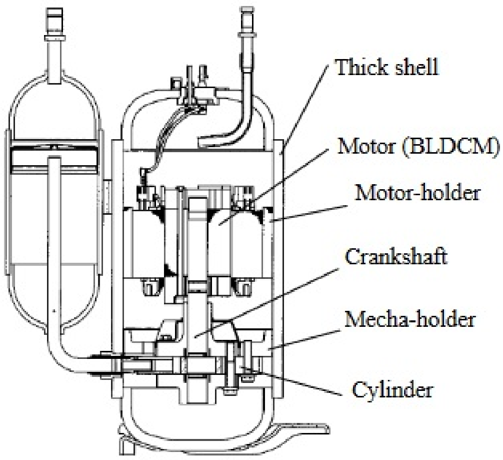
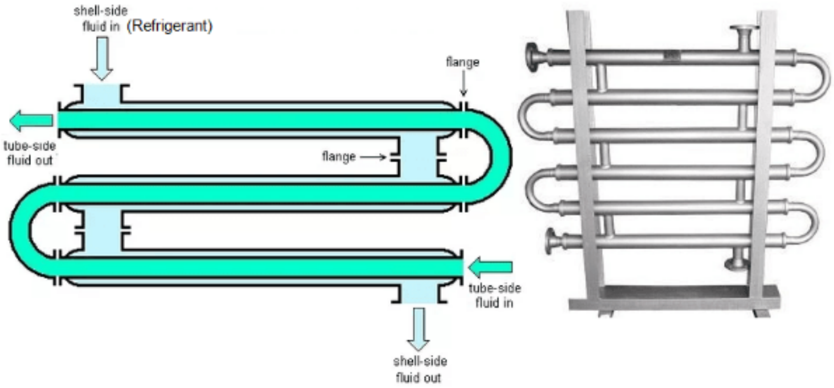


Figure 12: Single Rotary Compressor

Compressor type	Single Rotary
Displacement	4.5cm^3
Refrigerant	R744 (CO2)
Motor	BLDCM (Joint-Lapped Motor)
Usage	HP Water-Heater 4.5kW/6kW

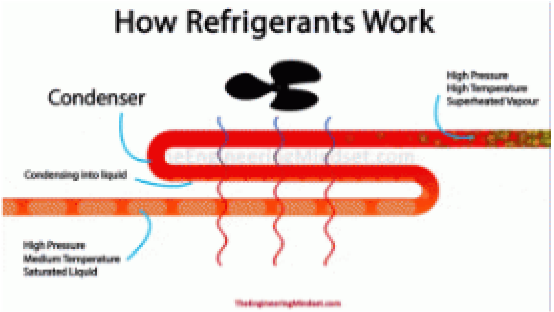
2. **Condenser**[10]

This component of the heat pump produces the heating effect. In practical application, where, heat pumps are used to heat the room, Condensers are placed inside the room, thus heating effect takes place.



Compressors changes the state of the refrigerant(carbon dioxide) to high temperature and pressure, and the refrigerant next passes to Condensers. Condensers are made up of Copper Coils, because Copper is considered to withstand high temperature and pressure for durable time. Refrigerant, thus makes the copper become very hot. Heated Copper, thus emits heat outside of the cycle to the room.Condensers carry a fan with it, thus absorbs or sucks the room air. Here, Condensers are classified based on the type of fan being used in it.

By First law of Thermodynamics, Heated Copper transfers the heat to the room air, and then the air is made to flow back to the room. Thus the room becomes hot. Since the heat is lost by the copper and refrigerant, their temperature decreases and the refrigerant tends to exist in a gaseous state.



3. **ExpansionValve**[11]

This component reduces the pressure of the refrigerant(carbon dioxide). Since the pressure reduces suddenly, there is a sudden reduction in temperature also. In heat pumps copper capillary tube is used as the expansion valve. Refrigerant at the exit of expansion valve, has the least temperature and pressure and also exists in semi liquid and gaseous state.

4. **Evaporator**[11]

Unlike the air conditioners, the evaporator of the heat pump is located outside the room and is exposed to the atmosphere (low temperature reservoir). The evaporator is also made with the material used to make condenser, i.e. copper.

The refrigerant, which is at low pressure and low temperature enters the evaporator. This results in the temperature of the refrigerant getting even lower than the atmospheric temperature. The refrigerant absorbs heat from the atmosphere as its temperature is lower than it. The blower blows atmospheric air into the evaporator to heat the refrigerant. As a result, the temperature of the refrigerant increases. However, the pressure remains constant and consequently, the refrigerant is converted to its gaseous state.