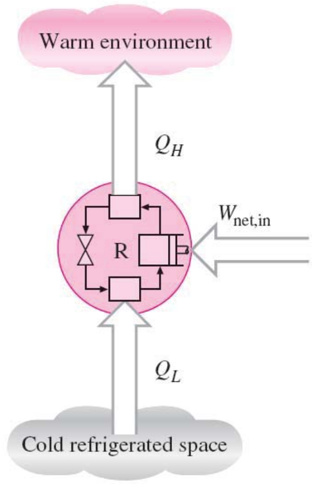
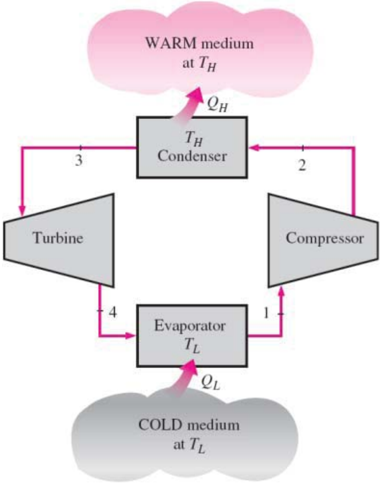
Vapour compression cycle

Refrigeration in the engineering sense, means maintaining a system at a temperature less than the temperature of the surroundings. This will not occur naturally, so a device must be developed that will maintain this condition. A reversed **Carnot** engine will removed heat from a low temperature reservoir and deliver this energy, plus work necessary to transfer the heat, to high temperature reservoir. The refrigerated system in this case is the low temperature reservoir.



Reversed Carnot Cycle There are two types of reversed **Carnot** cycle ; the first is:
1-Refrigeration **Carnot** cycle: in which the heat is absorbed from the cold reservoir and rejected to the hot reservoir.



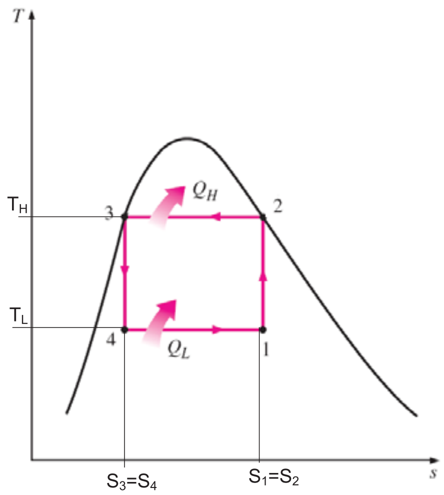
Processes of Refrigeration Carnot cycle

1-2 heat input to the compressor to compress dry saturated vapour, rising its pressure and temperature to dry or superheated condition.

2-3 heat rejected from the vapour to the ambient, changing the dry, or superheated vapour to saturated liquid.

3-4 throttling the saturated liquid (expansion) changing it to wet vapour.

1-4 heat absorbed from cold reservoir, changing the wet vapour of low quality to wet steam of high quality.



Work input (process 1-2)= $Q_H - Q_L$
Heat rejected (process 2-3) $Q_H = T_H(S_2 - S_3)$
Heat absorbed (process2-1) $Q_L = T_L(S_1 - S_4)$
Since S3=S4 & S2=S1 $Q_L = T_L(S_2 - S$

Coefficient Of Performance (COP)

The performance ratio of refrigeration system is not the efficiency, but rather the **C**oefficient **O**f **P**erformance, and define as the refrigeration effect (heat absorbed) divided by the net work done on the cycle(work input):

$$COP = \frac{QL}{W} = \frac{T_L(S_2 - S_3)}{T_H(S_2 - S_3) - T_L(S_2 - S_3)} = \frac{T_L}{T_H - T_L}$$

$$COP = \frac{T_L}{T_H - T_L}$$

It is more suitable to change the names of the processes of the reversed Carnot cycle to:

Heat absorbed	to	**Refrigeration effect**	Q_L	=	$T_L(S_2\text{-}S_3)$
Heat rejected	to	**Heat rejected from the condenser**	Q_H	=	$T_H(S_2\text{-}S_3)$
Work input	to	**Work input to compressor**	W	=	$Q_H\text{-}Q_L$

Example 1

A refrigerator has working temperature in the evaporator and condenser of -30°C and 32°C respectively, what is the maximum COP possible?, if the actual COP of 0.75 of the maximum COP, calculate the refrigeration effect in kW per kW of power input.

$$COP = \frac{TL}{TH - TL} = \frac{-30 + 273}{32 - (-30)} = 3.91$$

$$actual\ COP_r = 0.75 \times 3.91 = 2.939$$

$$COP_r = \frac{QL}{W}$$

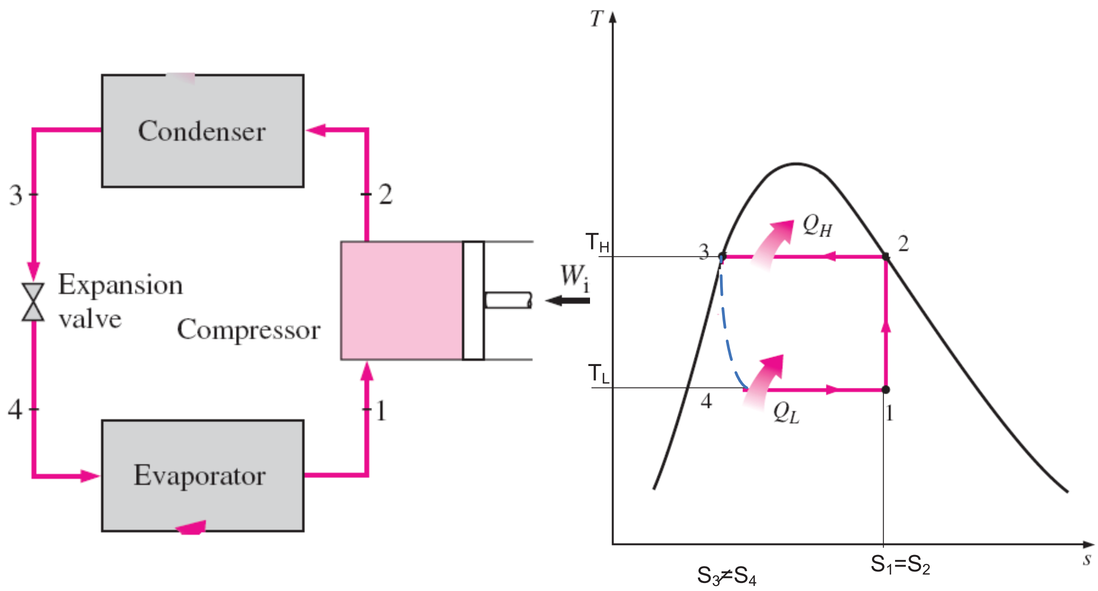
$$2.939 = \frac{QL}{1}$$

$$QL = 2.939\ kW_{of\ refrigeratin} / kW_{of\ work\ input}$$

Modifications to the ideal refrigeration cycle

a- Replacement of the expansion engine by a throttle valve.

The plant is simplified by placing the expansion engine by a simple expansion valve. The process is highly irreversible so that the whole cycle becomes irreversible. The process is representing by the dotted line 3-4 on the figure. The refrigeration effect $Q_L = T_1(S_1 - S_2)$ is reduced by using the expansion valve.



b- Condition at the compressor inlet

To make complete use of the latent heat of the refrigerant in the evaporator it is desirable to continue the process until the vapour is dry saturated.

In practical unit this process is extended to give the vapour a define amount of superheat as it leaves the evaporator. This really undesirable, since the work to be done by the compressor is increased. It is a practical necessity to allow the refrigerant to become superheated in this way in order to prevent the carry-over of liquid refrigerant into the compressor, where it interferes with the lubrication.

c- under-cooling of the condensed vapour

The condensed vapour can be cooled at constant pressure to a temperature below that of the saturation temperature corresponding to the condenser pressure. The effect of sub-cooling can increase the refrigeration effect.

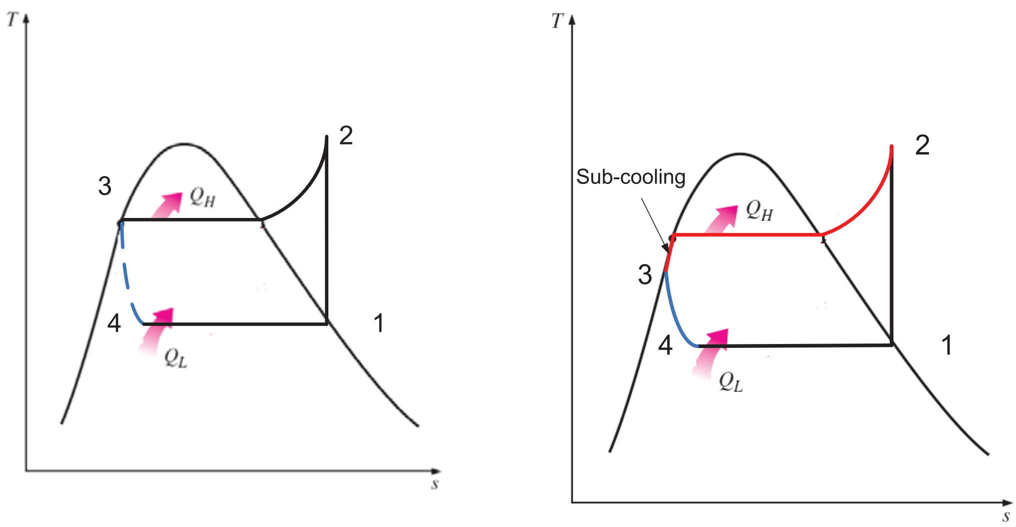


figure b Evaporation process Figure c sub-cooling process

Ideal cycle

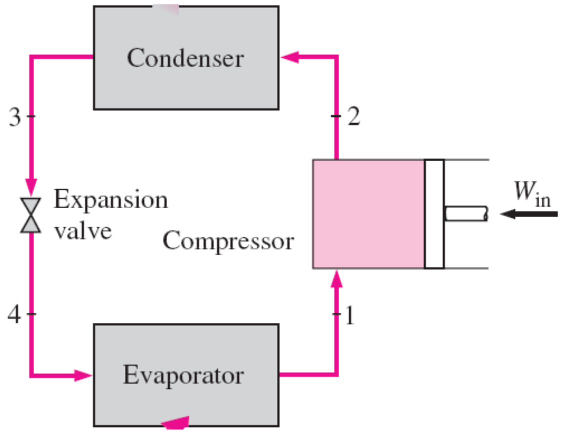
The figure bellow shows the ideal cycle schematically on a p-h diagram. We call this cycle is ideal cycle since pressure and temperature drops are ignored, superheating in the evaporator and sub-cooling in the condenser that are present in real equipment are ignored, and compressor in fluencies are omitted

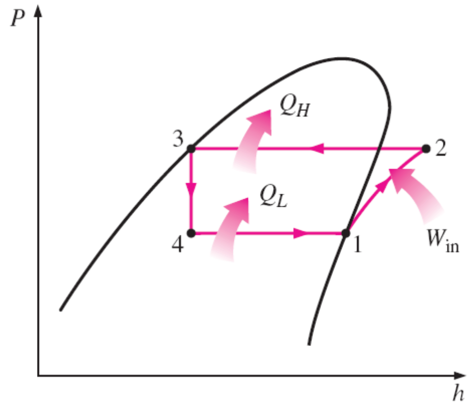
<u>Concept Development</u>

All vapour compression refrigeration system are designed and built around these basic thermodynamics principles.

1. fluid absorb heat while changing from a liquid phase to vapour phase and give up heat in changing from vapour phase to a liquid phase.
2. the temperature at which a change of phase occurs is constant during the change, but this temperature will vary with the pressure. At one fixed pressure vaporization take place only at fixed corresponding temperature. Whoever, the temperature of vaporization at a practical pressure, are different for different fluids.
3. heat will flow from body at higher temperature to a body at lower temperature.
4. in selection metallic parts of cooling and condensation units metal are selected which have a high heat conductivity.

5. heat energy and other forms of energy are mutually convertible with directional relationship imposed by the second law of thermodynamics.





The cycle consists of number of flow process and can be analyzed by the application of steady flow energy equation:

1- *Compression process (1-2):*

Process 1-2 take place in the compressor as the pressure of the vapour is increased by compression from the vaporizing pressure to the condensation pressure. For simple saturated cycle the compression is assumed isentropic. Hence the steady flow energy equation is

$$gz_1 + \frac{C_1^2}{2} + h_1 + Q = gz_2 + \frac{C_2^2}{2} + h_2 + W_{comp}$$

$$z_1 \approx z_2 \qquad Q = 0 \text{ isentropic} \quad C_2 \approx C_1$$

$$W_{comp} = h_2 - h_1$$

2- *Condensation process (2-3)*

Usually the process $2 - \bar{2}$ and $\bar{2} - 3$ take place in the condenser as the hot gas discharged from the compressor is cooled to the condensation temperature. During process $2 - \bar{2} - 3$ the pressure of the vapour remains constant. At point $\bar{2}$ the refrigerant is saturated vapour at condensation temperature and pressure. Process $2 - \bar{2}$ takes place at constant pressure, while process $\bar{2} - 3$ takes place at constant pressure and temperature. The condensation is assumed to be at constant pressure

$$gz_2 + \frac{C_2^2}{2} + h_2 + Q_{cond} = gz_3 + \frac{C_3^2}{2} + h_3 + W$$

$$z_3 \approx z_2 \qquad W = 0\, C_3 \approx C_1$$

$$Q_{cond} = h_2 - h_3$$

3- *Expansion process:*

The process described by initial and final state points 3-4 occur in the throttling valve when the pressure of the liquid is reduced from condensation pressure to evaporation pressure as the liquid passes through the throttle expansion valve. This process is throttling type adiabatic expansion in which enthalpy of working substance remains the same.

The expansion is assumed to be adiabatic process i.e $h_3 = h_4$

4- *Evaporation process:*

The process 4-1 is the evaporation process at evaporator pressure and temperature. In this process both pressure and temperature are remain constant for simple saturated ideal cycle.

The evaporation process is assumed to be at constant pressure

$$gz_4 + \frac{C_4^2}{2} + h_4 + Q_{evap} = gz_1 + \frac{C_1^2}{2} + h_1 + W$$

$$z_1 \approx z_4 \qquad W = 0 \; C_4 \approx C_1$$

$$Q_{evap} = h_4 - h_1$$

Then the equations related the case above can be writing as follow:

Work input to compressor $\mathbf{w_c = h_2 - h_1}$

Refrigeration effect $\mathbf{(Q_{evap}) = h_1 - h_4}$

Heat rejection from condenser $\mathbf{Q_{cond.} = h_2 - h_3}$

Coefficient of Performance **(COP)=** $\frac{Q_{evap}}{W_{comp}} = \frac{h_1 - h_4}{h_2 - h_1}$

h1= hg at condenser pressure or temperature

h2=h $_{superheated}$ at compressor pressure and temperature

h3= h$_f$ at condenser pressure and temperature

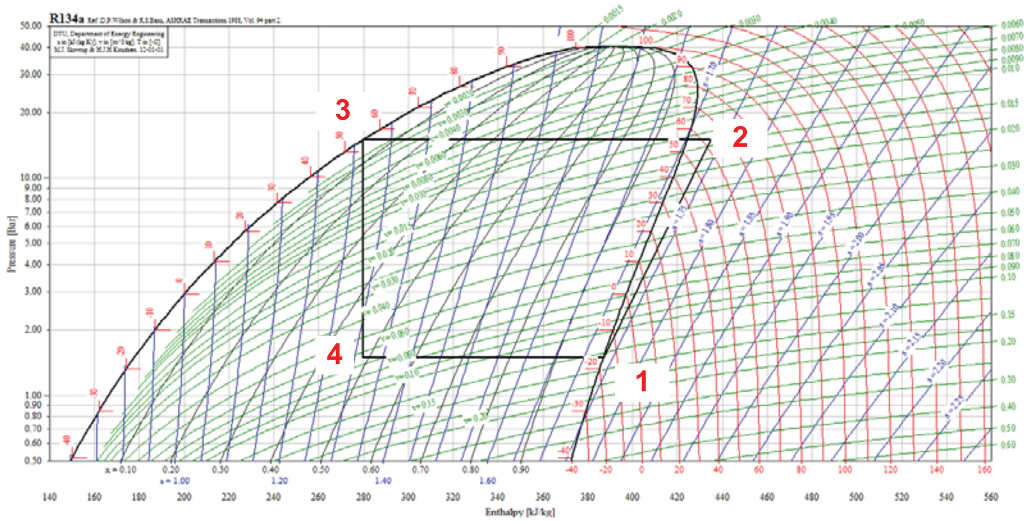
h3=h4

to find the dryness fraction at evaporator enter can be found as follow:

$h_3 = h_4 = hf + x_4 . h_{fg}$ ***at evaporator pressure or temperature***

Example 2

A refrigerator cycle uses refrigerant R-134a and operates between a low-side pressure of 0.15Mpa and high side of 1Mpa. The refrigerant mass flow rate is 0.05kg/s. find the cooling effect, work input, and COP of this machine.



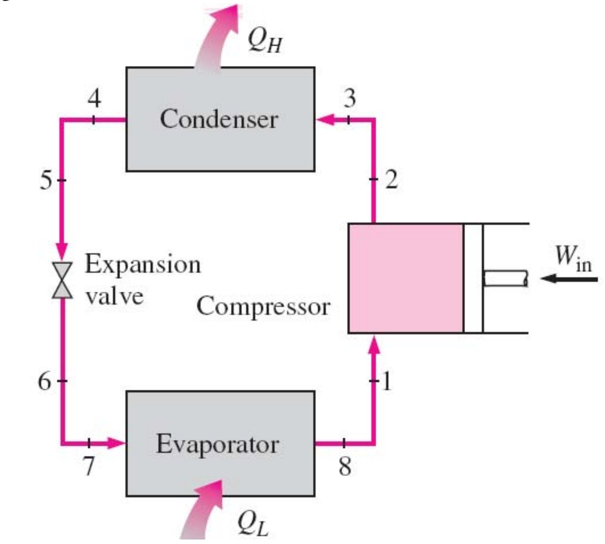
from the p-h diagram we can find the enthalpies at each point as follow:

Point	P Mpa	T °C	h kJ/kg	S kJ/kg K
1	0.15	-17.2	387	1.73
2	1	63	434	1.73
3	1	55	279	--
4	0.15	-17	279	--

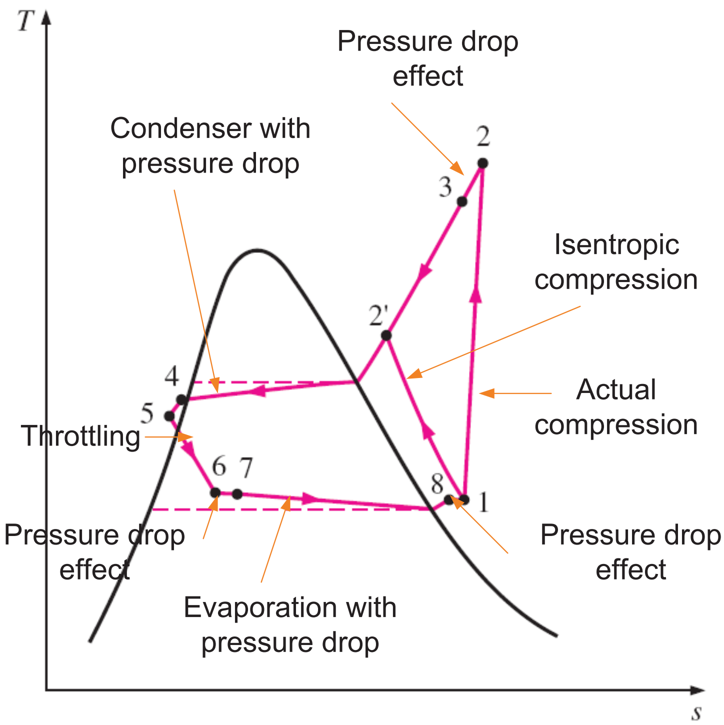
Work input to compressor $w_c = h_2 - h_1 = 434 - 387 = 47$ kJ/kg
Power input to the compressor=m(h2-h1)=0.05(434-387)=2.35kW
Refrigeration effect (Q_{evap})= $h_1 - h_4 = 387 - 279 = 108$kJ/kg
Refrigeration effect in kW=m(h1-h4)=0.05(387-279)=5.4kW

(COP)= $\frac{Q_{evap}}{W_{comp}} = \frac{108}{47} = 2.29$

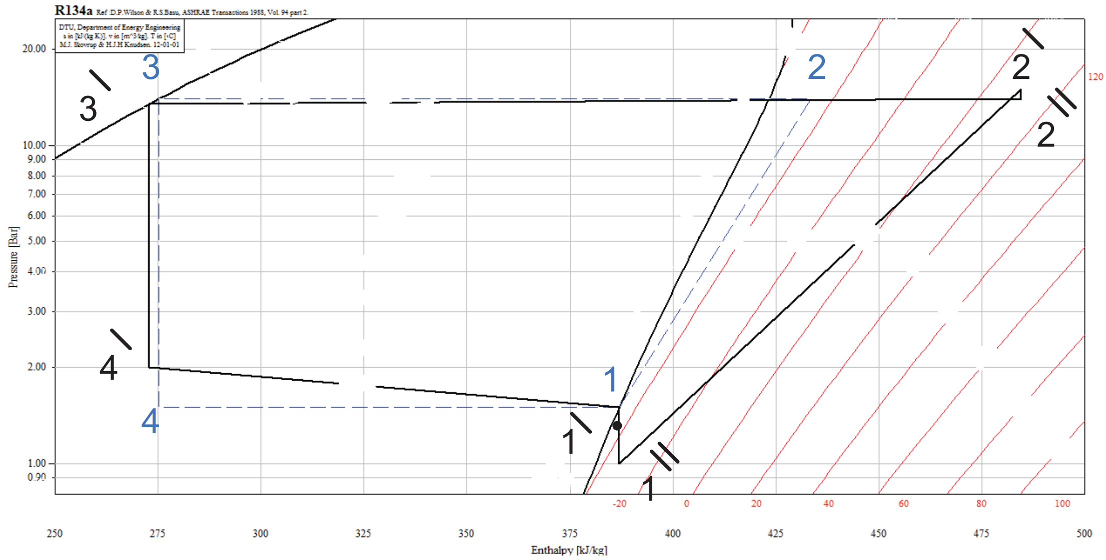
Real Cycle Analysis



Real cycle equipment with typical R22 operating temperatures and pressures



T-s diagram of actual VC cycle



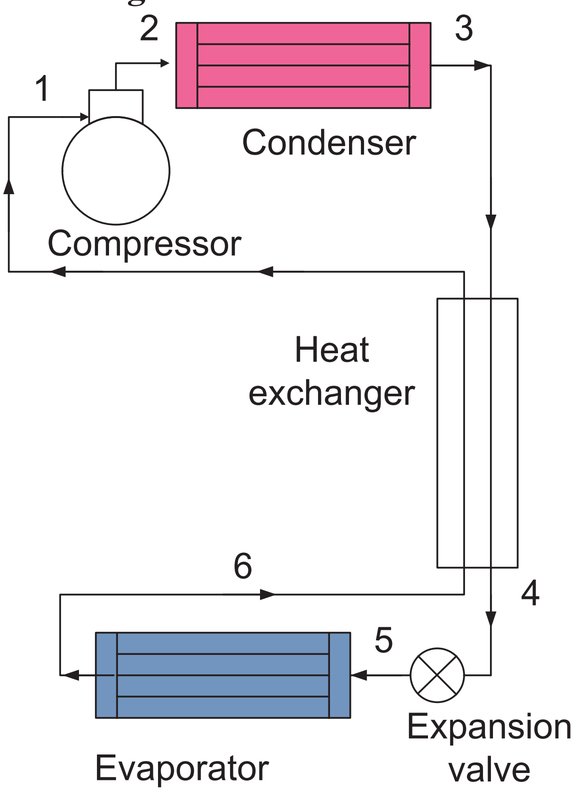
The effect of pressure loss in real cycle:

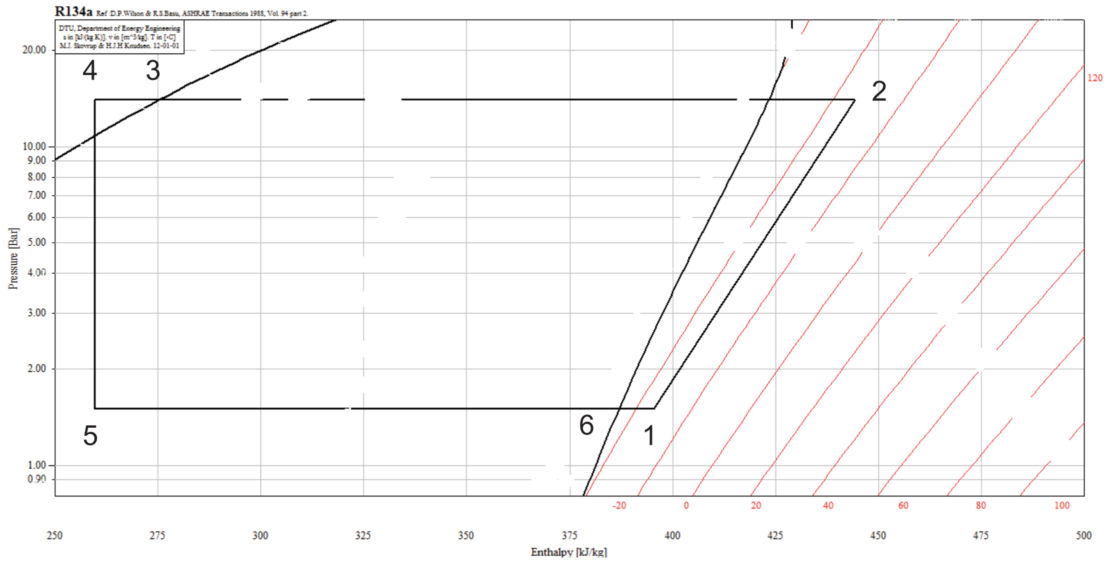
During the flow of the refrigerant through the piping, evaporator, condenser receiver, valves and pipe lines, there is pressure drop due to internal fluid friction. The figure shows a p-h representation of an actual cycle with pressure drops occurring in various components.

1. The line $4' - 1$ Vaporization process in the evaporator and the refrigerant during its flow drop in pressure.
2. $1 \rightarrow \bar{1}$ Pressure drop in the suction vapour through the suction line from evaporator to compressor. This loss in pressure increases the volume of vapour compressed per ton and horse power per ton.
3. $\bar{1} \rightarrow \bar{\bar{1}}$ Pressure drop of refrigerant vapour flow through the suction valve of compressor. The effect of this pressure drop is similar to that at suction line.
4. $\bar{\bar{1}} \rightarrow \bar{2}$ Compression process for the cycle with a pressure drop. Thus the vapour has to be compressed to a pressure much above that required for simple saturated cycle.
5. $\bar{2} \rightarrow \bar{\bar{2}}$ Pressure drop in the discharge valves of the compressor.
6. $\bar{\bar{2}} \rightarrow \bar{3}$ Condensation process and the pressure drop in the condenser piping.
7. $\bar{3} \rightarrow \bar{4}$ Expansion process by expansion device.

the dotted lines represent the ideal vapour compression cycle

The effect of heat exchangers:



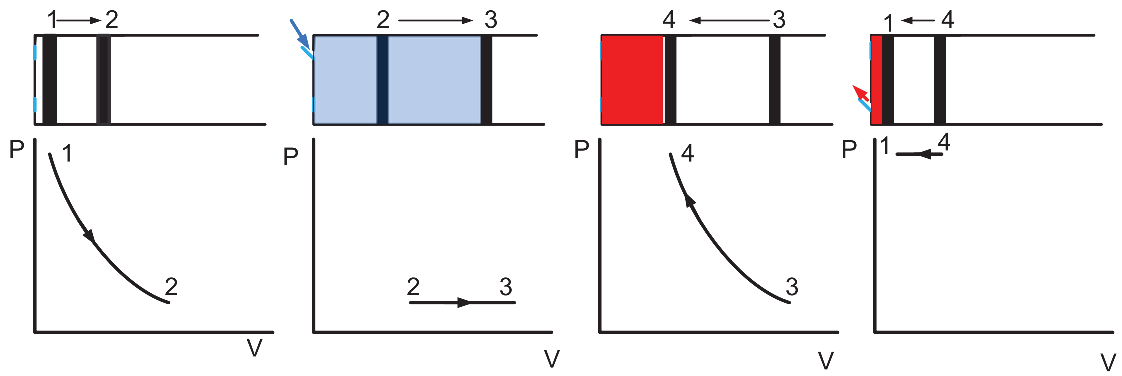


Some refrigeration cycles use a liquid to suction heat exchanger , which sub-cool the liquid from condenser with suction vapour coming from the evaporator. Saturated liquid at point 3 coming from condenser is cooled to point 4 by means of vapour at point 6 being heated to point 1. from the heat balance : $h_3 - h_4 = h_1 - h_6$ the refrigeration effect is either $h_6 - h_5$ *or* $h_1 - h_5$. The system use heat exchanger may seem to have obvious advantages because the increased refrigeration effect. Both capacity and COP may seemed to improved. This is not necessarily true, however. Even thought the refrigeration effect is increased, the compression is pushed farther out into the superheat region, where the work of compression in kJ/kg is greater than it is close the saturated vapour. The heat exchanger is important because of two reasons:

1. The vapour entering the compressor must be superheated to ensure that no liquid enters the compressor.
2. to sub cool the liquid from condenser to prevent bubbles of vapour from impeding the flow of refrigerant though the expansion valve.

Compressor capacity

The capacity of the compressor is ***the compressor swept volume per unit time***, while, the volumetric efficiency (η_{vol}) of the compressor is ***the actual of the sucked gas to the*** theoretical piston displacement. And clearance volumetric efficiency is the ***volumetric efficiency of the compressor when the clearance volume of the compressor is included.***



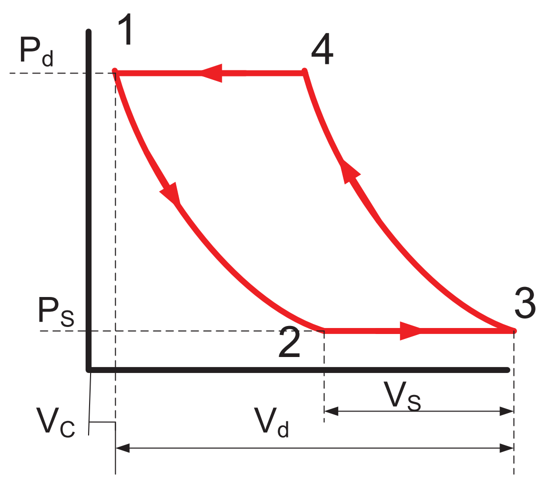
Suction of gas	***Counties suction of gas***	***Compression of gas***	***Compressed of gas***
$PV^{\gamma} = C$	P=C	$PV^{\gamma} = C$	P=C

Vc: Clearance volume=V_1
Vd: Discharge volume (V_3-V_1)
Vs: Sucked volume theoretical (V_3-V_2)

C: Clearance index $= \dfrac{Vc}{Vd} = \dfrac{V_1}{V_3 - V_1}$

$$\eta_{cv} = \frac{Vs}{Vd} = \frac{V_3 - V_2}{V_3 - V_1}$$

V_2 Cannot be measured



$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}} = V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

$$\eta_{cv} = \frac{V_3 - V_2}{V_3 - V_1} = \frac{V_3 - V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}}{V_3 - V_1}$$

$$\eta_{cv} = \frac{V_3 - V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}} - V_1 + V_1}{V_3 - V_1}$$

$$\eta_{cv} = \frac{V_3 - V_1 - V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}} + V_1}{V_3 - V_1}$$

$$\eta_{cv} = \frac{V_3 - V_1}{V_3 - V_1} + \frac{V_1}{V_3 - V_1} - \frac{V_1}{V_3 - V_1}\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

$$\eta_{cv} = 1 + C - C\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

$$where \quad C = \frac{V_1}{V_3 - V_1}$$

$$\sin ce \quad \frac{Vs}{Vd} = \left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

then

$$\eta_{cv} = 1 + C - C\frac{Vs}{Vd}$$

$$V_2 = V_1\frac{P_d}{P_s}$$

$$\eta_{cv} = 1 + C - C\frac{P_d}{P_s}$$

If the compression process is done at constant temperature then the clearance volume can be written as:

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}} = V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

$$\eta_{cv} = \frac{V_3 - V_2}{V_3 - V_1} = \frac{V_3 - V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}}{V_3 - V_1}$$

$$\eta_{cv} = \frac{V_3 - V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}} - V_1 + V_1}{V_3 - V_1}$$

$$\eta_{cv} = \frac{V_3 - V_1 - V_1\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}} + V_1}{V_3 - V_1}$$

$$\eta_{cv} = \frac{V_3 - V_1}{V_3 - V_1} + \frac{V_1}{V_3 - V_1} - \frac{V_1}{V_3 - V_1}\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

$$\eta_{cv} = 1 + C - C\left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

$$where \quad C = \frac{V_1}{V_3 - V_1}$$

$$\sin ce \quad \frac{Vs}{Vd} = \left(\frac{P_d}{P_s}\right)^{\frac{1}{\gamma}}$$

then

$$\eta_{cv} = 1 + C - C\frac{Vs}{Vd}$$

$$V_2 = V_1\frac{P_d}{P_s}$$

$$\eta_{cv} = 1 + C - C\frac{P_d}{P_s}$$

Piston displacement (V_D)of compressor can be calculated as :

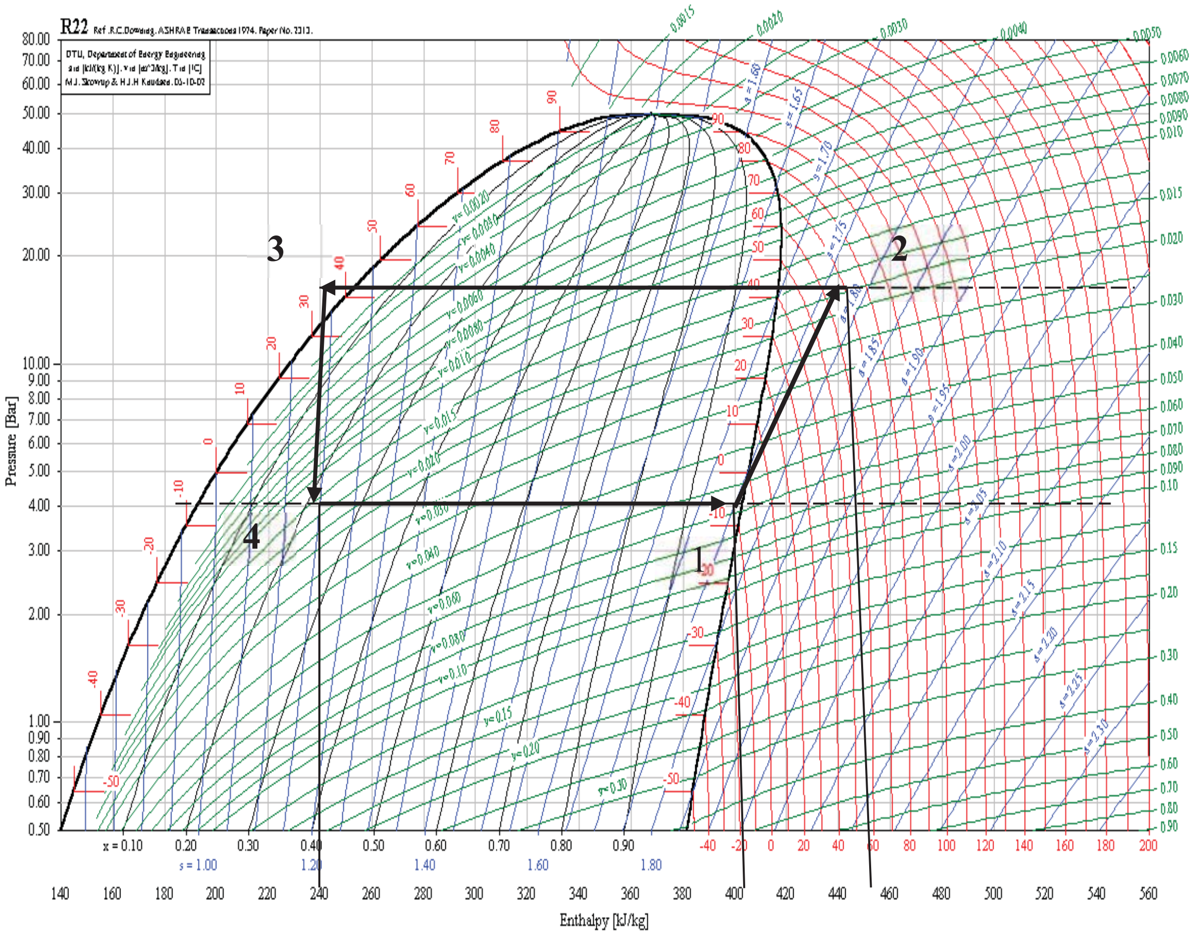
$$V_D = No.\frac{\pi.d^2}{4}.l.\frac{rpm}{60}$$

V_D	Piston displacement	m^3/s
No.	Number of cylinder in the compressor	-----
d	Piston diameter	m
l	Piston stroke	m
rpm	Revelation per min.	1/min.

Examples

Example 2:

A standard vapour compression cycle developed 50 kW of refrigeration using R-22 operates with condensing temperature of 35°C and evaporation temperature of (-10 °C). Calculate a-the refrigeration effect in kJ/kg b- the mass flow rate of refrigerant c-the power required for compression d-COP e- power per kW of refrigeration f-discharge temperature.



h1=hg=401 kJ/kg h2=$h_{super\ heated}$=435kJ/kg h3=h4=hf=243kJ/kg

a- Refrigeration effect= Qevap=(h1-h4)=401-243=158kJ/kg

b- mass flow rate of refrigerant:

Cycle Capacity $= \dot{m}(h1 - h4)$

$$\dot{m} = \frac{50}{158} = 0.316 kg/s$$

c- power required for compression P= $\dot{m}(h2-h1)=0.316(435-401)=10.744kW$

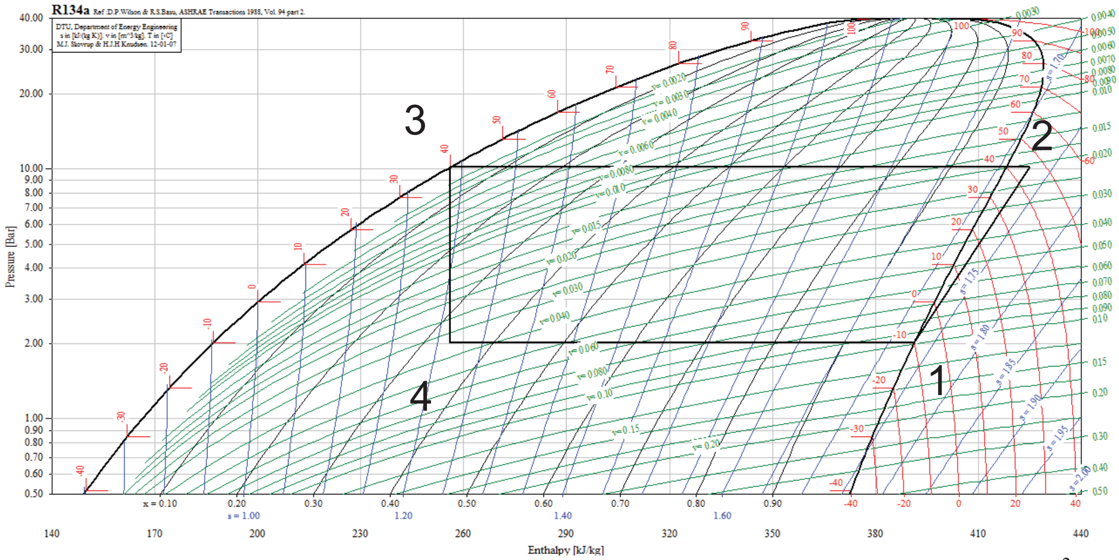
d- $COP=\dfrac{Qevap}{Wcomp}=\dfrac{h1-h4}{h2-h1}=\dfrac{401-234}{435-401}=4.911$

e- power per kW of refrigeration= $\dfrac{1}{COP}=\dfrac{1}{4.911}0.203kW/kWrefrig.$

f- discharge temperature. $= T_2 = 60^oC$

Example3

A two cylinder Freon 134a compressor has a bore and stroke of 5.65 cm and 5 cm respectively. It is speed is 1450 rpm and 100% volumetric efficiency. If the liquid reached the expansion valve at 40 ^oC saturated. Find the mass flow rate of the refrigerant and refrigeration capacity when the suction temperature is (-10 ^oC). How will be the result if the clearance index is 4%.



h1=hg=391 kJ/kg h2=424 kJ/kg h3=hf=256 kJ/kg v_1=0.098 m^3/kg, v_2=0.02 m^3/kg

$$Displacement\ volume=\eta_{cv}=1+C-C\frac{Vs}{Vd}=2\times\frac{\pi(5.65\times10^{-2})}{4}\times5\times10^{-2}\times\frac{1450}{60}\times1=5.95\times10^{-3}\,m^3/s$$

$$\dot{m}=\frac{V_D}{v_1}=\frac{5.95\times10^{-3}}{0.098}=0.06\quad kg/s$$

$$capacity=\dot{m}(h1-h4)=0.06\times(391-256)=8.1\ kW$$

b

$$\eta_{cv}=1+C-C\frac{vs}{vd}=1+0.04-0.04\frac{0.098}{0.02}=0.844$$

$$VD_2=VD_1=5.95\times10^{-3}\times0.844=5.338\times10^{-3}=5.02x10^{-3}\,m^3/s$$

$$mf=\dot{m}=\frac{V_D}{v_1}=\frac{5.02\times10^{-3}}{0.098}=0.0512\ kg/s$$

$$capacity=\dot{m}(h1-h4)=0.0512\times(391-256)=6.91\ kW$$

Sheet No. Three

1. *the temperature in evaporator coil is -6 ^oC and that in the condenser coil is 22 ^oC. assuming that the machine operates on the reversed Carnot cycle. Calculate the COP the refrigeration effect per kW of input work, and the heat rejected to the condenser. (9.54;9.54kW;10.4kW)*
2. *a Carnot refrigeration cycle absorbs heat at (-12 ^oC) and rejects it at 40 ^oC a- calculate the COP of this cycle d- If the cycle is absorbing 15 kW at (-12 ^oC) temperature, how much power is required. C- if the Carnot heat pump operates between the same temperature, what is the performance factor d- what is the rate of heat rejection at 40 ^oC if the heat pump absorbs 15 kW at the (-12 ^oC) temperature. (18kW)*
3. *in a standard vapour compression cycle using R-22 the evaporation temperature is (-5 ^oC) and the condensing temperature is 30 ^oC, calculate a-the work of compression b- the refrigeration effect c-the heat rejected in the condenser d- COP (6.47)*
4. *a refrigeration system using R-22 is to have a refrigerating capacity of 80 kW. The cycle is standard vapour compression cycle in which the evaporation temperature is (-8 ^oC) and the condensing temperature 42 ^oC a- determine the volume flow of refrigerant measured in cubic meter per second at the inlet to the compressor. B- calculate the power required by the compressor. C-at the entrance to the evaporator what is the fraction of vapour in the mixture expressed both on mass basis and volume basis(0.292,0.971)*
5. *a refrigerant R-22 vapour compression system includes a liquid to suction heat exchanger in the system. The heat exchanger warms saturated vapour coming from evaporator from (-10 ^oC) to 5 ^oC with liquid which comes from the condenser at 30 ^oC. the compression are isentropic in both cases below. A – calculate the COP of the system without the heat exchanger but with condensing temperature at 30 ^oC and evaporator temperature of (-10 ^oC)(5.46) b- calculate the COP with the heat exchanger (5.37) c- if the compressor is capable of pumping 12 lit/s measured at the compressor suction, what is the refrigeration capacity of the system without heat exchanger and with heat exchanger(30.3kW, 29.9kW)*
6. *calculate the displacement of a compressor having 176kW capacity if the refrigeration effect is 1097kJ/kg and the volume of the suction gas is 0.2675 m^3/kg. Assuming a volumetric efficiency of 75%, what cylinder size will be need if the speed is to be 25rps and there are 6 cylinders with equal bore and stroke (0.0429m^3/s and 78.6 mm)*
7. *a four cylinder 75 mm bore and 75 mm stroke compressor run at 25 rps and has a volumetric efficiency of 75%. If the volume of the suction gas is 0.248 m3/s and the machine has operating efficiency of 75%, what power will required on simple saturation cycle when difference between enthalpies of the suction and discharge gases is 150kJ/kg. If the refrigeration effect is 1087 kJ/kg what is the output in kW of refrigeration. State the COP .(20Kw, 108.7kW,COP=7.25)*

8. *an ammonia vapour compressor refrigerator has a single acting stage, single acting reciprocating compressor which has a bore of 127 mm, a stroke of 152 mm and speed 240 rpm. The pressure in the evaporator is 1.6 bar and that in condenser is 13.9 bar. The volumetric efficiency of the compressor is 80% and mechanical efficiency is 90%. The vapour is dry saturated on leaving evaporator and liquid leaves the condenser at 32 ^oC. calculate the mass flow rate of the refrigerant and the power ideally required to drive the compressor(0.502 kg/min, 9.04 kW, 2.73 kw)*
9. *the air conditioning in a car uses R-134 a when the power input to the compressor is 1.5kW, bringing the R-134a from 202 kPa to 1200 kPa by compressor. The cold space is heat exchanger that cool atmospheric air from outside down ti 10 ^oC and blow it into the car. What is the mass flow rate of the refrigerant and what is the low temperature heat transfer. How much is the mass flow rate of air at 10 ^oC.*
10. *a small heat pump unit is used to heat water. Assume that the unit uses R-22. the evaporator temperature is 15 ^oC and the condenser temperature is 40 ^oC. if the amount of hot water need is 0.1 kg/s. determine the amount of energy saved by using the heat pump instead of direct heating the water from 15 to 40^oC.*
11. *a heat pump using R-717 as a refrigerant operates between saturated temperature of 6 ^oC and 38 ^oC. the refrigerant is compressed isentropically from dry saturated and there is 6 K of under cooling in the condenser. Calculate P.F and the mass flow rate of refrigerant and the heat available per kW input. (8.8, 25.065 kg/hr, 8.8kW)*