## Refrigeration and liquefaction:

Refrigeration is best known for its use in the air conditioning of buildings and in the treatment, transportation, and preservation of foods and beverages. It also finds large scale Industrial application, for example, in the manufacture of ice and the dehydration of gases. Applications in the petroleum industry include lubricating-oil purification, low temperature reactions, and separation of volatile hydrocarbons.

A closely related process is gas liquefaction, which has important commercial applications.

The purpose of this chapter is to present a thermodynamic analysis of refrigeration and liquefaction processes. However, the details of equipment design are left to specialized books. The word refrigeration implies the maintenance of a temperature below that of the surroundings. This requires continuous absorption of heat at a low temperature level, usually accomplished by evaporation of a liquid in a steady-state flow process. The vapour formed may be returned to its original liquid state for re-evaporation in either of two ways. Most commonly, it is simply compressed and then condensed. Alternatively, it may be absorbed by a liquid of low volatility, from which it is subsequently evaporated at higher pressure.

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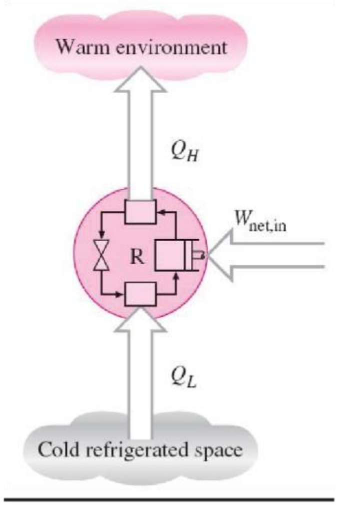
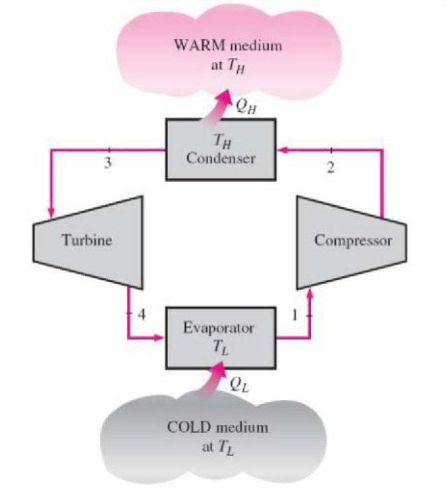
## Vapour Compression Cycle

**Refrigeration**, in the engineering sense, is the process of maintaining a system or space at a temperature lower than that of the surrounding environment. Since heat naturally flows from a region of higher temperature to a region of lower temperature, this condition cannot occur naturally without external work. Therefore, a device operating on a reversed thermodynamic cycle is required to remove heat from a low-temperature reservoir and transfer it to a high-temperature reservoir.



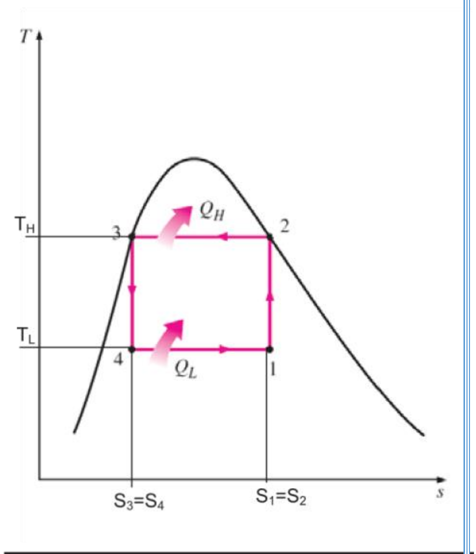
There are two main types of reversed thermodynamic cycles used in refrigeration systems. The first is the **reversed Carnot cycle**, which represents the ideal refrigeration cycle and serves as a theoretical standard for performance comparison. The second, and most practical one, is the **vapour-compression refrigeration cycle**, in which heat is absorbed from the cold reservoir in the evaporator and rejected to the surroundings at a higher temperature in the condenser.



## The process of vapour-compression refrigeration cycle:

The refrigerant undergoes four basic processes:

**1-2**: In the compressor, the refrigerant vapour is compressed, which increases its pressure and temperature.



**2-3**: In the condenser, the high-pressure vapour rejects heat to the surroundings and condenses into a saturated liquid.

**3-4**: The liquid refrigerant passes through an expansion valve where its pressure is reduced in a throttling process.

**4-1**: Finally, in the evaporator, the low-pressure refrigerant absorbs heat from the refrigerated space and evaporates, completing the cycle.

**Work input (Process 1-2) =** $Q_H - Q_L$
**Heat rejected (Process 2-3)** $Q_H = T_H (S_2 - S_3)$
**Heat absorbed (Process 4-1)** $Q_L = T_L (S_1 - S_4)$
And since $S_1 = S_2$ & $S_3 = S_4$, *then* $Q_L = T_L (S_2 - S_3)$

## Coefficient Of Performance (COP):

The performance of a refrigeration system is evaluated using the Coefficient of Performance (***COP***) rather than thermal efficiency. The ***COP*** of a refrigerator is defined as the ratio of the refrigeration effect (heat absorbed in the evaporator) to the net work input supplied to the compressor. Mathematically, it is expressed as

$$COP = \frac{Q_L}{W_{net}} = \frac{T_L(S_2-S_3)}{Q_H-Q_L} = \frac{T_L(S_2-S_3)}{T_H(S_2-S_3)-T_L(S_2-S_3)} = \frac{T_L}{T_H-T_L}$$

Where $\boldsymbol{Q_L}$ is the heat removed from the low-temperature reservoir and $\boldsymbol{W_{net}}$ is the work input to the cycle. A higher COP indicates better system performance.

In the ideal vapour-compression refrigeration cycle (Reversed Carnot Cycle), certain simplifying assumptions are made to facilitate analysis. The compression process is considered isentropic, meaning that it occurs without entropy change. Heat rejection in the condenser and heat absorption in the evaporator are assumed to occur at constant pressure. The expansion process through the throttling valve is considered adiabatic with no work interaction, and the enthalpy of the refrigerant remains constant during this process. These assumptions allow the cycle to be represented clearly on T–s and P–h diagrams for performance evaluation.

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

| | | | |
|---|---|---|---|
| Heat absorbed | to | Refrigeration effect | $Q_L = T_L(S_2 - S_3)$ |
| Heat rejected | to | Heat rejected from the condenser | $Q_H = T_H(S_2 - S_3)$ |
| Work input | to | Work input to compressor | $W_{net\ in} = Q_H - Q_L$ |

**Example 1:**

A refrigeration system operates between an evaporator temperature of **-30°C** and a condenser temperature of **30°C**:

1. Determine the **maximum possible COP** of the system?
2. If the actual COP is **75% of the maximum COP**, calculate the actual COP?
3. If the power input to the compressor is **1 kW**, determine the refrigeration effect (heat removed) in kW?

Solution:

Since the maximum possible *COP* corresponds to the **Carnot refrigeration cycle**, it is given by:

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

Where temperatures must be in Kelvin.

$$T_L = -30 + 273 = 243\ K$$

$$T_H = 30 + 273 = 303\ K$$

$$COP_{Carnot} = \frac{243}{303 - 243} = 3.91$$

Actual $COP = 0.75 * 3.91 = 2.939$

$$COP = \frac{Q_L}{W_{net}} = 2.939 = \frac{Q_L}{1}$$

$$Q_L = 2.939\ kW_{of\ refrigeration}/kW_{of\ work\ input}$$

## Modifications of the Ideal Refrigeration Cycle

The ideal vapour-compression refrigeration cycle assumes:

- Isentropic compression
- Constant-pressure heat rejection and absorption
- No pressure losses in pipes
- No superheating or subcooling

In practical systems, several modifications are introduced to improve performance and ensure safe operation.

## 1) Replacement of Expansion Engine by Throttling Valve

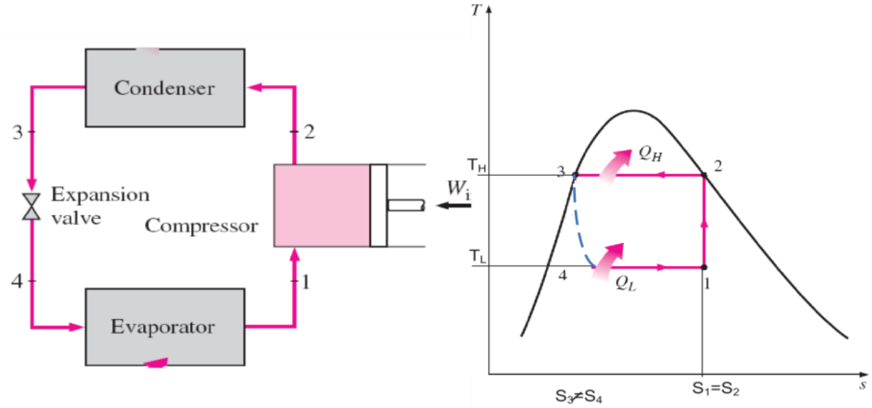
In the ideal cycle, expansion occurs in an isentropic expansion engine.
In practice, it is replaced by a **throttling (expansion) valve**.

**Reasons:**

- Simpler construction
- Lower cost
- Less maintenance

**Effect:**

- Expansion becomes **irreversible** ($S_3 \neq S_4$)
- Enthalpy remains constant ($h_3 = h_4$)
- Slight reduction in COP compared to ideal expansion



## 2) Superheating of Refrigerant Vapor

Before entering the compressor, the refrigerant vapor is slightly superheated in the evaporator.

**Purpose:**

- Ensures no liquid droplets enter the compressor
- Prevents compressor damage
- Improves operational safety

**Effect on Performance:**

- Increases refrigeration effect
- Increases compressor work
- COP may increase or decrease depending on conditions

## 3) Subcooling of Liquid Refrigerant

After condensation, the liquid refrigerant is subcooled below its saturation temperature.

**Purpose:**

- Prevents flash gas formation before expansion valve
- Increases refrigeration effect

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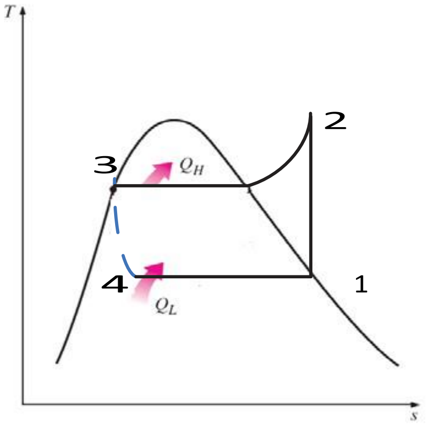
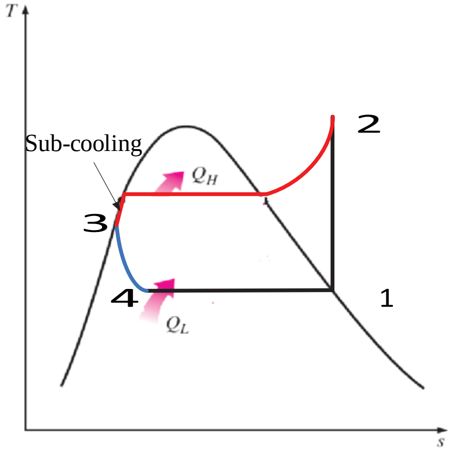
**Effect:**

- Larger refrigeration effect ($h_1 - h_4$ increases)
- COP generally improves



Evaporation process



Sub-cooling condensing process

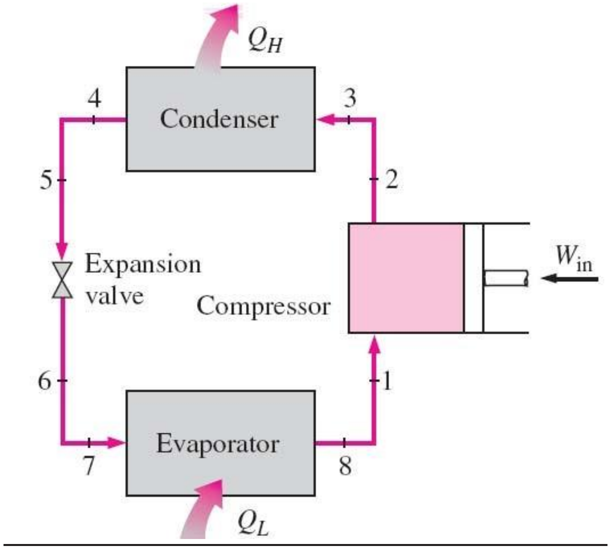
## 4) Pressure Drops in System Components

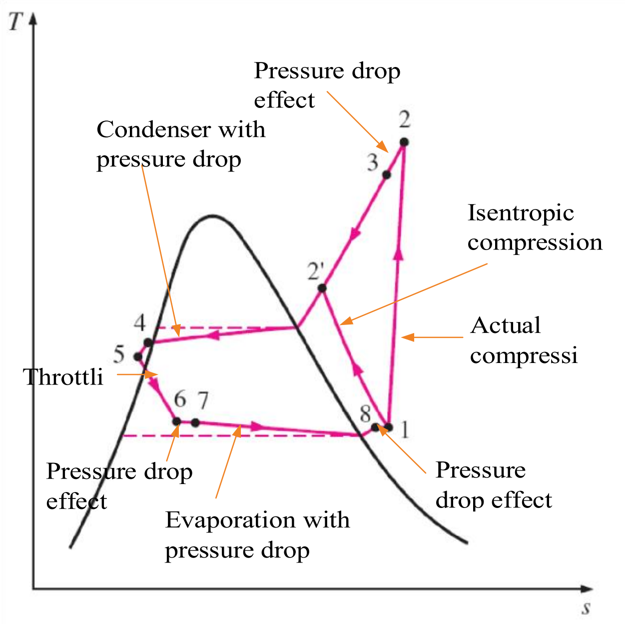
In real systems, pressure drops occur due to friction in:

- Evaporator
- Condenser
- Suction line
- Discharge line

**Effect:**

- Compressor must work at higher pressure ratio
- Increases power consumption
- Reduces *COP*





T-S diagram of actual VC cycle

## 5) Liquid-Suction Heat Exchanger

Some systems use an internal heat exchanger between:

- Liquid leaving condenser
- Vapour leaving evaporator

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## Advantages:

- Subcools liquid
- Superheats vapour
- Improves refrigeration effect

## Practical (Actual) Vapor Compression Cycle

The practical refrigeration cycle used in systems such as those operating with R-134a differs from the ideal cycle due to:

- Non-isentropic compression
- Throttling expansion
- Superheating and subcooling
- Pressure losses

## Summary of Differences

| Ideal Cycle | Actual Cycle |
|---|---|
| Isentropic compression | Non-isentropic compression |
| Expansion engine | Throttling valve |
| No superheating | Superheated vapour |
| No subcooling | Subcooled liquid |
| No pressure drops | Pressure losses present |

## Analysis of Steady Flow Energy Equation (SFEE) for Each Process in Vapour Compression Refrigeration Cycle:

The **Steady Flow Energy Equation (SFEE)** for a control volume is:

$$gz_1 + \frac{V_1^2}{2} + h_1 + Q = gz_2 + \frac{V_2^2}{2} + h_2 + W$$

For refrigeration systems:

- Changes in kinetic energy (KE) and potential energy (PE) are **negligible**
- Process is steady
- Mass flow rate is constant

So the equation simplifies to:

$$h_1 + Q = h_2 + W$$

Now we apply SFEE to each component of the vapor compression refrigeration cycle.

### 1) Compressor (Process 1 → 2)

**Assumptions:**

- Steady flow
- Adiabatic (no heat transfer)
- KE and PE negligible

So:

$$h_1 + 0 = h_2 + (-W_c) \quad \rightarrow \quad W_c = h_2 - h_1$$

### 2) Condenser (Process 2 → 3)

**Assumptions:**

- No work interaction

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- Steady flow
- KE and PE negligible

$$h_2 + (-Q_H) = h_3 + 0 \quad \rightarrow \quad Q_H = h_2 - h_3$$

## 3) Expansion Valve (Process 3 → 4)

**Assumptions:**

- No heat transfer
- No work
- Adiabatic throttling
- KE and PE negligible

$$h_3 + 0 = h_4 + 0 \quad \rightarrow \quad h_3 = h_4$$

Throttling process is **isenthalpic**: Pressure drops but enthalpy remains constant.

## 4) Evaporator (Process 4 → 1)

**Assumptions:**

- No work
- Steady flow
- KE and PE negligible

$$h_4 + Q_L = h_1 + 0 \quad \rightarrow \quad Q_L = h_1 - h_4 \quad \textbf{(Refrigeration effect per kg)}$$

## COP (Coefficient of Performance)

For refrigeration:

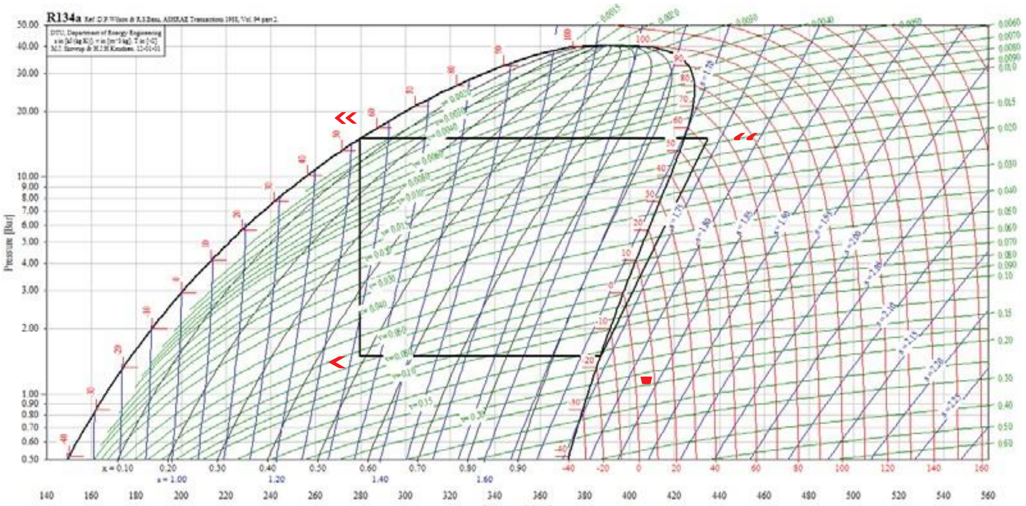
$$COP = \frac{Refrigeration\ Effect}{Work\ Input} = \frac{Q_L}{W_c} = \frac{h_1 - h_4}{h_2 - h_1}$$

## Example 2:

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

Solution:

From p-h diagram, we can find the enthalpies at each point as follows:



| 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 = $\dot{m}(h_2 - h_1) = 0.05(434 - 387) = 2.35\ kW$

Refrigeration effect $Q_L = h_1 - h_4 = 387 - 279 = 108\ kJ/kg$

Refrigeration effect in kW = $\dot{m}(h_1 - h_4) = 0.05(387 - 279) = 5.4\ kW$

$$COP = \frac{Q_L}{W_c} = \frac{108}{47} = 2.29$$

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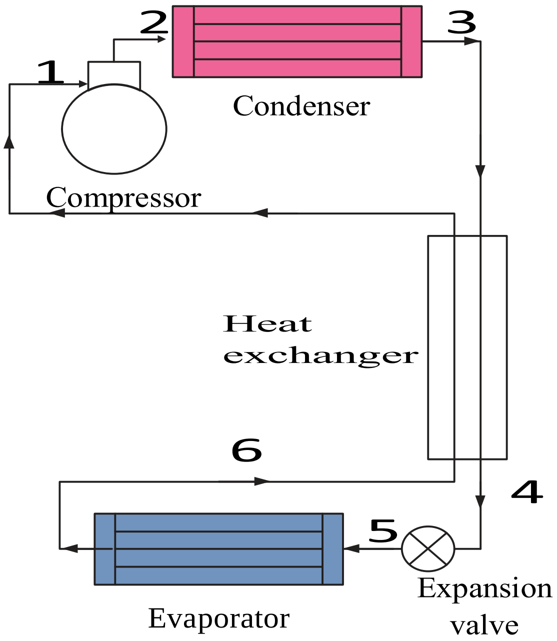
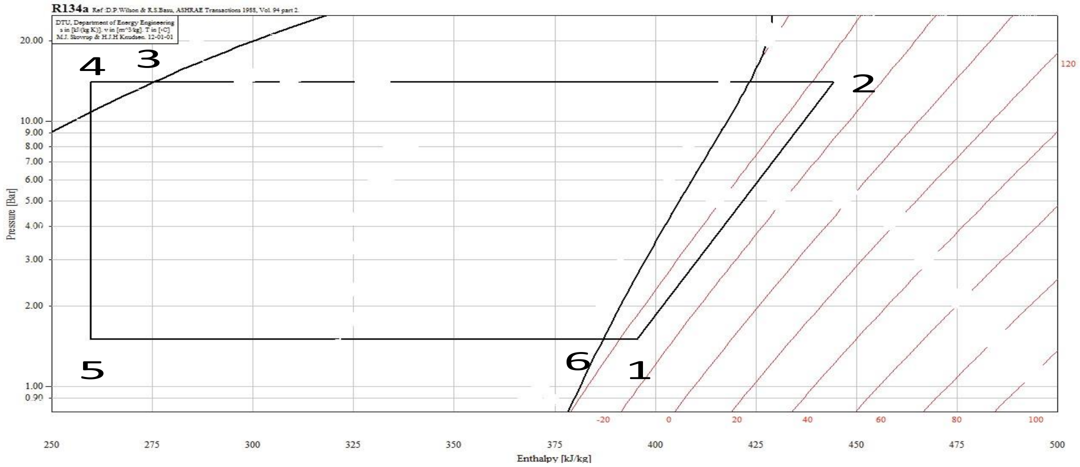
## The Effect of Heat Exchanger

Heat exchangers have an important effect in thermal and refrigeration systems because they transfer heat between two fluids without mixing them. Their main effect is improving energy efficiency by allowing heat to move from a hot fluid to a cold fluid, which reduces energy losses and saves fuel or electricity. In refrigeration and air-conditioning systems, heat exchangers use to sub-cool the liquid getting out from condenser with suction vapour coming from the evaporator. In other word, saturated liquid at point 3 coming out form condenser is cooled down to point 4 by means of vapour at point 6 being heated to point 1.





From the heat balanced: $h_3 - h_4 = h_1 - h_6$, 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 improve. This is not necessarily true, however, even though 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 through the expansion valve.

## Example 3:

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:

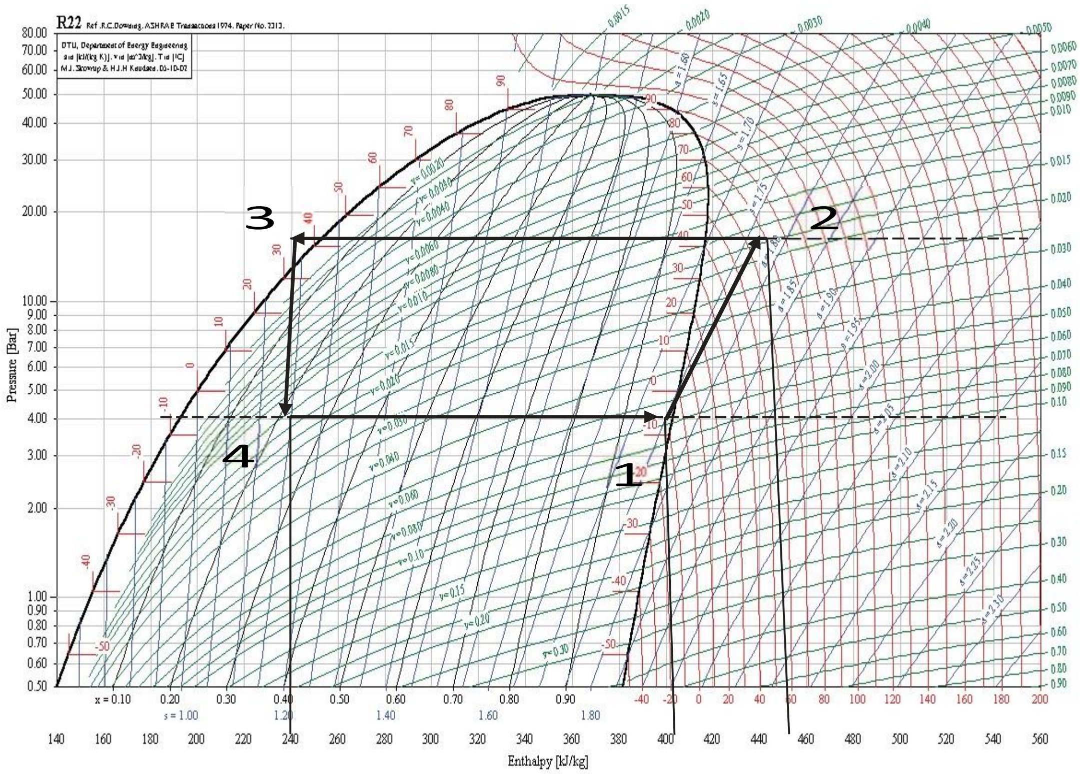
a- The refrigeration effect in kJ/kg?
b- The mass flow rate of refrigerant?
c- The power required for compression?
d- COP?
e- Power per kW of refrigeration?
f- Discharge temperature?

Solution:

From p-h diagram, we can find the enthalpies:

$$h_1 = 401\frac{kJ}{kg}, \qquad h_2 = 435\ \frac{kJ}{kg}\ , \quad h_3 = h_4 = 243\ \frac{kJ}{kg}$$

a- Refrigeration effect = $Q_L = h_1 - h_4 = 401 - 243 = 158\ \frac{kJ}{kg}$
b- Refrigeration effect in kW = $\dot{m}(h_1 - h_4)\ \rightarrow\ \dot{m} = \frac{50}{158} = 0.31\ kg/s$
c- $W_c$ in kW $= \dot{m}(h_2 - h_1) = 0.31(435 - 401) = 10.744\ kW$
d- $COP = \frac{Refrigeration\ Effect}{Work\ Input} = \frac{Q_L}{W_c} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{401-243}{435-401} = 4.911$
e- Power per kW of refrigeration = $\frac{1}{COP} = \frac{1}{4.911} = 0.203\ kW/kW_{refrig.}$
f- Discharge temperature = $T_2 = 60\ ℃$



## The Heat Pump:

The heat pump, a reversed heat engine, is a device for heating houses and commercial buildings during the winter and cooling them during the summer. In the winter it operates so as to absorb heat from the surroundings and reject heat into the building.

The heat pump also serves for air conditioning during the summer. The flow of refrigerant is simply reversed, and heat is absorbed from the building and rejected through underground coils or to the outside air.

## HW #1:

1- The temperature of the evaporator coil is **-6°C** and that of the condenser is **22°C**, assuming that the machine operates on the reversed Carnot cycle. Calculate the COP, the refrigeration effect per kJ of input work and the heat rejected to the condenser.
(9.54; 9.54 kW; 10.4 kW)

2- A Carnot refrigeration cycle absorbs heat at **(–12°C)** and rejects it at **40°C**. Calculate a- the COP of the cycle, b- If the cycle absorbs **15 kW** at (**–12°C**) temperature, how much power is required? (18 kW)

3- In a standard vapour compression cycle using R-22, the evaporator temperature is –5°C and the condensing temperature is 30°C. Calculate: a- Work of compression,b- Refrigeration effect, c- Heat rejected in the condenser, d- COP.
(6, 4, 7)

4- A refrigeration system using R-22 has a refrigerating capacity of 80 kW. The cycle is a standard vapour compression cycle with evaporator temperature –8°C and condenser temperature 42°C. Determine: a- Mass flow rate of refrigerant, b- Power required by the compressor, c- Quality of vapour at the evaporator inlet.

5- A refrigerant **R-22** vapour compression system includes a liquid-to-suction heat exchanger. The heat exchanger warms saturated vapour from **-10°C** to 5**°C** with liquid comes from condenser at **30°C**. The compression are isentropic in both cases below:

a- Calculate the COP without the heat exchanger?
b- Calculate the COP with the heat exchanger?
c- Determine the refrigeration capacity if the compressor pumps 12 lit/s measured at the compressor suction with and without heat exchanger?

6- An air-conditioning system in a car uses **R-134a**. When the power input to the compressor is **1.5 kW** bringing the refrigerant from 202 kpa to 1200 kpa. The cold space is heat exchanger that cool a temperature air from outside down to 10°C and blow it into the car. Calculate:

a- Mass flow rate of the refrigerant?

b- Heat transfer rate?

c- Mass flow rate of air entering the car?