ENG 3165 LECTURE 12

THERMODYNAMICS COMPONENT

Refrigeration

Introduction

- This lecture provides an introduction to the concept of **Refrigeration** and its theoretical working cycle based on the **Reverse Carnot Cycle**.
- In Summary the **Refrigeration Cycle** or **Heat Pump**

GENERAL INTRODUCTION

- If a body is to be maintained at a temperature lower than that of its surrounding, or ambient temperature, then any heat transfer which will naturally occur down the temperature gradient from the surroundings to the body (second law of thermodynamics) must be transferred back to the surroundings.
- Unless this is done, the temperature of the body will increase to that of its surroundings. Now the transfer of heat from a colder to a hotter body is contrary to the second law of thermodynamics, which implies that, if such a transfer of heat is required, then, external energy is required to facilitate the transfer.

GENERAL INTRODUCTION

- This external energy can be supplied either by means of a heating device as a compressor (or pump), the use of either producing the necessary increase in temperature.
- The cyclic process by which natural heat transfer down a temperature gradient is returned up the temperature gradient by means of the supply of external energy is the process of **refrigeration**.
- In any **refrigerator**, as the plant is called there will be an amount of energy removed from the cold body by the refrigeration process. This is referred to as the **refrigerating effect.**

GENERAL INTRODUCTION

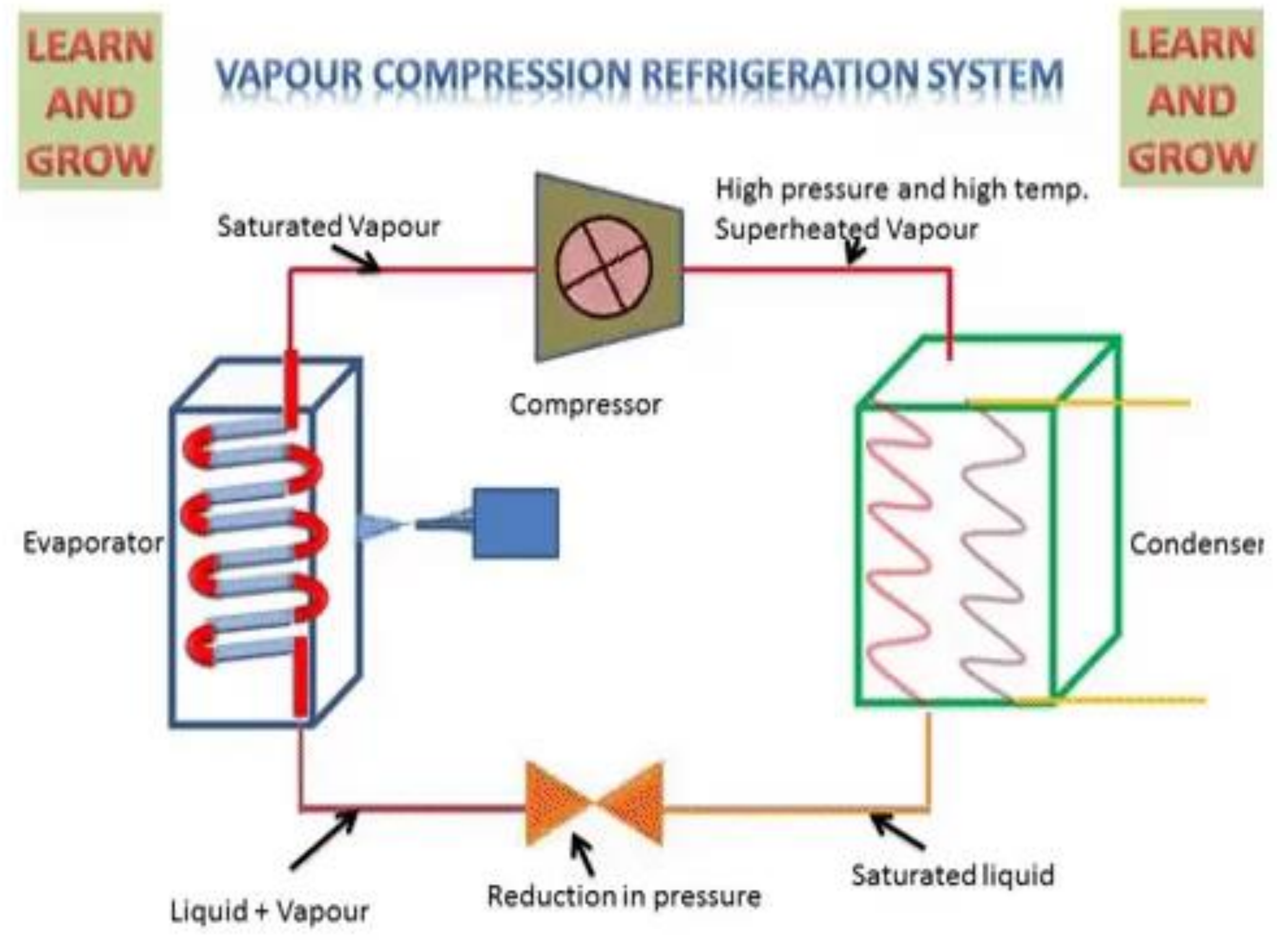
- The ratio:

$$\frac{\boldsymbol{Refrigerating\ Effect}}{\boldsymbol{External\ Energy\ Supplied}}$$

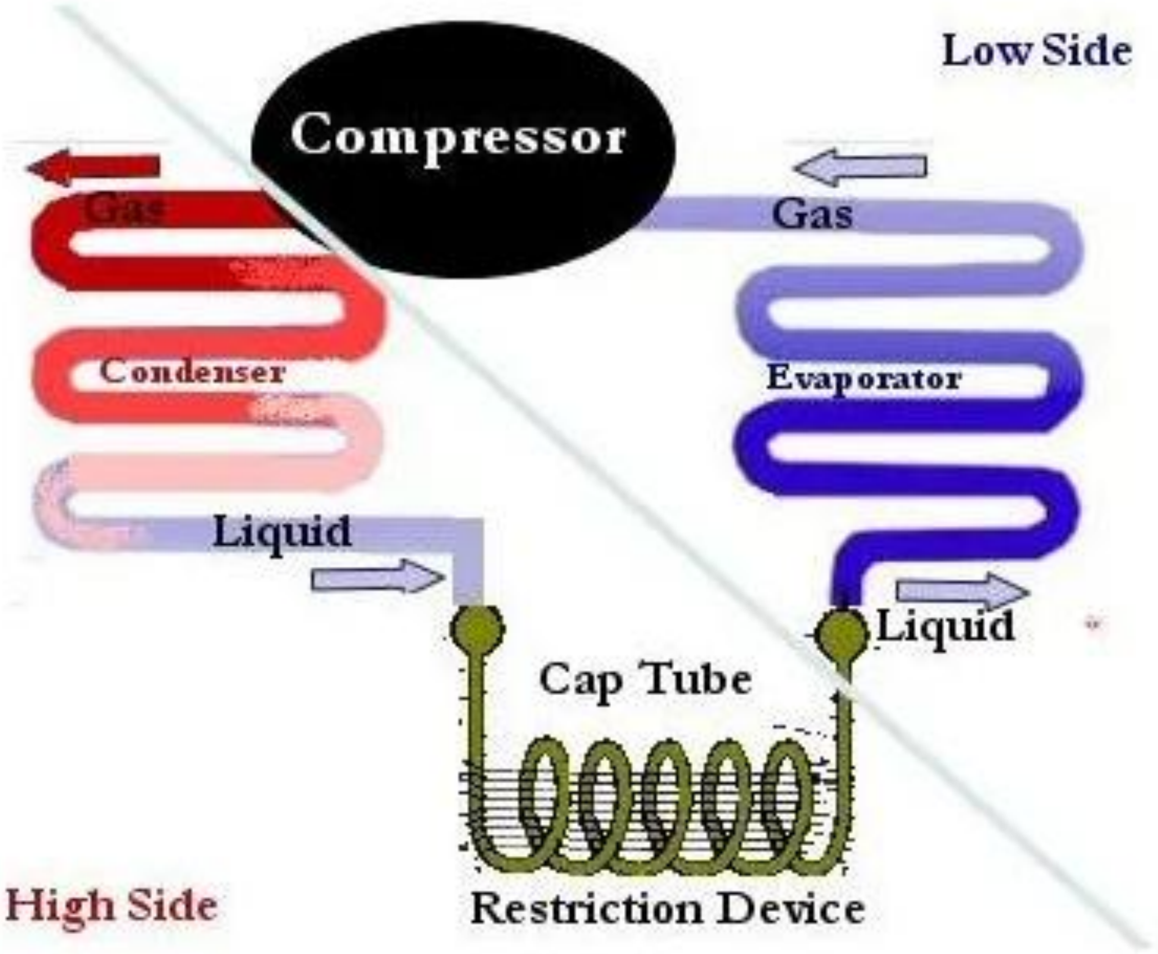
$$= \boldsymbol{C.O.P\ (Coefficient\ of\ Performance)}$$

- This definition is similar to that used for efficiency. The term efficiency is not used here, however, because very often C.O.P> 1, and hence the term coefficient is used rather than efficiency.

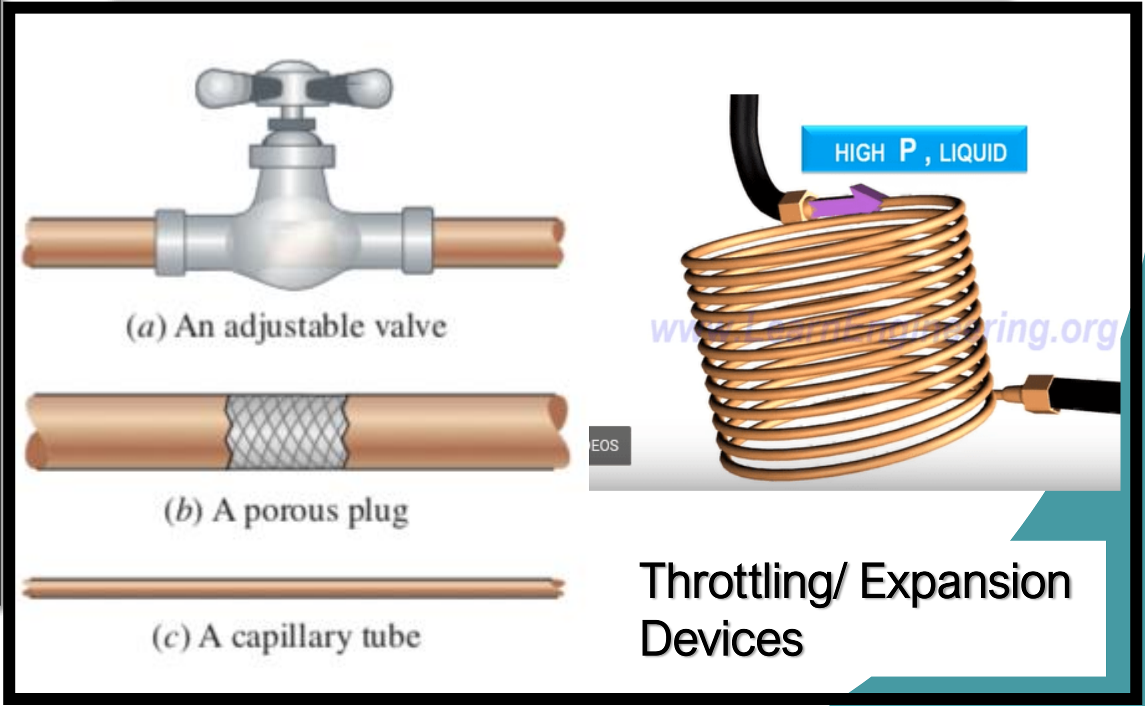
REFRIGERATION PROCESS



REFRIGERATION PROCESS



REFRIGERATION
Parts of a Refrigerator



STAGES OF REFRIGERATION

The four stages of refrigeration are:

1. **Cooling** the refrigerant to a suitable temperature below the surrounding. This can either be achieved by **expanding it** (so that part of its heat energy is converted to mechanical work) or by **throttling.**
2. **Heat transfer** by conduction from the body to be cooled to the refrigerant
3. Raising the temperature of the refrigerant by **compression** (this involves the input of mechanical energy via a compressor).
4. Heat transfer from the refrigerant by conduction to a **condensing** media (normally water or air).

REFRIGERATION

- The various heat transfers associated with the refrigeration process are illustrated.
- The high temperature is higher than the ambient temperature in order that heat transfer can take place.
- The heat transfer from the high to the low refrigeration temperature takes place in two stages. There is a natural heat transfer to the surroundings from the high to ambient temperature. This is followed by a natural heat transfer from ambient to the low refrigeration temperature.
- The heat transfer from the low to high temperature requiring external energy is direct.

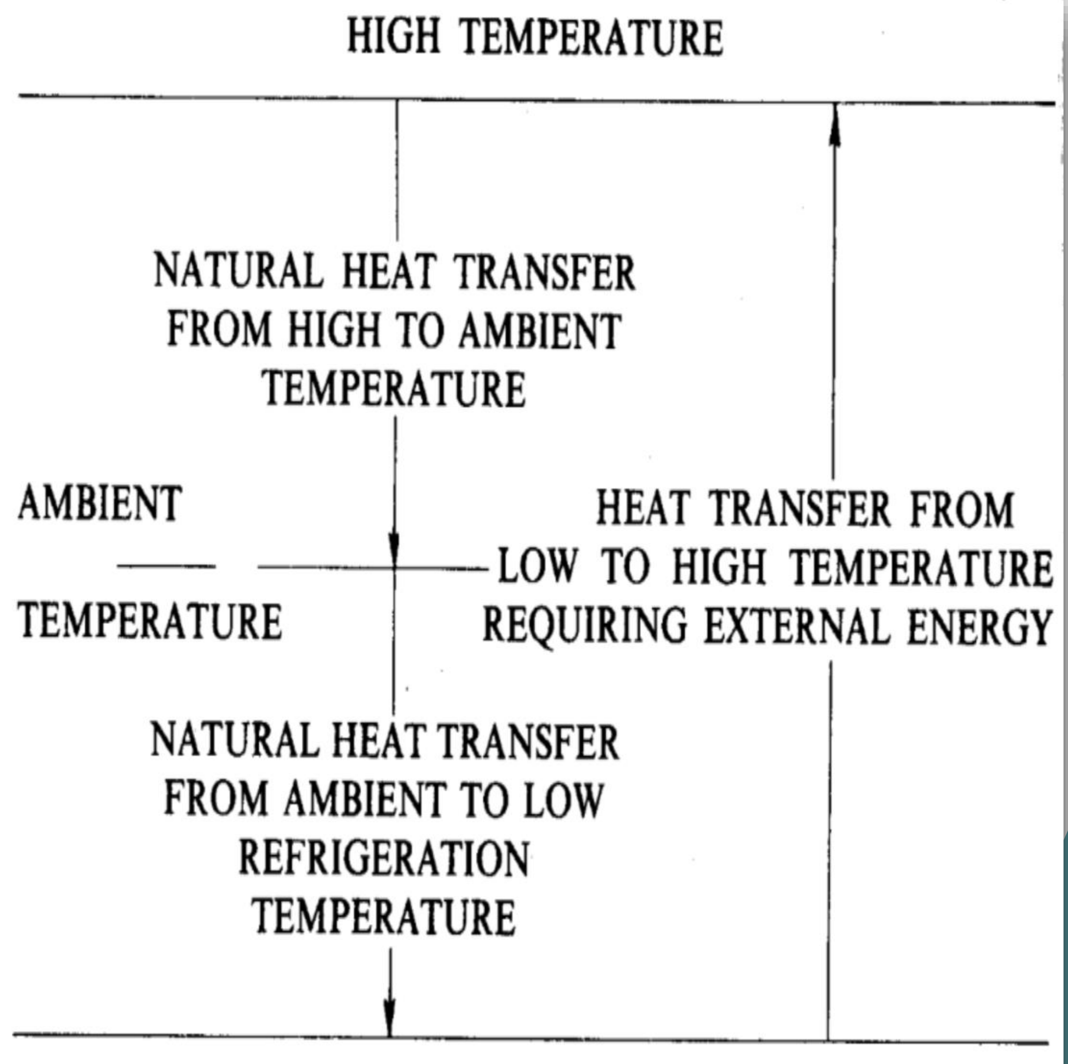


Fig. 17.1

REFRIGERATION

- When working at very low temperatures (generally below -150 °C) the term **cryogenics** is used rather than refrigeration .
- The refrigeration cycle is the reverse of the heat engine cycle. In the heat engine cycle energy is received at high temperature, rejected at low temperature and work is obtained from the cycle.
- In the refrigeration cycle, however, energy is received at low temperature, rejected at high temperature and work (or heat) is required to perform the cycle.
- Due to the transfer of energy from low to high temperature, the refrigerator is sometimes referred to as a heat **pump**.

UNITS OF REFRIGERATION

- The capacity of mechanical equipment is normally given in Horse Power (H.P.):

  1 H.P. = 0.746 kW

- The capacity of electrical equipment is normally given in Kilowatts (kW)
- The capacity of refrigeration is normally expressed as '**Tonne of Refrigeration**' (T.R.): 1 tonne of refrigeration is the rate of heat removal required .to freeze a metric ton (1000 kg) of water at 0°C in 24 hours.

  1 T.R. = 13,898 kJ/h = 3.861 kW

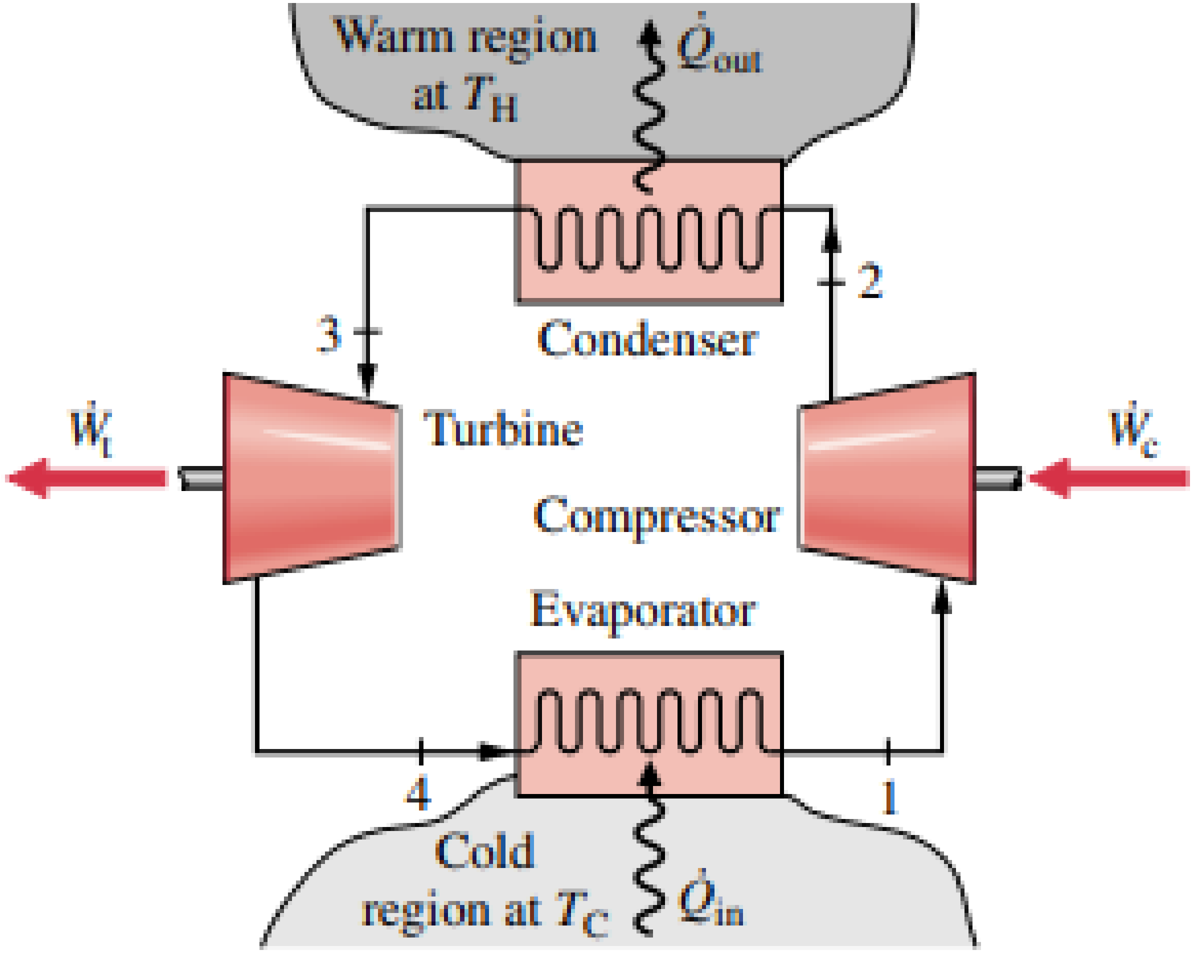
REFIGERANTS AND THEIR PROPERTIES

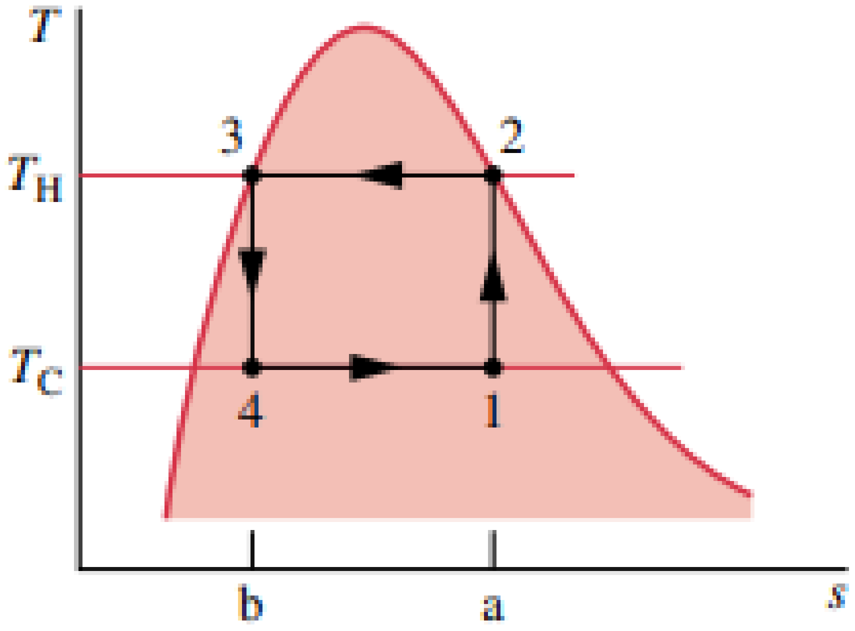
- The working substance which flows through a refrigerator is called a **refrigerant.**
- It is usual that heat transfer into the refrigerant at low temperature evaporates the refrigerant. Heat transfer from the refrigerant at high temperature condenses the refrigerant. Commonly used refrigerants are **Ammonia** (NH_3), **Methyl Chloride** (CH_3Cl), **Freon-l2 (Refrigerant-12) (Dichlorodifluoromethane,** CCl_2F_2**), Isobutane** and **Carbon Dioxide** (CO_2).
- These substances remain as liquids and can be evaporated at suitable pressures and sub-zero low temperatures which make them suitable for use as refrigerants.
- From about 1940 to the early 1990s, the most common class of refrigerants used in vapor compression refrigeration systems was the chlorine-containing **CFCs (chlorofluorocarbons).** Due to the effects of chlorine in refrigerants on the earth's protective ozone layer, they have been phased out.

REFIGERANTS AND THEIR PROPERTIES

- Classes of refrigerants containing various amounts of hydrogen in place of chlorine atoms have been developed that have less potential to deplete atmospheric ozone than do more fully chlorinated ones, such as Refrigerant 12.
- One such class, the **HFCs - Hydrofluorocarbons**, contain no chlorine. **Refrigerant 134a (Tetraflouroethane) (CF_3CH_2F)** is the HFC considered by many to be an environmentally acceptable substitute for Refrigerant 12, and Refrigerant 134a has replaced Refrigerant 12 in many applications
- Ammonia (NH3), which was widely used in the early development of vapor compression refrigeration, is again receiving some interest as an alternative to the CFCs because it contains no chlorine.

THE REVERSED CARNOT CYCLE





THE REVERSED CARNOT CYCLE

- As already stated, the coefficient of performance, sometimes *denoted as* β:

$$\beta_{\max} = \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m} - \dot{W}_t/\dot{m}}$$

$$= \frac{\text{area } 1\text{–a–b–4–1}}{\text{area } 1\text{–2–3–4–1}} = \frac{T_C(s_a - s_b)}{(T_H - T_C)(s_a - s_b)}$$

$$= \frac{T_C}{T_H - T_C}$$

- The above equation, represents the maximum theoretical coefficient of performance of any refrigeration cycle operating between regions at T_C and T_H.

THE REVERSED CARNOT CYCLE

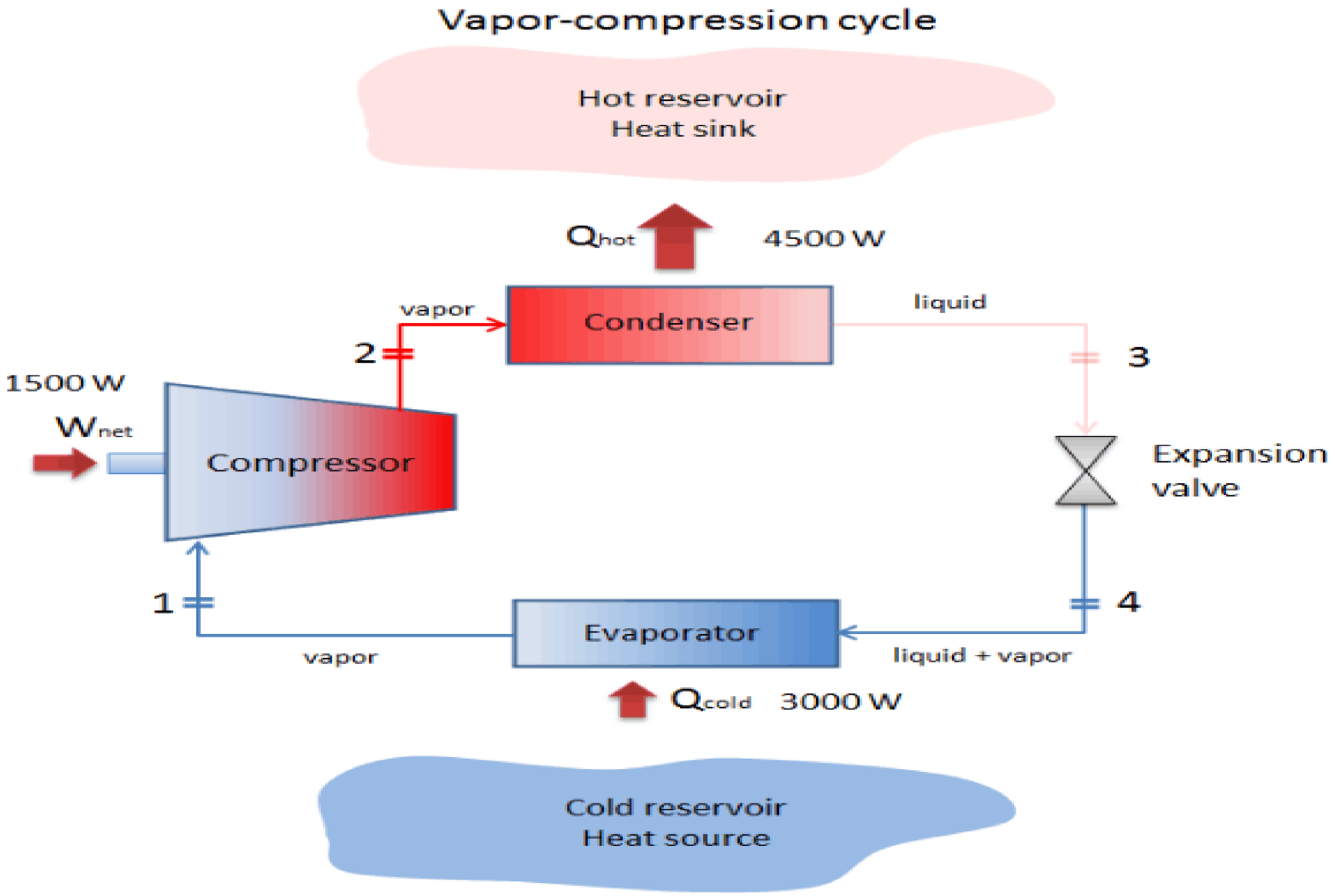
- Now, the Carnot cycle is composed of reversible processes which are the most efficient thermodynamic processes possible. Hence, the reversed Carnot cycle will have the highest C.O.P possible between any given limits of temperature. Note that the equation,

$$\text{C.O.P} = \frac{T_1}{T_2 - T_1}$$

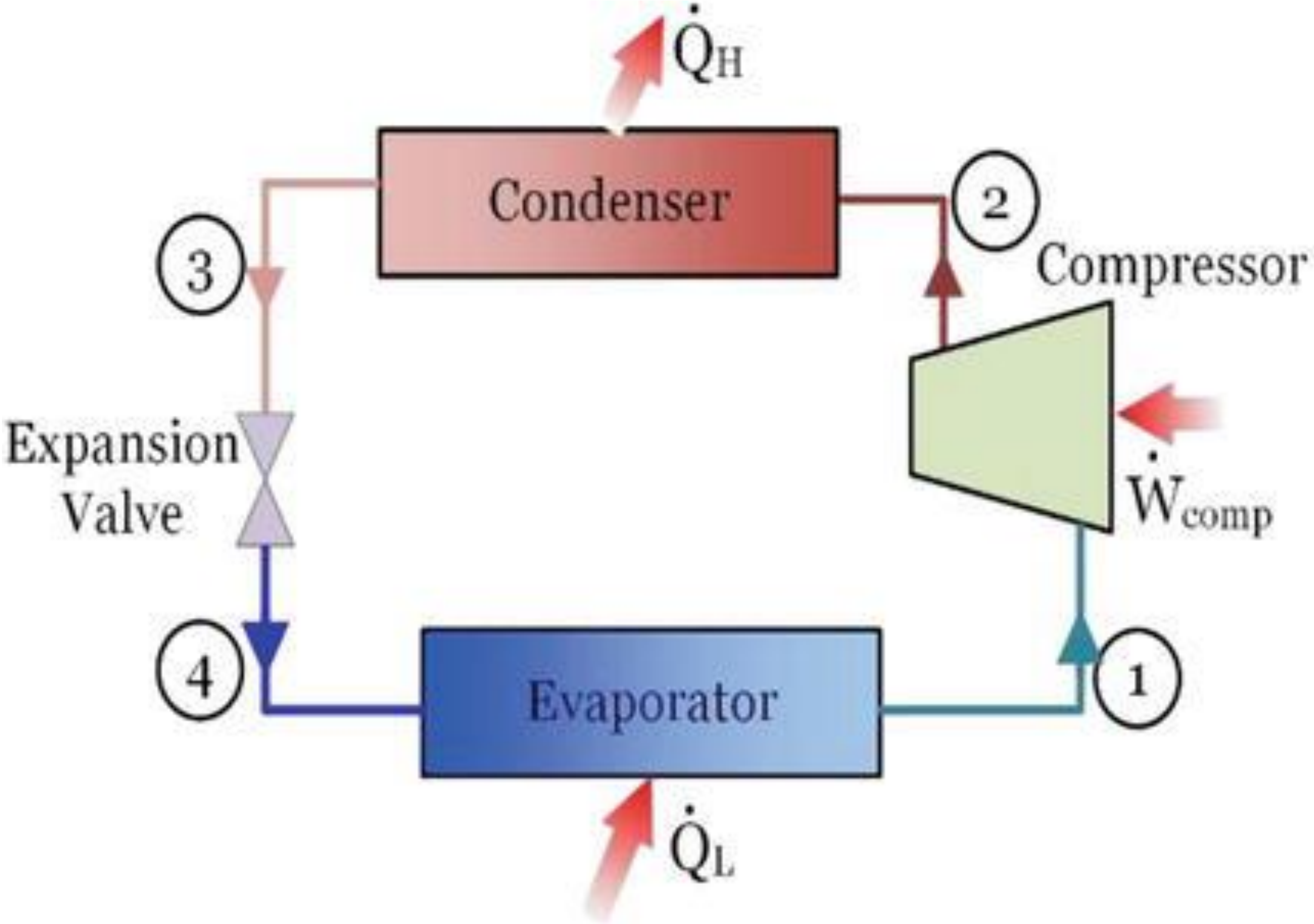
can be rewritten,

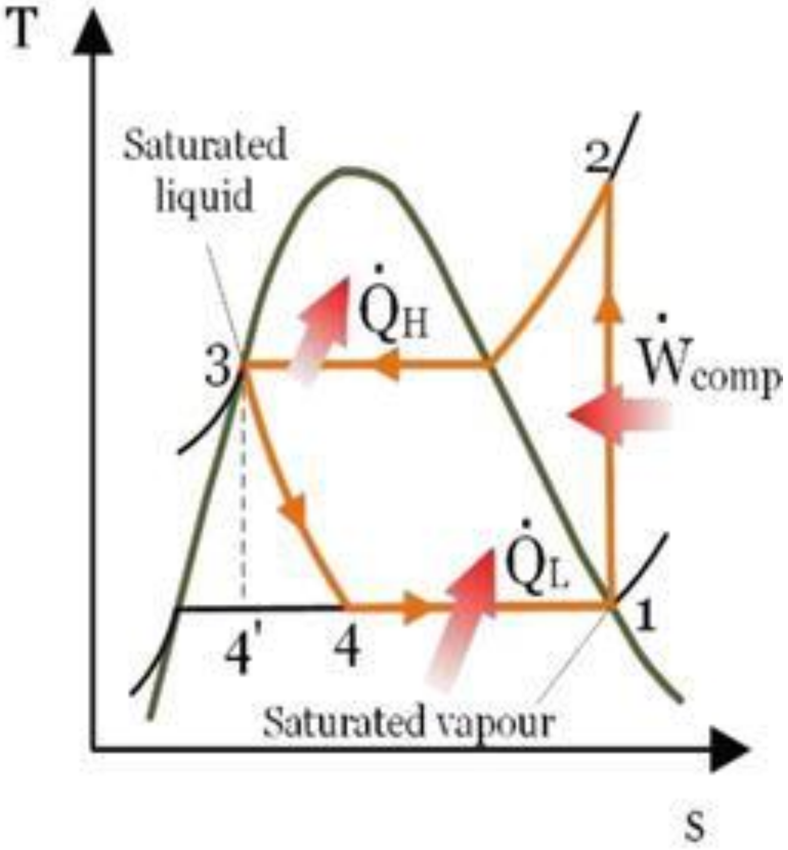
$$\text{C.O.P} = \frac{1}{\frac{T_2}{T_1} - 1}$$

VAPOUR COMPRESSION REFRIGERATOR



VAPOUR COMPRESSION REFRIGERATOR





VAPOUR COMPRESSION REFRIGERATOR

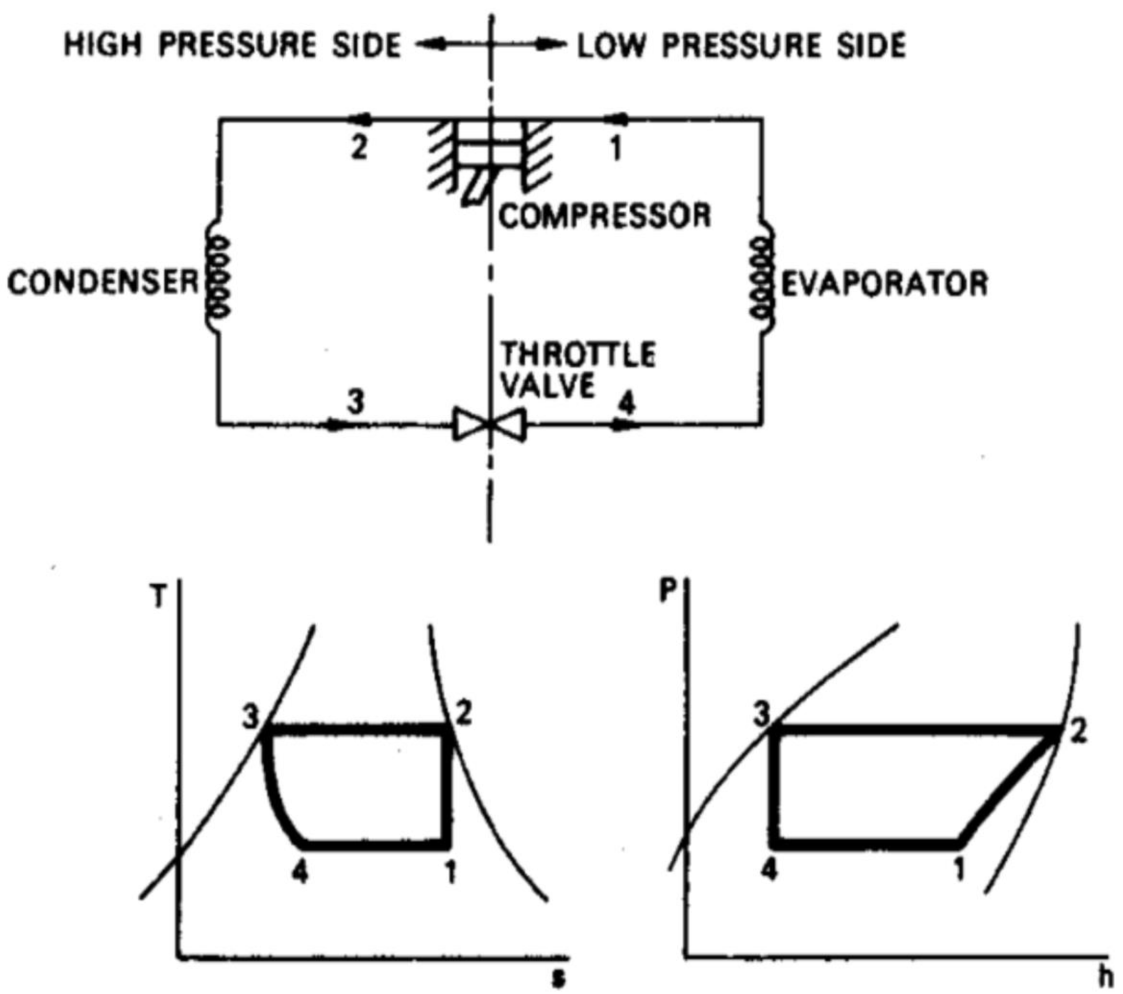
- In the vapour-compression refrigerator, liquid refrigerants are used which are alternately evaporated and condensed.
- Using a liquid refrigerant, the Carnot cycle could be closely approximated.
- It has been shown in work on two-phase systems that during the evaporation of a liquid at constant pressure the temperature remains constant.
- Then, a wet low-pressure, low-temperature refrigerant enters the evaporator at 4 in which it is evaporated to a nearly dry state at 1.

VAPOUR COMPRESSION REFRIGERATOR

- This evaporation process produces the refrigerating effect. The refrigerant then enters a compressor in which it is compressed, theoretically isentropically, to 2.
- The refrigerant would then be dry saturated at a higher pressure and temperature. The refrigerant then passes through a condenser at constant pressure and temperature and is condensed to liquid at 3. The refrigerant then passes through an expander in which it is expanded theoretically isentropically, back to its original low-pressure, low temperature, wet state at 4.

VAPOUR COMPRESSION REFRIGERATOR

- It is common practice, however, to use a throttle valve or regulator in place of the expander. This is illustrated here and most vapour compression refrigerators have this basic arrangement.
- The throttling process 3-4 moves the cycle away from the Carnot cycle but the refrigerator has now become a more simple and practical arrangement.

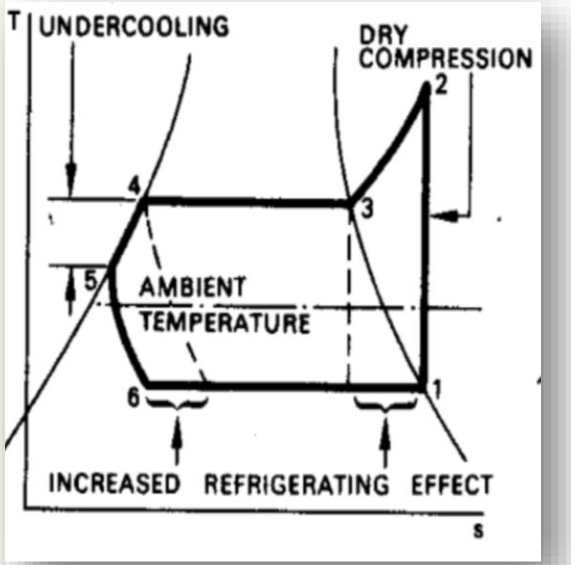


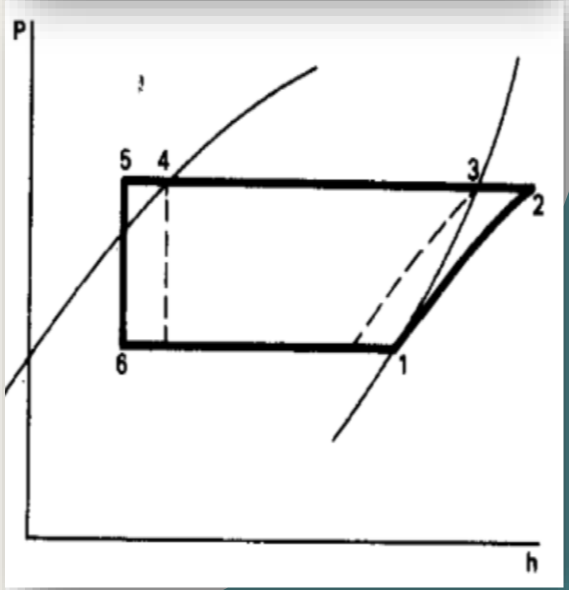
VAPOUR COMPRESSION REFRIGERATOR

- In large refrigeration plant the evaporator may be suspended in a secondary refrigerant such as brine and the heat exchange then takes place in two stages. This is between the cold chamber and the secondary refrigerant, which is pumped round the cold chamber, and then between the secondary refrigerant and the primary refrigerant in the evaporator in the refrigerator.
- Again, in large refrigeration plant, the condenser may be water cooled or have forced-draught air cooling using fans.
- In small refrigeration plant, such as in the domestic refrigerator, evaporator is suspended directly in the cold chamber and the condenser is suspended in the surrounding atmospheric air.
- Also, in small refrigeration plants, the throttling process may be accomplished by using a length of capillary tubing. This produces a fixed low temperature in evaporator.
- The control of the cold chamber temperature is obtained using a thermostat in the cold chamber. When the required temperature is reached in the cold chamber, controls connected to the thermostat switch off the motor driving the refrigerator. The temperature in the cold chamber then slowly rises and the thermostat controls then switch on the motor and the process is then repeated. If a throttle valve is fitted, then there is a control on the evaporator temperature.

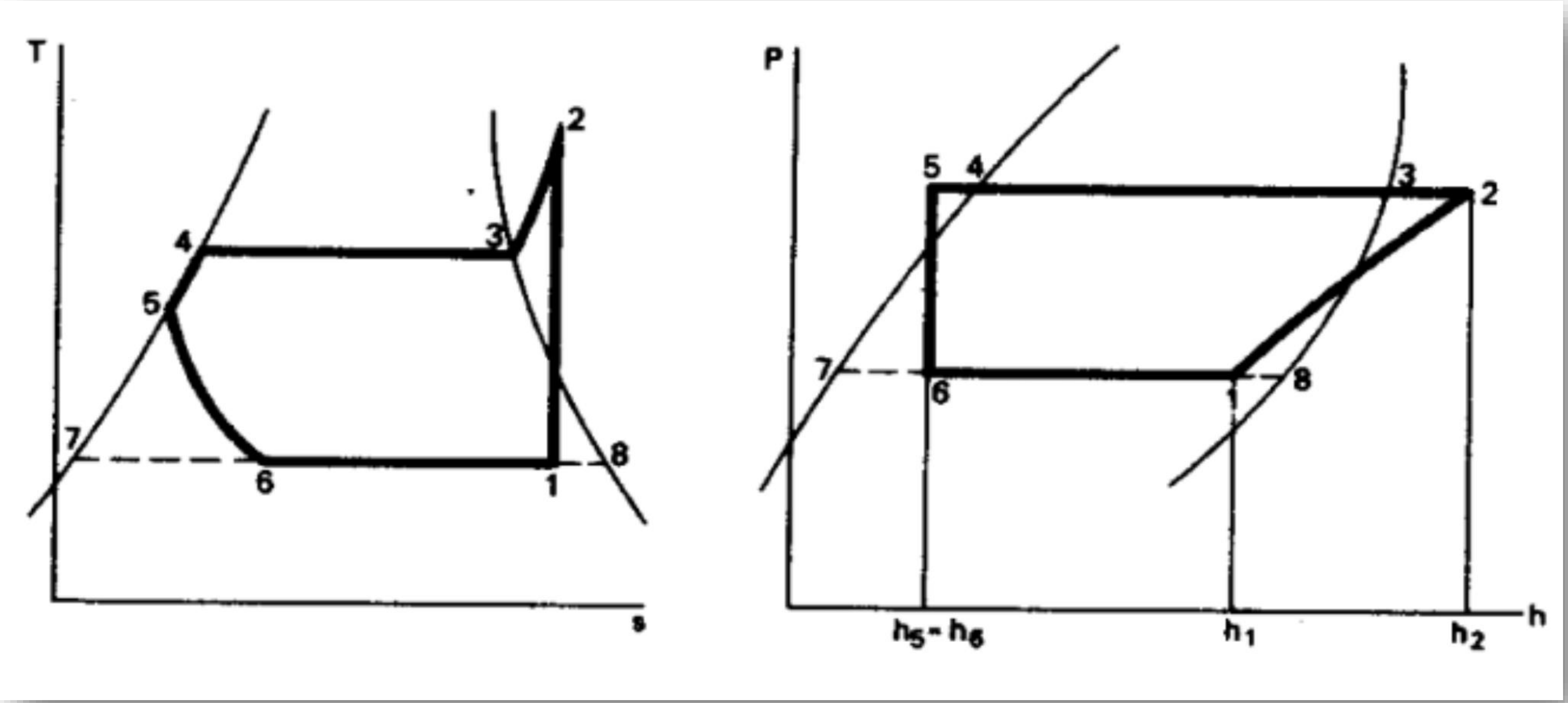
VAPOUR COMPRESSION REFRIGERATOR

- The diagrams of the type of cycle more commonly used in the vapour compression refrigerator are shown.
- The modifications made to the cycle already illustrated in the previous slide produce a more effective operation of the plant.
- Entry to the compressor at 1, the refrigerant is shown as being dry saturated. Sometimes there is a slight degree of superheat. The effect of this is to increase the refrigerating effect and also to produce dry compression in the refrigerator, shown as process 1-2. This means that there is no loss of mass flow due to evaporation of the liquid refrigerant in the compressor during the induction stroke.
- A further improvement can be obtained by undercooling (or subcooling) the refrigerant after condensation, shown as process 4-5. Here, the refrigerant is cooled toward the ambient temperature. This produces a wetter vapour, at 6, after the throttling process and an improved refrigerating effect follows.
- It should be noted that the refrigerating effect per unit time is called the **duty of the refrigerator**. This will depend upon the end states of the refrigerant in the evaporator and also the mass flow rate of the refrigerant.
- Tables of properties for various refrigerants exist and are similar to the tables for the properties of steam.

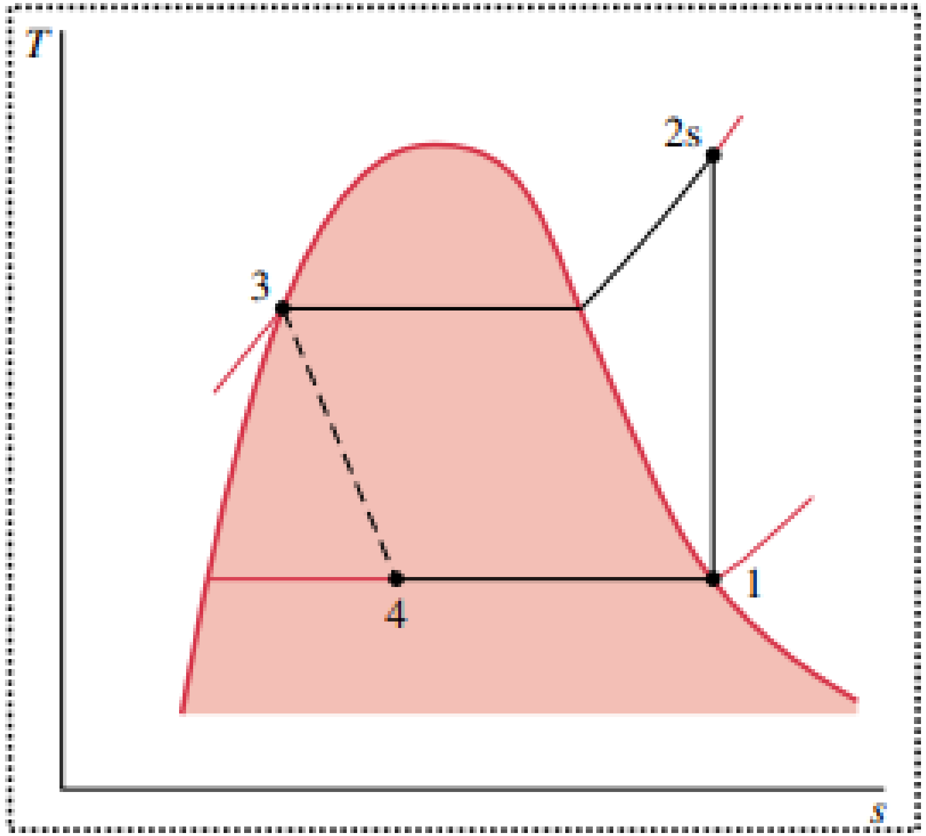




CALCULATIONS FOR THE VAPOUR COMPRESSION REFRIGERATOR



VAPOUR COMPRESSION REFRIGERATOR



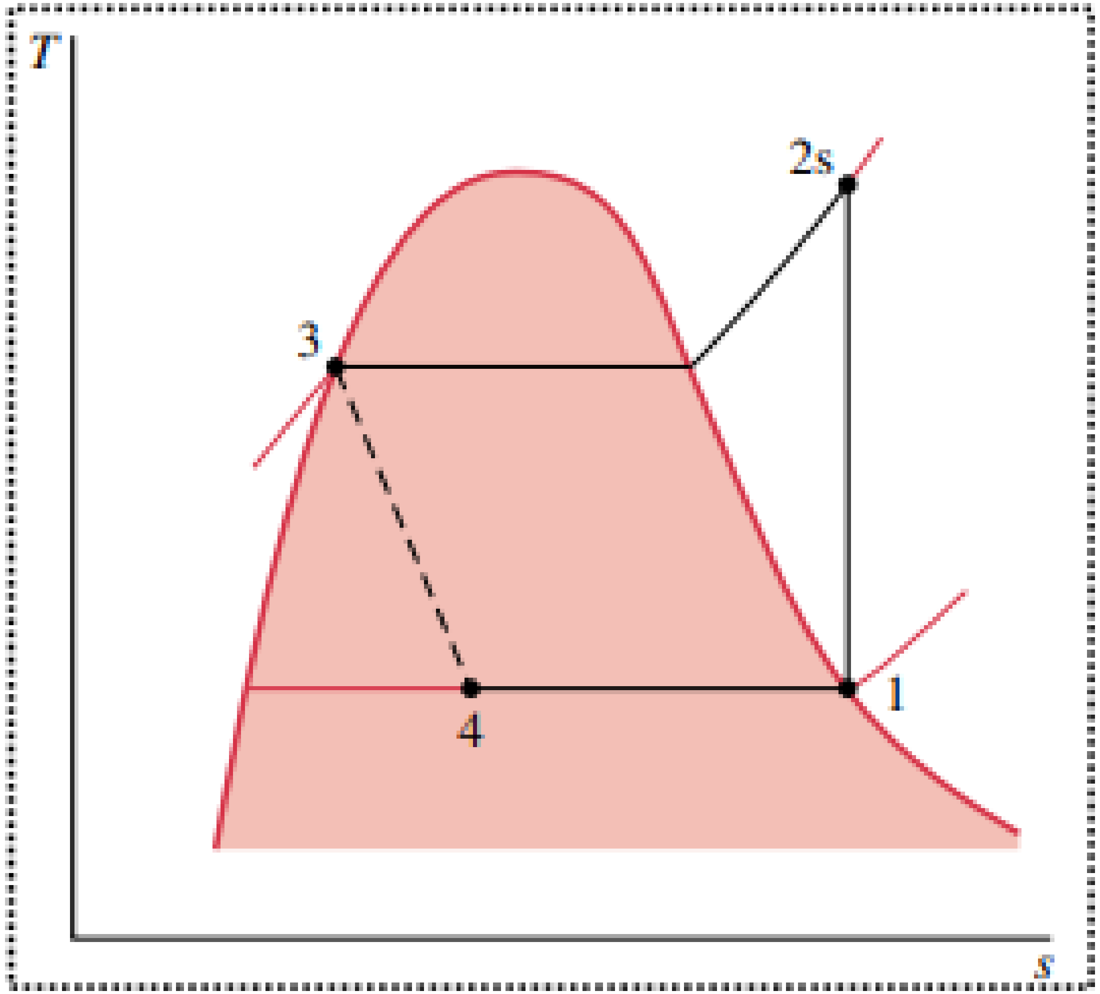
• As the refrigerant passes through the evaporator, heat transfer from the refrigerated space results in the vaporization of the refrigerant

$$\frac{\dot{Q}_{\text{in}}}{\dot{m}} = h_1 - h_4$$

The refrigerant leaving the evaporator is compressed to a relatively high pressure and temperature by the compressor.

$$\frac{\dot{W}_c}{\dot{m}} = h_2 - h_1$$

VAPOUR COMPRESSION REFRIGERATOR



Next, the refrigerant passes through the condenser, where the refrigerant condenses and there is heat transfer from the refrigerant to the cooler surroundings.

$$h_4 = h_3$$

In the vapor-compression system, the net power input is equal to the compressor power, since the expansion valve involves no power input or output. Using the quantities and expressions introduced above, the coefficient of performance of the vapor-compression refrigeration system is:

$$\beta = \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m}} = \frac{h_1 - h_4}{h_2 - h_1}$$

Example

Example 8.5 Ideal Vapor-Compression Refrigeration Cycle

Refrigerant 134a is the working fluid in an ideal vapor-compression refrigeration cycle that communicates thermally with a cold region at 0°C and a warm region at 26°C. Saturated vapor enters the compressor at 0°C and saturated liquid leaves the condenser at 26°C. The mass flow rate of the refrigerant is 0.08 kg/s. Determine (a) the compressor power, in kW, (b) the refrigeration capacity, in tons, (c) the coefficient of performance, and (d) the coefficient of performance of a Carnot refrigeration cycle operating between warm and cold regions at 26 and 0°C, respectively.

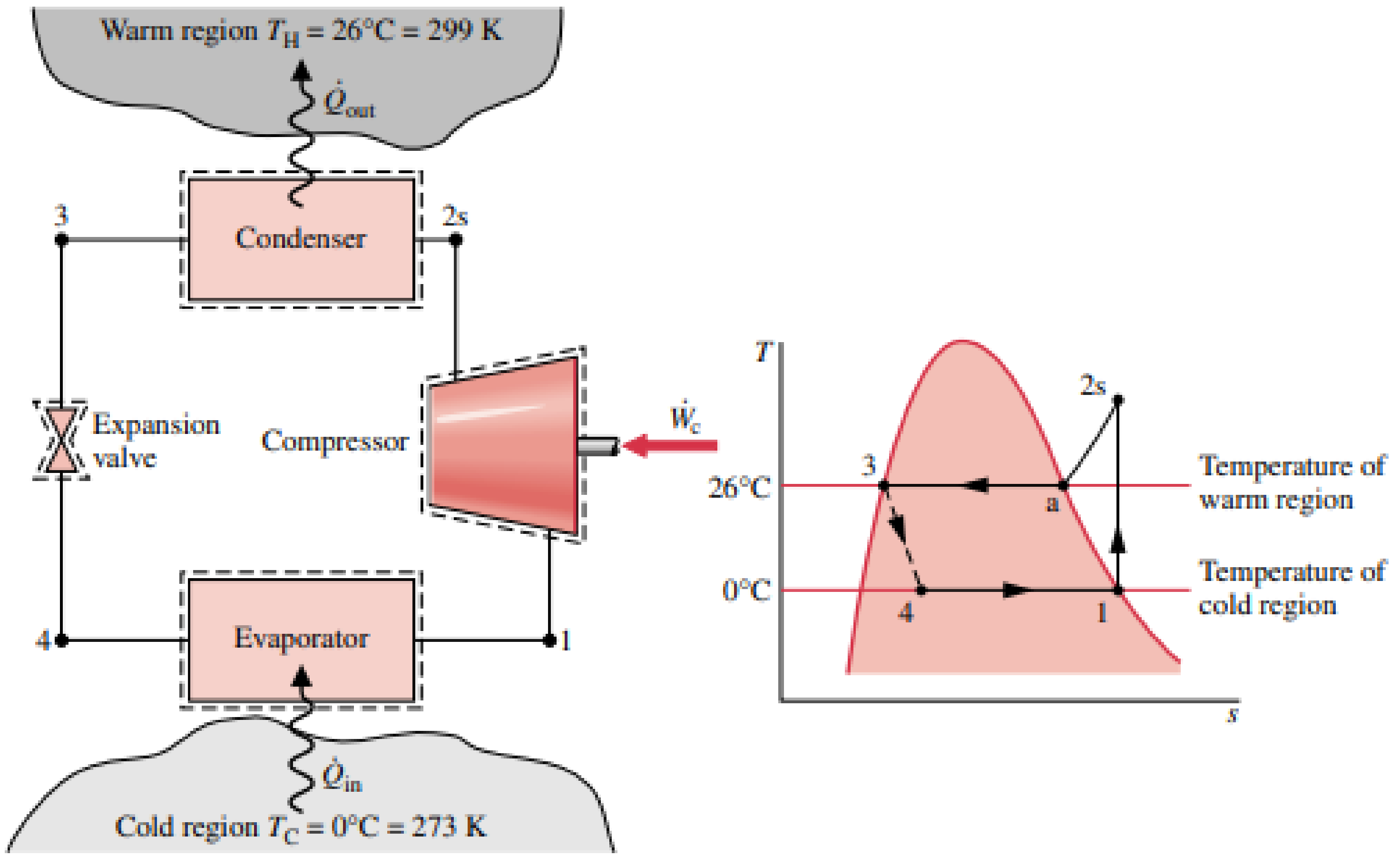
Solution

Known: An ideal vapor-compression refrigeration cycle operates with Refrigerant 134a. The states of the refrigerant entering the compressor and leaving the condenser are specified, and the mass flow rate is given.

Find: Determine the compressor power, in kW, the refrigeration capacity, in tons, the coefficient of performance, and the coefficient of performance of a Carnot vapor refrigeration cycle operating between warm and cold regions at the specified temperatures.

Example

Schematic and Given Data:



Example

Assumptions:

1. Each component of the cycle is analyzed as a control volume at steady state. The control volumes are indicated by dashed lines on the accompanying sketch.
2. Except for the expansion through the valve, which is a throttling process, all processes of the refrigerant are internally reversible.
3. The compressor and expansion valve operate adiabatically.
4. Kinetic and potential energy effects are negligible.
5. Saturated vapor enters the compressor, and saturated liquid leaves the condenser.

Properties: Let us begin by fixing each of the principal states located on the accompanying schematic and T–s diagrams. At the inlet to the compressor, the refrigerant is a saturated vapor at 0°C, so from Table T-6, $h_1 = 247.23$ kJ/kg and $s_1 = 0.9190$ kJ/kg · K.

The pressure at state 2s is the saturation pressure corresponding to 26°C, or $p_2 = 6.853$ bar. State 2s is fixed by p_2 and the fact that the specific entropy is constant for the adiabatic, internally reversible compression process. The refrigerant at state 2s is a superheated vapor with $h_{2s} = 264.7$ kJ/kg.

State 3 is saturated liquid at 26°C, so $h_3 = 85.75$ kJ/kg. The expansion through the valve is a throttling process (assumption 2), so $h_4 = h_3$.

Analysis: (a) The compressor work input is

$$\dot{W}_c = \dot{m}(h_{2s} - h_1)$$

Example

where $\dot{m}$ is the mass flow rate of refrigerant. Inserting values

$$\dot{W}_c = (0.08\text{ kg/s})(264.7 - 247.23)\text{ kJ/kg}\left|\frac{1\text{ kW}}{1\text{ kJ/s}}\right|$$

$$= 1.4\text{ kW} \triangleleft$$

(b) The refrigeration capacity is the heat transfer rate to the refrigerant passing through the evaporator. This is given by

$$\dot{Q}_{in} = \dot{m}(h_1 - h_4)$$

$$= (0.08\text{ kg/s})|60\text{ s/min}|(247.23 - 85.75)\text{ kJ/kg}\left|\frac{1\text{ ton}}{211\text{ kJ/min}}\right|$$

$$= 3.67\text{ ton} \triangleleft$$

(c) The coefficient of performance β is

$$\beta = \frac{\dot{Q}_{in}}{\dot{W}_c} = \frac{h_1 - h_4}{h_{2s} - h_1} = \frac{247.23 - 85.75}{264.7 - 247.23} = 9.24 \triangleleft$$

(d) For a Carnot vapor refrigeration cycle operating at $T_H = 299$ K and $T_C = 273$ K, the coefficient of performance determined from Eq. 8.18 is

$$\beta_{max} = \frac{T_C}{T_H - T_C} = 10.5 \triangleleft$$

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❶ The value for h_{2s} can be obtained by double interpolation in Table T-8 or by using the *Interactive Thermodynamics: IT* software that accompanies this book.

❷ As expected, the ideal vapor-compression cycle has a lower coefficient of performance than a Carnot cycle operating between the temperatures of the warm and cold regions. The smaller value can be attributed to the effects of the external irreversibility associated with desuperheating the refrigerant in the condenser (Process 2s–a on the *T–s* diagram) and the internal irreversibility of the throttling process.

Example

(b) Specific volume of refrigerant at entry to compressor $= v_1 =$ $\underline{0{\cdot}233 \text{ m}^3/\text{kg}}$

Swept volume of compressor/rev

$$= \left(\pi \times \frac{0{\cdot}075^2}{4} \times 0{\cdot}075\right) \text{m}^3$$

Effective swept volume/rev

$$= 0{\cdot}8\left(\pi \times \frac{0{\cdot}075^2}{4} \times 0{\cdot}075\right) \text{m}^3$$

Effective swept volume/h

$$= 0{\cdot}8 \times 8 \times 3600\left(\pi \times \frac{0{\cdot}075^2}{4} \times 0{\cdot}075\right)$$

$\therefore$ Mass flow of refrigerant/h

$$= \frac{0{\cdot}8 \times 8 \times 3600}{0{\cdot}233}\left(\pi \times \frac{0{\cdot}075^2}{4} \times 0{\cdot}075\right)$$

$$= \underline{32{\cdot}8 \text{ kg}}$$

Example

(c) Heat transfer in condenser $= h_2 - h_5$

$$= 544 - 116{\cdot}8 = \underline{427{\cdot}2 \text{ kJ/kg}}$$

$\therefore$ Heat transfer/h $= (427{\cdot}2 \times 32{\cdot}8)$ kJ

Let $\dot{m}$ = mass of cooling water required, kg/h.

Then,

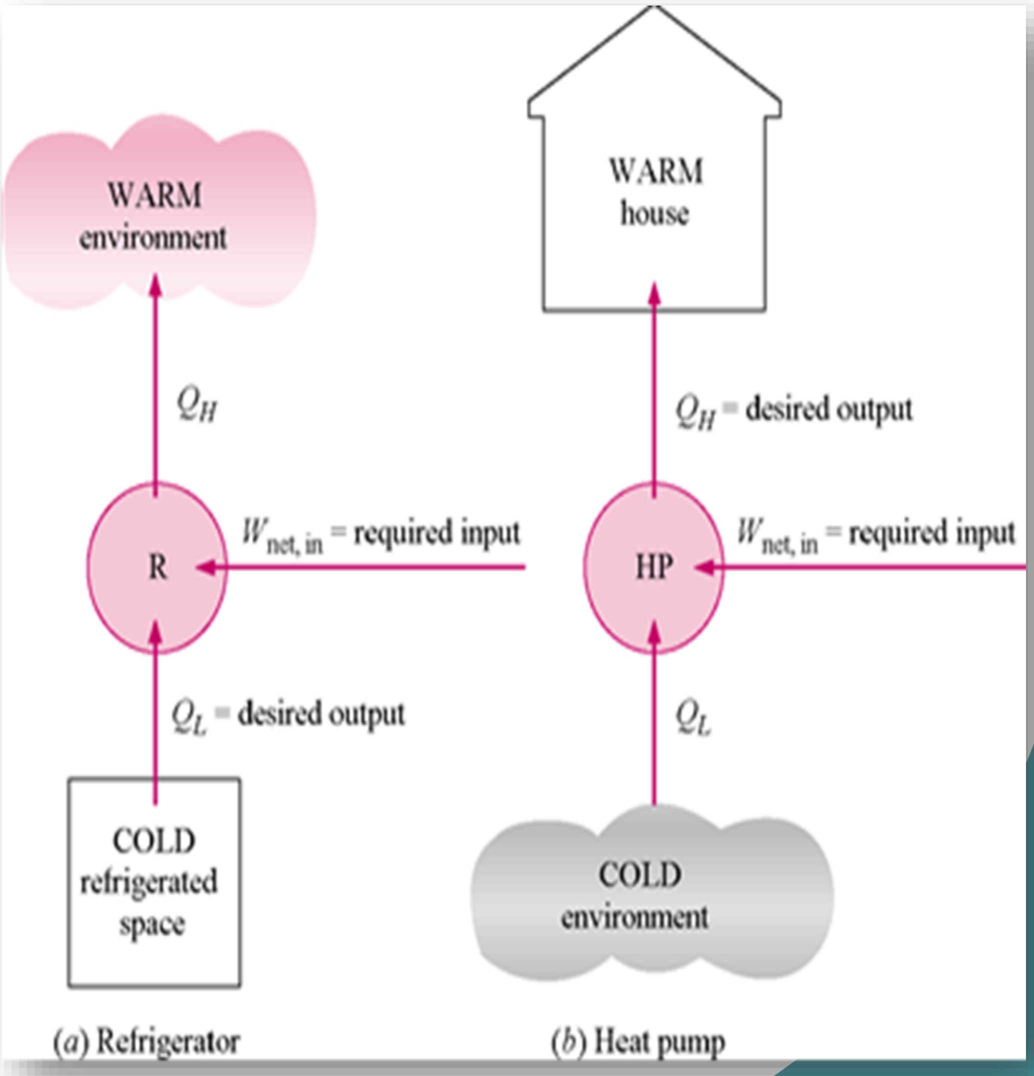
$$\dot{m} \times 4{\cdot}187 \times 12 = 427{\cdot}2 \times 32{\cdot}8$$

$$\dot{m} = \frac{427{\cdot}2 \times 32{\cdot}8}{4{\cdot}187 \times 12}$$

$$= \underline{279 \text{ kg/h}}$$

THE HEAT PUMP

- The figure shows the objectives of **refrigerators** and **heat pumps**.
- The purpose of a refrigerator is the removal of heat, called **the cooling load**, from a low temperature medium.
- The purpose of a heat pump is the transfer of heat to a high temperature medium, called the **heating load**.
- When we are interested in the heat energy removed from a low temperature space, the device is called a refrigerator. When we are interested in the heat energy supplied to the high temperature space, the device is called a heat pump.
- In general, the term "heat pump" is used to describe the cycle as heat energy is removed from the low temperature space and rejected to the high temperature space.



THE HEAT PUMP

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

Both COP_R and COP_{HP} can be larger than 1. Under the same operating conditions, the COPs are related by

$$COP_{HP} = COP_R + 1$$

Example

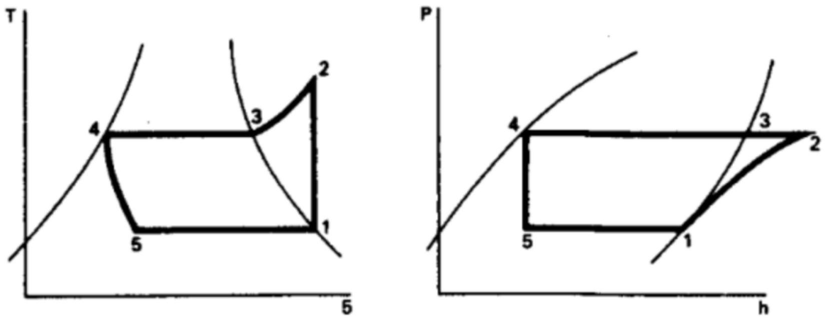
A simple heat pump circulates Freon-12 and is required for space heating. The heat pump consists of an evaporator, compressor, condenser and a throttle regulator. The pump works between the pressure limits of 0·491 MN/m² and 1·219 MN/m². The heat transfer required from the condenser unit is 100 MJ/h. The Freon-12 is assumed dry saturated at the beginning of compression and to have a temperature of 55°C after compression. At the end of the condensation process the refrigerant is liquid but not undercooled. The specific heat capacity of the superheated vapour can be assumed constant. Determine:

(a) the mass flow of the Freon-12 in kg/h assuming no energy loss;
(b) the dryness fraction of the Freon-12 at entry to the evaporator;
(c) the power of the driving motor assuming that only 70% of the power of the driving motor appears in the Freon-12.
(d) the ratio of the heat transferred from the condenser to the power required to drive the motor in the same time.

The relevant properties of the Freon-12 are as follows:

Press. MN/m²	Sat. temp. °C	Spec. enthalpy kJ/kg		Spec. entropy kJ/kg K	
		h_f	h_g	s_f	s_g
0·491	15	50·1	193·8	0·1915	0·6902
1·219	50	84·9	206·5	0·3037	0·6797

Example



(a) $s_1 = \underline{0{\cdot}6902 \text{ kJ/kg K}}$

$$s_2 = s_3 + c_{pv} \ln \frac{T_2}{T_1}$$

$$s_1 = s_2$$

$T_2 = 55 + 273 = \underline{328\ K}$ and $T_3 = 50 + 273 = \underline{323\ K}$

$$\therefore\ 0{\cdot}6902 = 0{\cdot}6797 + c_{pv} \ln \frac{328}{323}$$

$$= 0{\cdot}6797 + c_{pv} \ln 1{\cdot}015$$

$$= 0{\cdot}6797 + 0{\cdot}0149\, c_{pv}$$

$$\therefore\ c_{pv} = \frac{0{\cdot}6902 - 0{\cdot}6797}{0{\cdot}0149} = \frac{0{\cdot}0105}{0{\cdot}0149} = \underline{0{\cdot}705 \text{ kJ/kg K}}$$

$$h_2 = h_3 + c_{pv}(T_2 - T_3) = 206{\cdot}5 + 0{\cdot}705(328 - 323)$$

$$= 206{\cdot}5 + (0{\cdot}705 \times 5) = 206{\cdot}5 + 3{\cdot}525$$

Example

$$= 210{\cdot}025 \text{ kJ/kg}$$

$$h_4 = \underline{84{\cdot}9 \text{ kJ/kg}}$$

$$\text{Heat transfer from condenser} = 210{\cdot}025 - 84{\cdot}9 = \underline{125{\cdot}125 \text{ kJ/kg}}$$

$$\therefore \text{ mass flow of refrigerant} = \frac{100\,000}{125{\cdot}125} = \underline{799 \text{ kg/h}}$$

(b) $h_4 = h_5 = \underline{84{\cdot}9 \text{ kJ/kg}}$

$$\therefore \; 84{\cdot}9 = 50{\cdot}1 + x_5(193{\cdot}8 - 50{\cdot}1)$$

$$x_5 = \frac{84{\cdot}9 - 50{\cdot}1}{143{\cdot}7} = \frac{34{\cdot}8}{143{\cdot}7} = \underline{0{\cdot}242}$$

(c) $\text{Specific work} = h_2 - h_1$

$$= 210{\cdot}025 - 193{\cdot}8 = \underline{16{\cdot}225 \text{ kJ/kg}}$$

$$\text{Mass flow of refrigerant} = \frac{798}{3\,600} = \underline{0{\cdot}222 \text{ kg/s}}$$

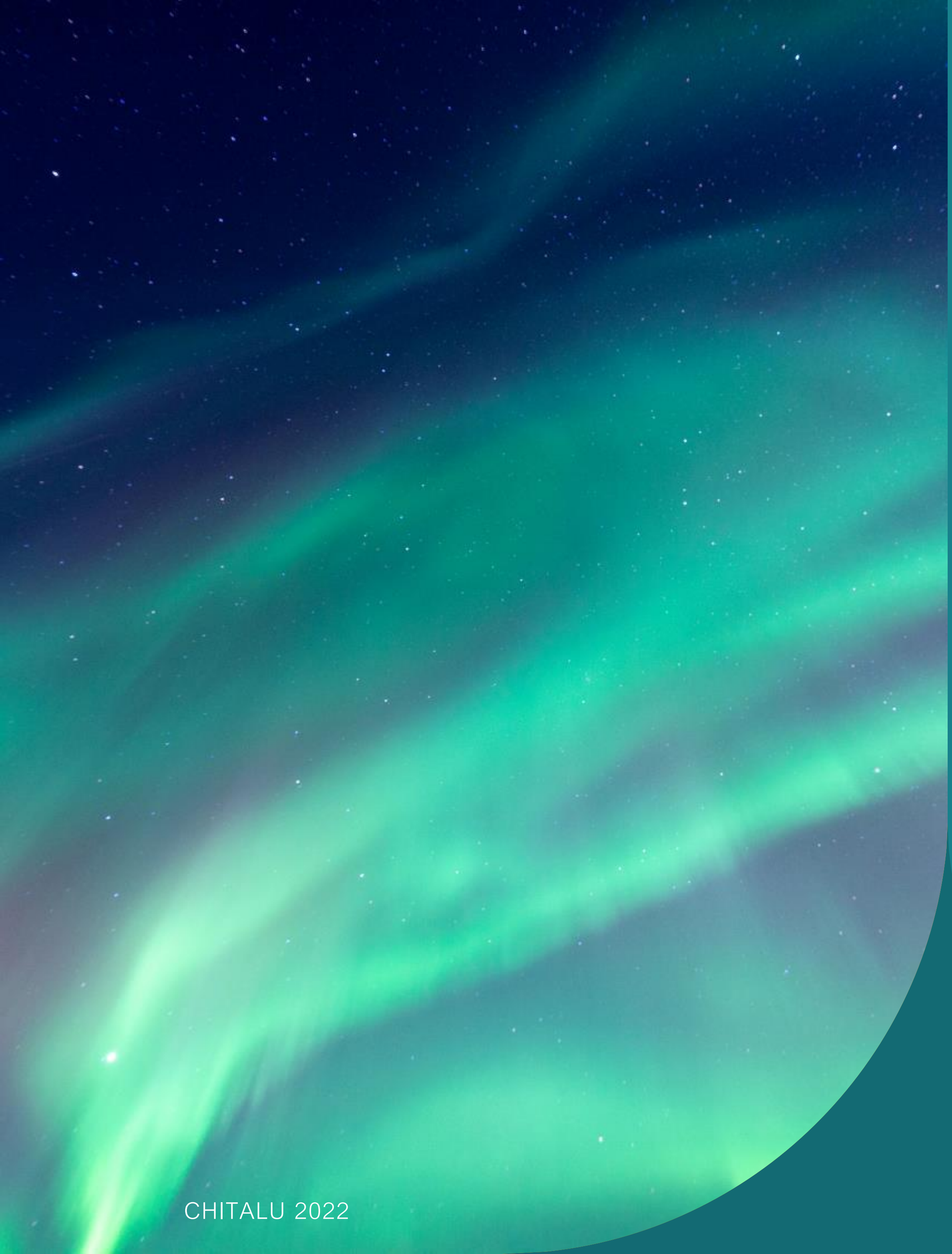
$$\therefore \; \text{Power of driving motor} = \frac{16{\cdot}225 \times 0{\cdot}222}{0{\cdot}7} = \underline{5{\cdot}15 \text{ kW}}$$

(d) $\text{Heat transfer from condenser} = \dfrac{100\,000}{3\,600} \text{ kJ/s}$

$$\therefore \; \text{Ratio} = \frac{100\,000}{3\,600 \times 5{\cdot}15} = \underline{5{\cdot}39:1}$$

“With the advance of Refrigeration, I hope that along with the frozen foods, someday we will have frozen conversation. A person will be able to keep a frozen promise indefinitely”

FRED ALLEN



Thank You

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