

**24AG301- APPLIED THERMODYNAMICS AND THERMAL
SYSTEMS IN AGRICULTURAL ENGINEERING**

**UNIT 3 REFRIGERATION SYSTEMS IN AGRICULTURAL
STORAGE**

HANDLED BY

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Problem

A refrigeration machine is required to produce i.e., at 0°C from water at 20°C . The machine has a condenser temperature of 298 K while the evaporator temperature is 268 K . The relative efficiency of the machine is 50% and 6 kg of Freon-12 refrigerant is circulated through the system per minute. The refrigerant enters the compressor with a dryness fraction of 0.6 . Specific heat of water is 4.187 kJ/kg K and the latent heat of ice is 335 kJ/kg . Calculate the amount of ice produced on 24 hours . The table of properties of Freon-12 is given below :

Temperature K	Liquid heat kJ/kg	Latent heat kJ/g	Entropy of liquid kJ/kg
298	59.7	138.0	0.2232
268	31.4	154.0	0.1251

(U.P.S.C.)

Solution. Given : $m = 6\text{ kg/min.}$; $\eta_{\text{relative}} = 50\%$; $x_2 = 0.6$;
 $c_{pw} = 4.187\text{ kJ/kg K}$; Latent heat of ice = 335 kJ/kg .

Refer to Fig. 26.23

$$h_{f_2} = 31.4\text{ kJ/kg} ; h_{fg_2} = 154.0\text{ kJ/kg} ;$$

$$h_{f_3} = 59.7\text{ kJ/kg} ;$$

$$h_{fg_3} = 138\text{ kJ/kg} ; h_{f_4} = 59.7\text{ kJ/kg}$$

...From the table given above

$$h_2 = \overline{h_{f_2}} + x_2 h_{fg_2}$$

$$= 31.4 + 0.6 \times 154 = 123.8\text{ kJ/kg}$$

For isentropic compression 2-3, we have

$$s_3 = s_2$$

$$s_{f_3} + x_3 \frac{h_{fg_3}}{T_3} = s_{f_2} + x_2 \frac{h_{fg_2}}{T_2}$$

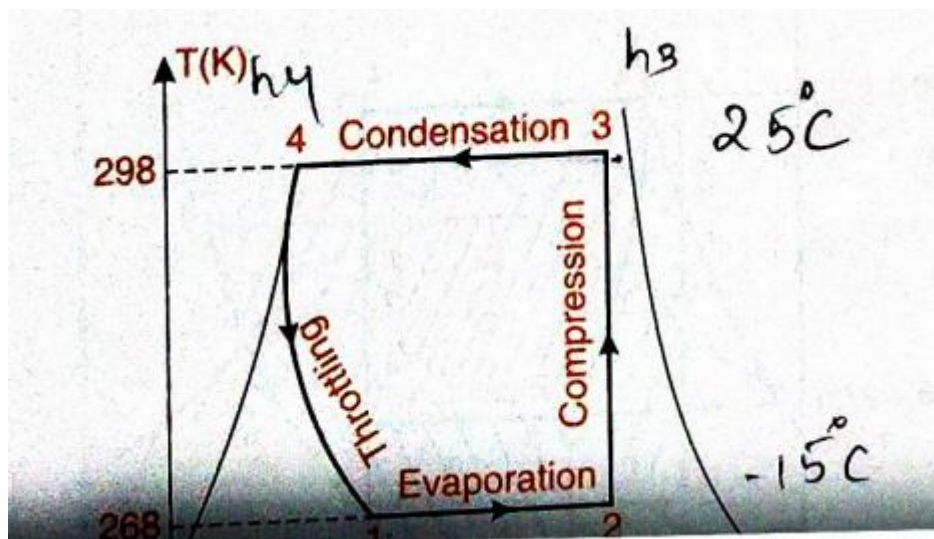
$$s_{f_3} + x_3 \frac{h_{fg_3}}{T_3} = s_{f_2} + x_2 \frac{h_{fg_2}}{T_2}$$

$$0.2232 + x_3 \times \frac{138}{298} = 0.1251 + 0.6 \times \frac{154}{268}$$

$$= 0.4698$$

$$x_3 = (0.4698 - 0.2232) \times \frac{298}{138}$$

$$= 0.5325$$



Now, $h_3 = h_{f_3} + x_3 h_{fg_3} = 59.7 + 0.5325 \times 138$
 $= 133.2 \text{ kJ/kg}$

Also, $h_1 = h_{f_1} = 59.7 \text{ kJ/kg}$

Theoretical C.O.P. = $\frac{R_n}{W}$

$$= \frac{h_2 - h_1}{h_3 - h_2} = \frac{123.8 - 59.7}{133.2 - 123.8} = 6.82$$

Actual C.O.P. = $\eta_{\text{relative}} \times (\text{C.O.P.})_{\text{theoretical}}$
 $= 0.5 \times 6.82 = 3.41$

Heat extracted from 1 kg of water at 20°C for the formation of 1 kg of ice at 0°C

$$= 1 \times 4.187 \times (20 - 0) + 335$$

$$= 418.74 \text{ kJ/kg}$$

Let m_{ice} = Mass of ice formed in kg/min.

$$(\text{C.O.P.})_{\text{actual}} = 3.41 = \frac{R_n(\text{actual})}{W}$$

$$= \frac{m_{\text{ice}} \times 418.74}{m(h_3 - h_2)} = \frac{m_{\text{ice}} \times 418.74 \text{ (kJ/min)}}{6(133.2 - 123.8) \text{ (kJ/min)}}$$

$$\therefore m_{\text{ice}} = \frac{6(133.2 - 123.8) \times 3.41}{418.74} = 0.459 \text{ kg/min}$$

$$= \frac{0.459 \times 60 \times 24}{1000} \text{ tonnes (in 24 hours)}$$

$$= \mathbf{0.661 \text{ tonne. (Ans.)}}$$

Problem

A simple vapour compression plant produces 5 tonnes of refrigeration. The enthalpy values at inlet to compressor, at exit from the compressor, and at exit from the condenser are 183.19, 209.41 and 74.59 kJ/kg respectively. Estimate :

- The refrigerant flow rate,
- The C.O.P.,
- The power required to drive the compressor, and
- The rate of heat rejection to the condenser.

Solution. Total refrigeration effect produced = 5 TR (tonnes of refrigeration)

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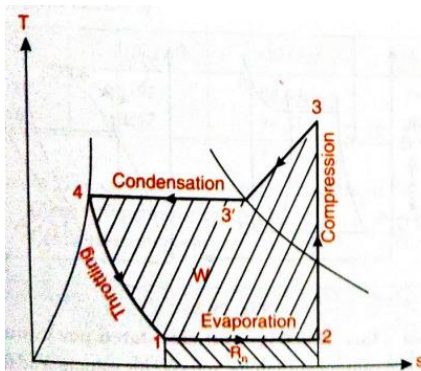
$$= 5 \times 14000 = 70000 \text{ kJ/h or } 19.44 \text{ kJ/s}$$

Handwritten: 5 x 1000 / 24 kJ/3600

$$= 19.38 \quad (\because 1 \text{ TR} = 14000 \text{ kJ/h})$$

Refer to Fig. 26.26.

Given : $h_2 = 183.19 \text{ kJ/kg}$; $h_3 = 209.41 \text{ kJ/kg}$;
 $h_4 (= h_1) = 74.59 \text{ kJ/kg}$ (Throttling process)



(i) The refrigerant flow rate, $\dot{m}$:

$$\begin{aligned}\text{Net refrigerating effect produced per kg} &= h_2 - h_1 \\ &= 183.19 - 74.59 = 108.6 \text{ kJ/kg}\end{aligned}$$

$\therefore$ Refrigerant flow rate,

$$\dot{m} = \frac{19.44}{108.6} = 0.179 \text{ kg/s. (Ans.)}$$

(ii) The C.O.P. :

$$\begin{aligned}\text{C.O.P.} &= \frac{R_n}{W} = \frac{h_2 - h_1}{h_3 - h_2} = \frac{183.19 - 74.59}{209.41 - 183.19} \\ &= 4.142. \text{ (Ans.)}\end{aligned}$$

(iii) The power required to drive the compressor, P :

$$\begin{aligned}P &= \dot{m} (h_3 - h_2) = 0.179 (209.41 - 183.19) \\ &= 4.69 \text{ kW. (Ans.)}\end{aligned}$$

(iv) The rate of heat rejection to the condenser :

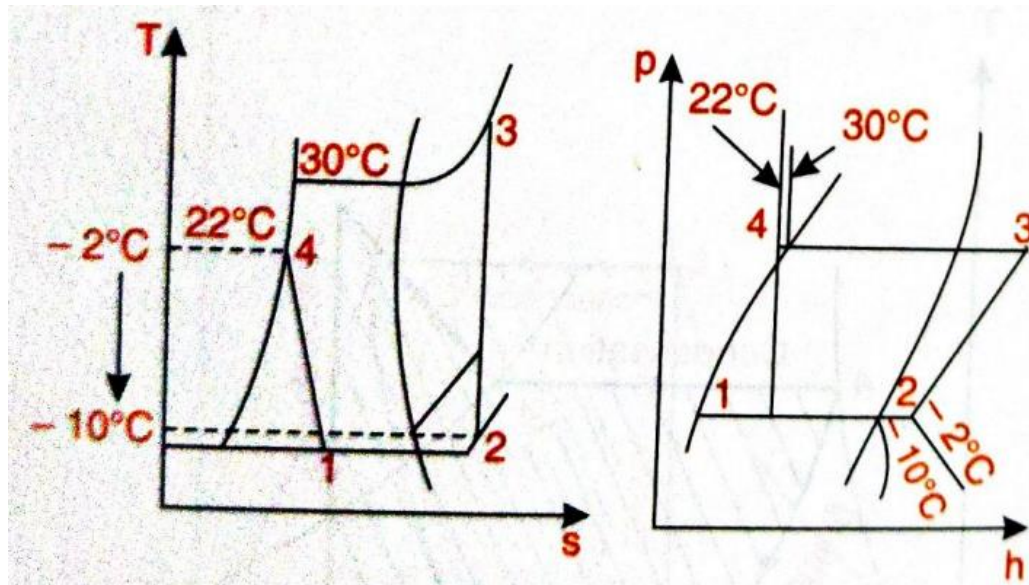
The rate of heat rejection to the condenser

$$\begin{aligned}&= \dot{m} (h_3 - h_4) \\ &= 0.179 (209.41 - 74.59) \\ &= 24.13 \text{ kW. (Ans.)}\end{aligned}$$

Problem

A R-12 refrigerator works between the temperature limits of -10°C and $+30^\circ\text{C}$. The compressor employed is of $20 \text{ cm} \times 15 \text{ cm}$, twin cylinder, single-acting compressor having a volumetric efficiency of 85%. The compressor runs at 500 r.p.m. The refrigerant is sub-cooled and it enters at 22°C in the expansion valve. The vapour is superheated and enters the compressor at -2°C . Work out the following :

(i) Show the process on T - s and p - h diagrams ; (ii) The amount of refrigerant circulated per minute ; (iii) The tonnes of refrigeration ; (iv) The C.O.P. of the system.



(ii) Mass of refrigerant circulated per minute :

The value of enthalpies and specific volume read from $p-h$ diagram are as under :

$$h_2 = 352 \text{ kJ/kg} ; h_3 = 374 \text{ kJ/kg}$$

$$h_4 = h_1 = 221 \text{ kJ/kg} ; v_2 = 0.08 \text{ m}^3/\text{kg}$$

Refrigerants effect per kg =

$$= h_2 - h_1 = 352 - 221 = 131 \text{ kJ/kg}$$

Volume of refrigerant admitted per min.

$$= \frac{\pi}{4} D^2 L \times \text{r.p.m.} \times 2 \times \eta_{\text{vol}}, \text{ for twin cylinder, single acting}$$

$$= \frac{\pi}{4} (0.2)^2 \times 0.15 \times 500 \times 2 \times 0.85$$

$$= 4 \text{ m}^3/\text{min}$$

Mass of refrigerant per min

$$= \frac{4}{0.08} = 50 \text{ kg/min. (Ans.)}$$

(iii) Cooling capacity in tonnes of refrigeration :

$$\begin{aligned}\text{Cooling capacity} &= 50(h_2 - h_1) = 50 \times 131 \\ &= 6550 \text{ kJ/min or } 393000 \text{ kJ/h} \\ &= \frac{393000}{14000} = \mathbf{28.07 \text{ TR. (Ans.)}}\end{aligned}$$

($\because$ 1 tonne of refrigeration TR = 14000 kJ/h)

(iv) The C.O.P. of the system :

$$\begin{aligned}\text{Work per kg} &= (h_2 - h_1) = 374 - 352 = 22 \text{ kJ/kg} \\ \text{C.O.P.} &= \frac{131}{22} = \mathbf{5.95. (Ans.)}\end{aligned}$$

Example A refrigerator uses R-134a as the working fluid and operates on an ideal vapour compression cycle between 0.14 MPa and 0.8 MPa. If the mass flow rate of the refrigerant is 0.06 kg/s, determine (a) the rate of heat removal from the refrigerated space, (b) the power input to the compressor, (c) the heat rejection rate in the condenser, and (d) the COP.

Solution From the R-134a tables, the enthalpies at the four states (Fig.) are:

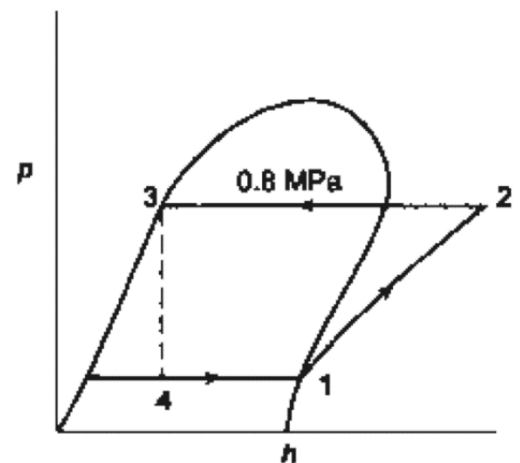


Fig.

$$h_1 = 236.04 \text{ kJ/kg}$$

$$s_1 = 0.9322 \text{ kJ/kg K} = s_2$$

$$p_2 = 0.8 \text{ MPa}, s_2 = 0.9322 \text{ kJ/kgK},$$

$$h_2 = 272.05 \text{ kJ/kg}, h_3 = h_4 = 93.42 \text{ kJ/kg}$$

$$Q_2 = 0.06 (236.04 - 93.42) = 8.56 \text{ kW} \quad \text{Ans. (a)}$$

$$W_c = 0.06 (272.05 - 236.04) = 2.16 \text{ kW} \quad \text{Ans. (b)}$$

$$\begin{aligned}
 \text{Heat rejected to the condenser} &= \dot{m}(h_2 - h_3) \\
 &= 0.18 (209.41 - 74.59) \\
 &= 24.27 \text{ kW} \quad \text{Ans. (e)} \\
 h_4 &= h_f + x_4 h_{fg} = 26.87 + x_4 \times 156.31 = 74.59 \\
 \therefore x_4 &= \frac{47.72}{156.31} = 0.305
 \end{aligned}$$

$$\therefore \text{Flash gas percentage} = 30.5\% \quad \text{Ans. (f)}$$

$$\begin{aligned}
 \text{COP} &= \frac{h_1 - h_4}{h_2 - h_1} = \frac{183.19 - 74.59}{209.41 - 183.19} \\
 &= \frac{108.60}{26.22} = 4.14 \quad \text{Ans. (g)}
 \end{aligned}$$

$$\begin{aligned}
 \text{Power required to drive the compressor} \\
 &= \dot{m}(h_2 - h_1) = 0.18 \times 26.22 = 4.72 \text{ kW} \quad \text{Ans. (h)}
 \end{aligned}$$

$$\text{COP (Reversible)} = \frac{T_2}{T_1 - T_2} = \frac{263}{50} = 5.26$$

$$\therefore \frac{\text{COP (Vap. Comp. cycle)}}{\text{COP (Carnot cycle)}} = \frac{4.14}{5.26} = 0.787 \quad \text{Ans.}$$

Example A Refrigerant-12 vapour compression plant producing 10 tonnes of refrigeration operates with condensing and evaporating temperatures of 35°C and -10°C respectively. A suction line heat exchanger is used to subcool the saturated liquid leaving the condenser. Saturated vapour leaving the evaporator is superheated in the suction line heat exchanger to the extent that a discharge temperature of 60°C is obtained after isentropic compression.

Determine (a) the subcooling achieved in the heat exchanger, (b) the refrigerant flow rate in kg/s, (c) the cylinder dimensions of the two-cylinder compressor, if the speed is 900 rpm, stroke-to-bore ratio is 1.1, and the volumetric efficiency is 80%, (d) the COP of the plant, and (e) the power required to drive the compressor in kW.

Solution From the p - h chart of R-12, the property values at the states, as shown in Fig. Ex.

$$\begin{aligned}
 h_3 &= 882, h_2 = 1034 \\
 h_6 &= 998, h_1 = 1008 \text{ kJ/kg} \\
 v_1 &= 0.084 \text{ m}^3/\text{kg}
 \end{aligned}$$

$$h_3 - h_4 = h_1 - h_6$$