AIR REFRIGERATION SYSTEM

3.2 Merits and Demerits of Air Refrigeration System

Following are the merits and demerits of air refrigeration system:

Merits

1. The air is easily available and there is no cost of the refrigerant.
2. The air is non-toxic and non-inflammable.
3. The leakage of air in small amounts is tolerable.
4. Since the main compressor is employed for the compressed air source, therefore there is no problem of space for extra compressor.
5. The air is light in weight per tonne of refrigeration.
6. The chilled air is directly used for cooling, there by eliminating the cost of separate evaporator.
7. Since the pressure in the whole system is quite low, therefore the piping, ducting etc. are quite simple to design, fabricate and maintain.

Demerits

1. It has low coefficient of performance.
2. The rate of air circulation is relatively large.

3.4 Simple Air Cooling System

A simple air cooling system for aircrafts is shown in Fig. 3.1. The main components of this system are the main compressor driven by a gas turbine, a heat exchanger, a cooling turbine and a cooling air fan. The air required for refrigeration system is bled off from the main compressor. This high pressure and high temperature air is cooled initially in the heat exchanger where ram air is used for cooling. It is further cooled in the cooling turbine by the process of expansion. The work of this turbine is used to drive the cooling fan which draws cooling air through the heat exchanger. This system is good for ground surface cooling and for low flight speeds.

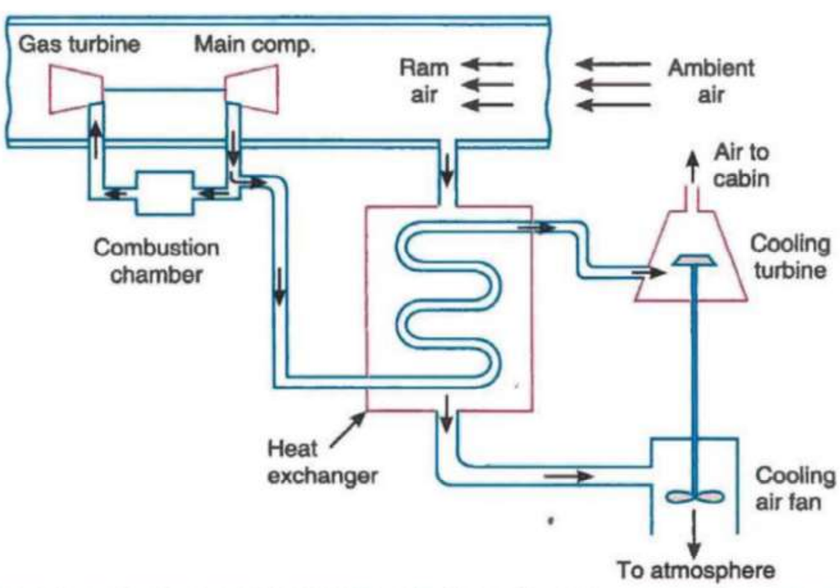
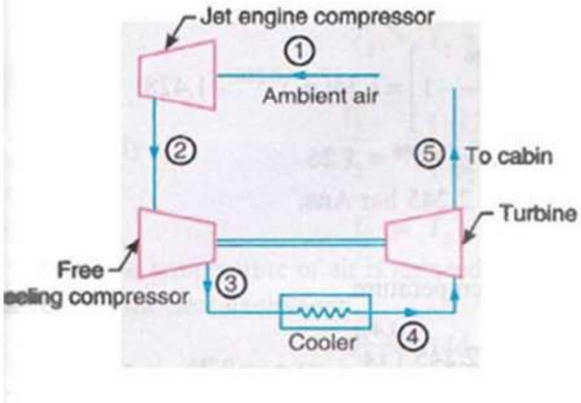
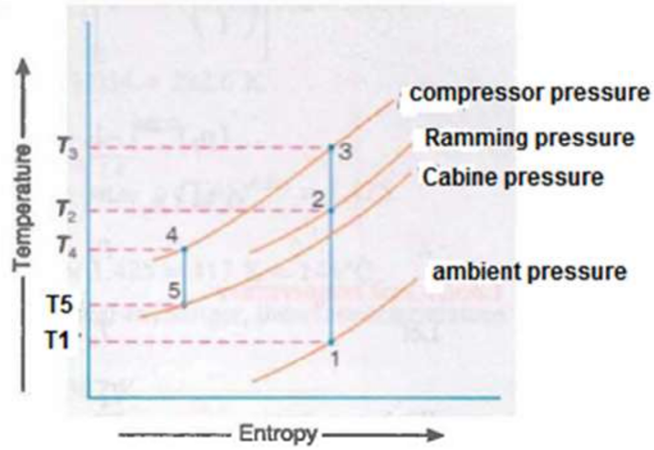


Fig. 3.1. Simple air cooling system.

The schematic diagram and T-s diagram of the simple air-conditioning system



(*a*) Schematic diagram.



(*b*) T-s diagram.

Example 3.2. *A simple air cooled system is used for an aeroplane having a load of* **10** *tonnes. The atmospheric pressure and temperature are 0.9 bar and 10°C respectively.* **The** *pressure increases to 1.013 bar due to ramming. The temperature of the air is reduced by 50°C* **in** *the heat exchanger. The pressure in the cabin is 1.01 bar and the temperature of air leaving* **the** *cabin is 25°C. Determine : 1 Power required to take the load of cooling in the cabin; and C.O.P. of the system.*

Assume that all the expansions and compressions are isentropic. The pressure of the compressed air is 3.5 bar.

Solution. Given : $Q = 10$ TR ; $p_1 = 0.9$ bar ; $T_1 = 10°C = 10 + 273 = 283$ K ; $p_2 = 1.013$ bar ; $p_5 = p_6 = 1.01$ bar ; $T_6 = 25°C = 25 + 273 = 298$ K ; $p_3 = 3.5$ bar

1. *Power required to take the load of cooling in the cabin*

First of all, let us find the mass of air (m_a) required for the refrigeration purpose. Since the compressions and expansions are isentropic, therefore the various processes on the T-s diagram are as shown in Fig. 3.4.

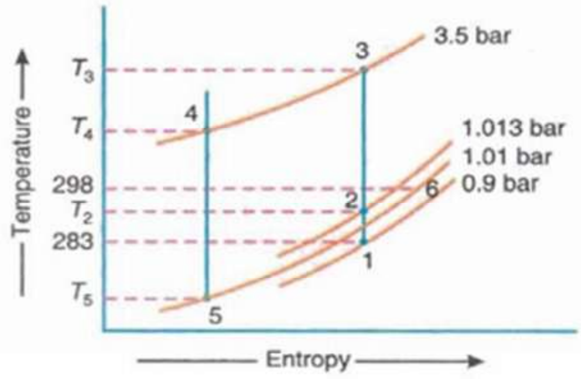
Let

T_2 = Temperature of air at the end of ramming or entering the main compressor,

T_3 = Temperature of air leaving the main compressor after isentropic compression,

T_4 = Temperature of air leaving the heat exchanger, and

T_5 = Temperature of air leaving the cooling turbine.



We know that $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.013}{0.9}\right)^{\frac{1.4-1}{1.4}} = (1.125)^{0.286} = 1.034$

$\therefore \quad T_2 = T_1 \times 1.034 = 283 \times 1.034 = 292.6 \text{ K}$

Similarly $\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.5}{1.013}\right)^{\frac{1.4-1}{1.4}} = (3.45)^{0.286} = 1.425$

$\therefore \quad T_3 = T_2 \times 1.425 = 292.6 \times 1.425 = 417 \text{ K} = 144°\text{C}$

Since the temperature of air is reduced by 50°C in the heat exchanger, therefore temperature of air leaving the heat exchanger,

$$T_4 = 144 - 50 = 94°\text{C} = 367 \text{ K}$$

We know that $\frac{T_5}{T_4} = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.01}{3.5}\right)^{\frac{1.4-1}{1.4}} = (0.288)^{0.286} = 0.7$

$\therefore \quad T_5 = T_4 \times 0.7 = 367 \times 0.7 = 257 \text{ K}$

We know that mass of air required for the refrigeration purpose,

$$m_a = \frac{210\,Q}{c_p(T_6 - T_5)} = \frac{210 \times 10}{1\,(298 - 257)} = 51.2 \text{ kg/min}$$

... (Taking c_p for air = 1 kJ/kg K)

$\therefore$ Power required to take the load of cooling in the cabin,

$$P = \frac{m_a c_p (T_3 - T_2)}{60} = \frac{51.2 \times 1\,(417 - 292.6)}{60} = 106 \text{ kW}$$ **Ans.**

Rotary engine power generator sets for air-crafts.

C.O.P. of the system

We know that C.O.P. of the system

$$= \frac{210\,Q}{P \times 60} = \frac{210 \times 10}{106 \times 60} = 0.33$$ **Ans.**

Example 3.3. *An aircraft refrigeration plant has to handle a cabin load of 30 tonnes. The atmospheric temperature is 17°C. The atmospheric air is compressed to a pressure of 0.95 bar and temperature of 30°C due to ram action. This air is then further compressed in a compressor to 4.75 bar, cooled in a heat exchanger to 67°C, expanded in a turbine to 1 bar pressure and supplied to the cabin. The air leaves the cabin at a temperature of 27°C. The isentropic efficiencies of both compressor and turbine are 0.9. Calculate the mass of air circulated per minute and the C.O.P. For air, c_p = 1.004 kJ/kg K and c_p / c_v = 1.4*

Solution. Given : Q = 30 TR ; T_1 = 17°C = 17 + 273 = 290 K ; p_2 = 0.95 bar ; T_2 = 30°C = 30 + 273 = 303 K ; $p_3 = p_{3'}$ = 4.75 bar ; T_4 = 67°C = 67 + 273 = 340 K ; $p_5 = p_{5'}$ = 1 bar ; T_6 = 27°C = 27 + 273 = 300 K ; $\eta_C = \eta_T$ = 0.9 ; c_p = 1.004 kJ/kg K ; $c_p / c_v = \gamma$ = 1.4

The *T-s* diagram for the simple air refrigeration cycle with the given conditions is shown in Fig. 3.5.

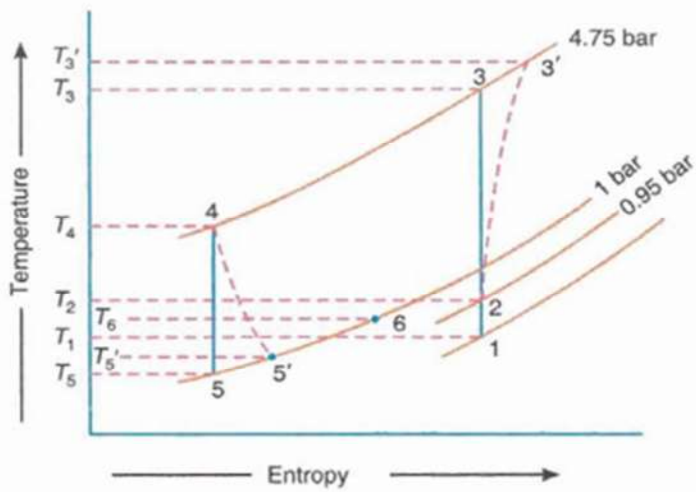


Fig. 3.5

Let T_3 = Temperature of the air after isentropic compression in the compressor,

$T_{3'}$ = Actual temperature of the air leaving the compressor,

T_5 = Temperature of the air leaving the turbine after isentropic expansion, and

$T_{5'}$ = Actual temperature of the air leaving the turbine.

We know that for isentropic compression process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.75}{0.95}\right)^{\frac{1.4-1}{1.4}} = (5)^{0.286} = 1.584$$

$$\therefore \quad T_3 = T_2 \times 1.584 = 303 \times 1.584 = 480 \text{ K}$$

and isentropic efficiency of the compressor,

$$\eta_C = \frac{\text{Isentropic increase in temperature}}{\text{Actual increase in temperature}} = \frac{T_3 - T_2}{T_{3'} - T_2}$$

$$0.9 = \frac{480 - 303}{T_{3'} - 303} = \frac{177}{T_{3'} - 303}$$

$$\therefore \quad T_{3'} - 303 = 177/0.9 = 196.7 \quad \text{or} \quad T_{3'} = 303 + 196.7 = 499.7 \text{ K}$$

Now for the isentropic expansion process 4-5,

$$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.75}{1}\right)^{\frac{1.4-1}{1.4}} = (4.75)^{0.286} = 1.561$$

$$\therefore \quad T_5 = T_4 / 1.561 = 340 / 1.561 = 217.8 \text{ K}$$

and isentropic efficiency of the turbine,

$$\eta_T = \frac{\text{Actual increase in temperature}}{\text{Isentropic increase in temperature}} = \frac{T_4 - T_{5'}}{T_4 - T_5}$$

$$0.9 = \frac{340 - T_{5'}}{340 - 217.8} = \frac{340 - T_{5'}}{122.2}$$

$$\therefore \quad T_{5'} = 340 - 0.9 \times 122.2 = 230 \text{ K}$$

Mass of air circulated per minute

We know that mass of air circulated per minute,

$$m_a = \frac{210\,Q}{c_p(T_6 - T_{5'})} = \frac{210 \times 30}{1.004\,(300 - 230)} = 89.64 \text{ kg/min} \textbf{ Ans.}$$

C.O.P.

We know that $\quad \text{C.O.P.} = \dfrac{210\,Q}{m_a c_p (T_{3'} - T_2)} = \dfrac{210 \times 30}{89.64 \times 1.004\,(499.7 - 303)} = 0.356$ **Ans.**

3.6 Boot-strap Air Cooling System

A boot-strap air cooling system is shown in Fig. 3.14. This cooling system has two heat exchangers instead of one and a cooling turbine drives a secondary compressor instead of cooling fan. The air bled from the main compressor is first cooled by the ram air in the first heat exchanger. This cooled air, after compression in the secondary compressor, is led to the second heat exchanger where it is again cooled by the ram air before passing to the cooling turbine. This type of cooling system is mostly used in transport type aircraft.

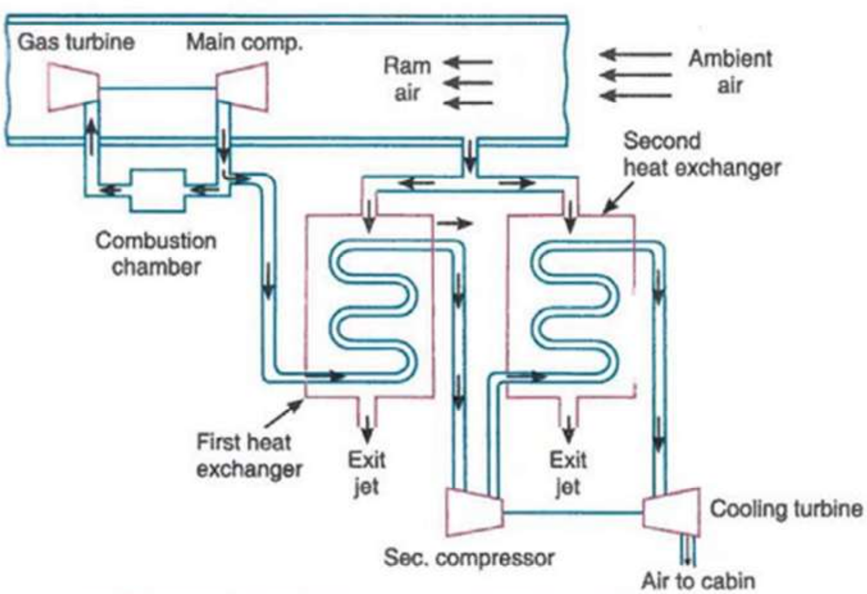
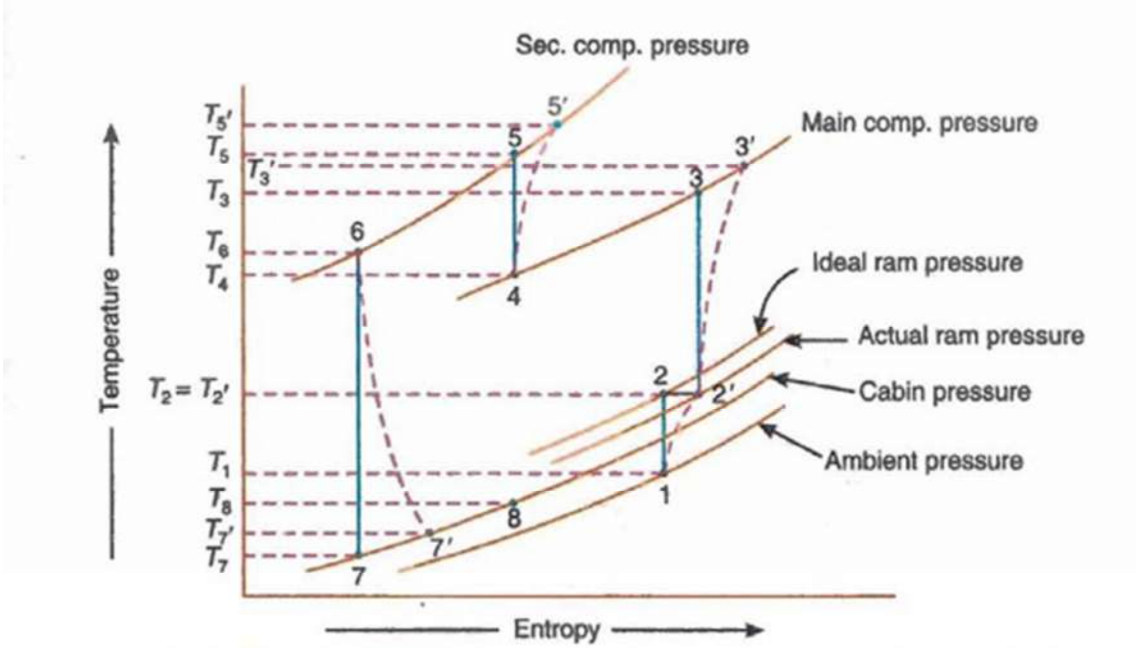


Fig. 3.14. Boot-strap air cooling system.



Example 3.9. *A boot-strap cooling system of 10 TR capacity is used in an aeroplane. The ambient air temperature and pressure are 20°C and 0.85 bar respectively. The pressure of air increases from 0.85 bar to 1 bar due to ramming action of air. The pressure of air discharged from the main compressor is 3 bar. The discharge pressure of air from the auxiliary compressor is 4 bar. The isentropic efficiency of each of the compressor is 80%, while that of turbine is 85%. 50% of the enthalpy of air discharged from the main compressor is removed in the first heat exchanger and 30% of the enthalpy of air discharged from the auxiliary compressor is removed in the second heat exchanger using rammed air. Assuming ramming action to be isentropic, the required cabin pressure of 0.9 bar and temperature of the air leaving the cabin not more than 20°C, find : 1. the power required to operate the system; and 2. the C.O.P. of the system. Draw the schematic and temperature -entropy diagram of the system. Take* $\gamma = 1.4$ *and* $c_p = 1$ *kJ/kg K.*

Solution. Given : $Q = 10$ TR ; $T_1 = 20°C = 20 + 273 = 293$ K ; $p_1 = 0.85$ bar ; $p_2 = 1$ bar ; $p_3 = p_{3'} = p_4 = 3$ bar ; $p_5 = p_{5'} = p_6 = 4$ bar ; $\eta_{C1} = \eta_{C2} = 80\% = 0.8$; $\eta_T = 85\% = 0.85$; $p_7 = p_{7'} = p_8 = 0.9$ bar ; $T_8 = 20°C = 20 + 273 = 293$ K ; $\gamma = 1.4$; $c_p = 1$ kJ/kg K

The schematic diagram for a boot-strap cooling system is shown in Fig. 3.14. The temperature- entropy (*T-s*) diagram with the given conditions is shown in Fig. 3.16.

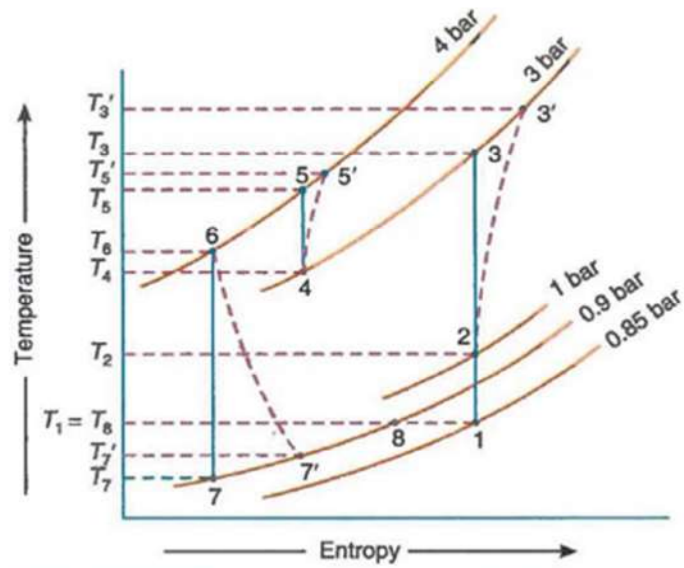


Fig. 3.16

We know that for isentropic ramming process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{0.85}\right)^{\frac{1.4-1}{1.4}} = (1.176)^{0.286} = 1.047$$

$\therefore$ $$T_2 = T_1 \times 1.047 = 293 \times 1.047 = 306.8 \text{ K} = 33.8°\text{C}$$

Now for isentropic process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3}{1}\right)^{\frac{1.4-1}{1.4}} = (3)^{0.286} = 1.37$$

$\therefore$ $$T_3 = T_2 \times 1.37 = 306.8 \times 1.37 = 420.3 \text{ K} = 147.3°\text{C}$$

We know that isentropic efficiency of the compressor,

$$\eta_{C1} = \frac{\text{Isentropic increase in temperature}}{\text{Actual increase in temperature}} = \frac{T_3 - T_2}{T_{3'} - T_2}$$

$$0.8 = \frac{420.3 - 306.8}{T_{3'} - 306.8} = \frac{113.5}{T_{3'} - 306.8}$$

$\therefore$ $$T_{3'} = 306.8 + 113.5/0.8 = 448.7 \text{ K} = 175.7°\text{C}$$

Since 50% of the enthalpy of air discharged from the main compressor is removed in the first heat exchanger (*i.e.* during the process 3'– 4), therefore temperature of air leaving the first heat exchanger,

$$T_4 = 0.5 \times 175.7 = 87.85°\text{C} = 360.85 \text{ K}$$

Now for the isentropic process 4–5,

$$\frac{T_5}{T_4} = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4}{3}\right)^{\frac{1.4-1}{1.4}} = (1.33)^{0.286} = 1.085$$

$\therefore$ $$T_5 = T_4 \times 1.085 = 360.85 \times 1.085 = 391.5 \text{ K} = 118.5°\text{C}$$

We know that isentropic efficiency of the auxiliary compressor,

$$\eta_{C2} = \frac{T_5 - T_4}{T_{5'} - T_4}$$

$$0.8 = \frac{391.5 - 360.85}{T_{5'} - 360.85} = \frac{30.65}{T_{5'} - 360.85}$$

$\therefore$ $$T_{5'} = 360.85 + 30.65/0.8 = 399.16 \text{ K} = 126.16°\text{C}$$

Since 30% of the enthalpy of air discharged from the auxiliary compressor is removed in the second heat exchanger (*i.e.* during the process 5′– 6), therefore temperature of air leaving the second heat exchanger,

$$T_6 = 0.7 \times 126.16 = 88.3°\text{C} = 361.3 \text{ K}$$

For the isentropic process 6–7,

$$\frac{T_7}{T_6} = \left(\frac{p_7}{p_6}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{0.9}{4}\right)^{\frac{1.4-1}{1.4}} = (0.225)^{0.286} = 0.653$$

$\therefore$ $$T_7 = T_6 \times 0.653 = 361.3 \times 0.653 = 236 \text{ K} = -37°\text{C}$$

We know that turbine efficiency,

$$\eta_T = \frac{\text{Actual increase in temperature}}{\text{Isentropic increase in temperature}} = \frac{T_6 - T_{7'}}{T_6 - T_7}$$

$$0.85 = \frac{361.3 - T_{7'}}{361.3 - 236} = \frac{361.3 - T_{7'}}{125.3}$$

$\therefore$ $$T_{7'} = 361.3 - 0.85 \times 125.3 = 254.8 \text{ K} = -18.2°\text{C}$$

1. Power required to operate the system

We know that amount of air required for cooling the cabin,

$$m_a = \frac{210\,Q}{c_p(T_8 - T_{7'})} = \frac{210 \times 10}{1\,(293 - 254.8)} = 55 \text{ kg / min}$$

and power required to operate the system,

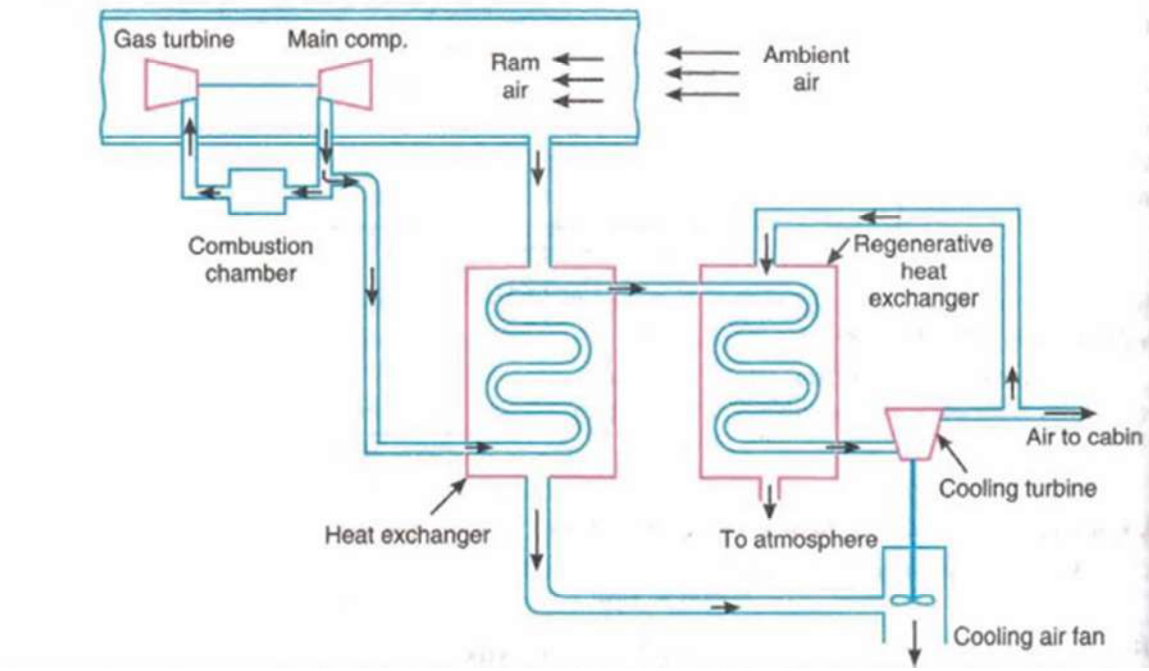
$$P = \frac{m_a c_p (T_{3'} - T_2)}{60} = \frac{55 \times 1\,(448.7 - 306.8)}{60} = 130 \text{ kW} \quad \textbf{Ans.}$$

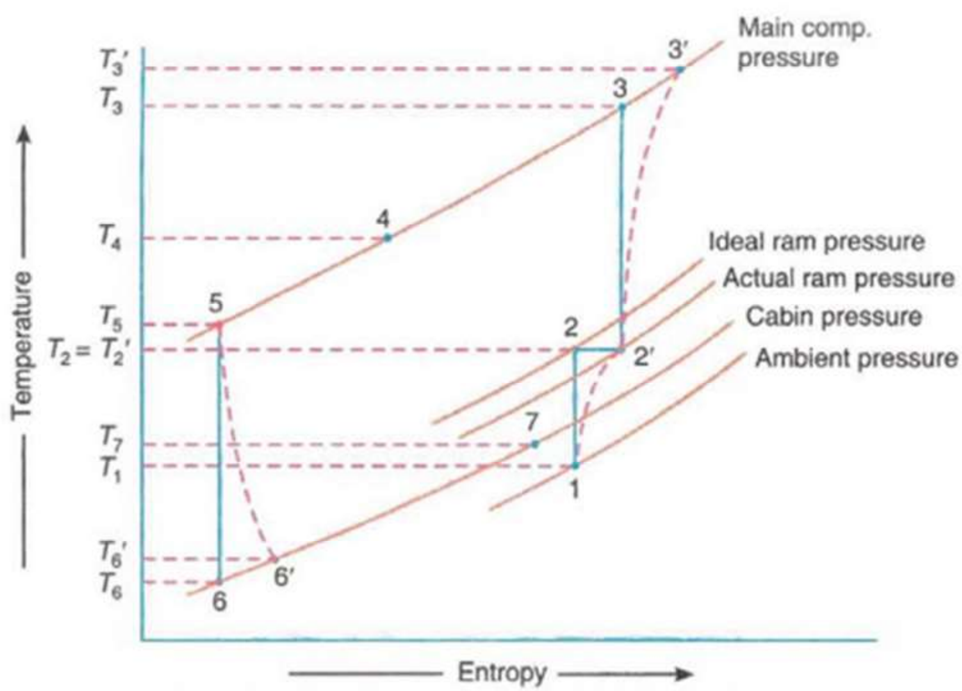
2. C.O.P. of the system

We know that C.O.P. of the system

$$= \frac{210\,Q}{m_a c_p (T_{3'} - T_2)} = \frac{210 \times 10}{55 \times 1\,(448.7 - 306.8)} = 0.27 \quad \textbf{Ans.}$$

3.9 Regenerative Air Cooling System





Example 3.13. *A regenerative air cooling system is used for an air plane to take 20 tonnes of refrigeration load. The ambient air at pressure 0.8 bar and temperature 10°C is rammed isentropically till the pressure rises to 1.2 bar. The air bled off the main compressor at 4.5 bar is cooled by the ram air in the heat exchanger whose effectiveness is 60%. The air from the heat exchanger is further cooled to 60°C in the regenerative heat exchanger with a portion of the air bled after expansion in the cooling turbine. The cabin is to be maintained at a temperature of 25°C and a pressure of 1 bar. If the isentropic efficiencies of the compressor and turbine are 90% and 80% respectively, find :*

1. *Mass of the air bled from cooling turbine to be used for regenerative cooling ;*
2. *Power required for maintaining the cabin at the required condition ; and*
3. *C.O.P. of the system.*

Assume the temperature of air leaving to atmosphere from the regenerative heat exchanger as 100°C.

Solution. Given : $Q = 20$ TR ; $p_1 = 0.8$ bar ; $T_1 = 10°C = 10 + 273 = 283$ K ; $p_2 = 1.2$ bar ; $p_3 = p_4 = p_5 = 4.5$ bar ; $\eta_H = 60\% = 0.6$; $T_5 = 60°C = 60 + 273 = 333$ K ; $T_7 = 25°C = 25 + 273 = 298$ K; $p_7 = p_6 = p_{6'} = 1$ bar ; $\eta_C = 90\% = 0.9$; $\eta_T = 80\% = 0.8$; $T_8 = 100°C = 100 + 273 = 373$ K

The *T-s* diagram for the regenerative air cooling system with the given conditions is shown in Fig. 3.27.

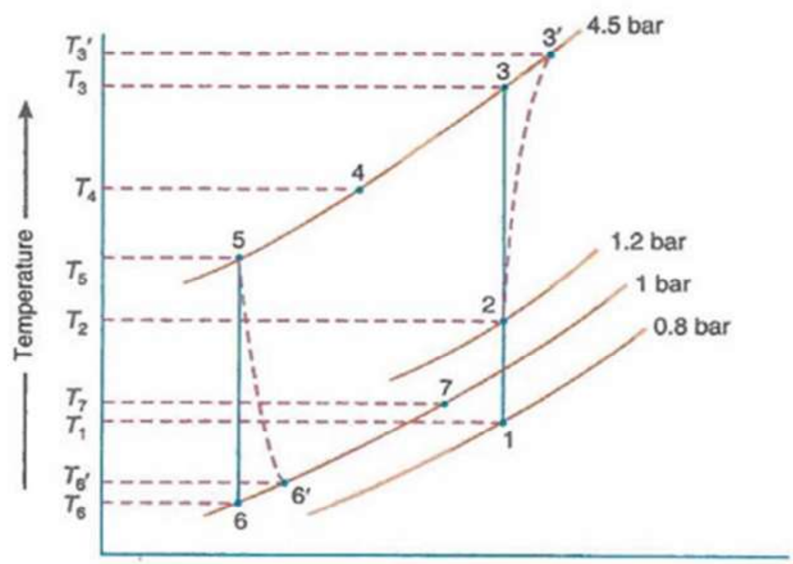


Fig. 3.27

Let

T_2 = Temperature of air at the end of ramming and entering to the main compressor,

T_3 = Temperature of air after isentropic compression in the main compressor, and

$T_{3'}$ = Actual temperature of air leaving the main compressor.

We know that for the isentropic ramming of air (process 1–2),

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.2}{0.8}\right)^{\frac{1.4-1}{1.4}} = (1.5)^{0.286} = 1.123$$

$\therefore$ $$T_2 = T_1 \times 1.123 = 283 \times 1.123 = 317.8 \text{ K}$$

and for the isentropic compression process 2–3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.5}{1.2}\right)^{\frac{1.4-1}{1.4}} = (3.75)^{0.286} = 1.46$$

$\therefore$ $$T_3 = T_2 \times 1.46 = 317.8 \times 1.46 = 464 \text{ K}$$

Isentropic efficiency of the compressor,

$$\eta_C = \frac{\text{Isentropic increase in temp.}}{\text{Actual increase in temp.}} = \frac{T_3 - T_2}{T_{3'} - T_2}$$

$$0.9 = \frac{464 - 317.8}{T_{3'} - 317.8} = \frac{146.2}{T_{3'} - 317.8}$$

$\therefore$ $$T_{3'} = 317.8 + 146.2 / 0.9 = 480 \text{ K}$$

We know that effectiveness of the heat exchanger (η_H),

$$0.6 = \frac{T_{3'} - T_4}{T_{3'} - T_2} = \frac{480 - T_4}{480 - 317.8} = \frac{480 - T_4}{162.2}$$

$\therefore$ $$T_4 = 480 - 0.6 \times 162.2 = 382.7 \text{ K}$$

Now for the isentropic cooling in the cooling turbine (process 5–6),

$$\frac{T_5}{T_6} = \left(\frac{p_5}{p_6}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.5}{1}\right)^{\frac{1.4-1}{1.4}} = (4.5)^{0.286} = 1.54$$

$\therefore$ $$T_6 = T_5 / 1.54 = 333 / 1.54 = 216 \text{ K}$$

and isentropic efficiency of the cooling turbine,

$$\eta_T = \frac{\text{Actual increase in temp.}}{\text{Isentropic increase in temp.}} = \frac{T_5 - T_{6'}}{T_5 - T_6}$$

$$0.8 = \frac{333 - T_{6'}}{333 - 216} = \frac{333 - T_{6'}}{117}$$

$\therefore$ $$T_{6'} = 333 - 0.8 \times 117 = 239.4 \text{ K}$$

1. *Mass of air bled from the cooling turbine to be used for regenerative cooling*

Let m_a = Mass of air bled from the cooling turbine to be used for regenerative cooling,

m_1 = Total mass of air bled from the main compressor, and

m_2 = Mass of cold air bled from the cooling turbine for regenerative heat exchanger.

We know that the mass of air supplied to the cabin,

$$m_a = m_1 - m_2$$

$$= \frac{210\,Q}{c_p(T_7 - T_{6'})} = \frac{210 \times 20}{1(298 - 239.4)} = 71.7 \text{ kg / min} \quad \ldots (i)$$

and $$m_2 = \frac{m_1(T_4 - T_5)}{(T_8 - T_{6'})} = \frac{m_1(382.7 - 333)}{(373 - 239.4)} = 0.372\, m_1 \quad \dots (ii)$$

From equation (*i*), we find that

$$m_1 - m_2 = 71.7 \quad \text{or} \quad m_1 - 0.372\, m_1 = 71.7$$

$$\therefore \quad m_1 = \frac{71.7}{1 - 0.372} = 113.4 \text{ kg / min}$$

and $$m_2 = 0.372\, m_1 = 0.372 \times 113.4 = 42.2 \text{ kg / min}$$ **Ans.**

Note: From equation (*ii*), $m_2 / m_1 = 0.372$. Therefore we can say that the air bled from the cooling turbine for regenerative cooling is 37.2% of the total air bled from the main compressor.

2. Power required for maintaining the cabin at the required condition

We know that the power required for maintaining the cabin at the required condition,

$$P = \frac{m_1 c_p (T_{3'} - T_2)}{60} = \frac{113.4 \times 1\,(480 - 317.8)}{60} = 307 \text{ kW}$$ **Ans.**

3. C.O.P. of the system

We know that C.O.P. of the system

$$= \frac{210\, Q}{m_1 c_p (T_{3'} - T_2)} = \frac{210 \times 20}{113.4 \times 1\,(480 - 317.8)} = 0.23$$ **Ans.**