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Boot-Strap Air Cooling Systems

A boot-strap air cooling system is shown in Figure inserted below. 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.

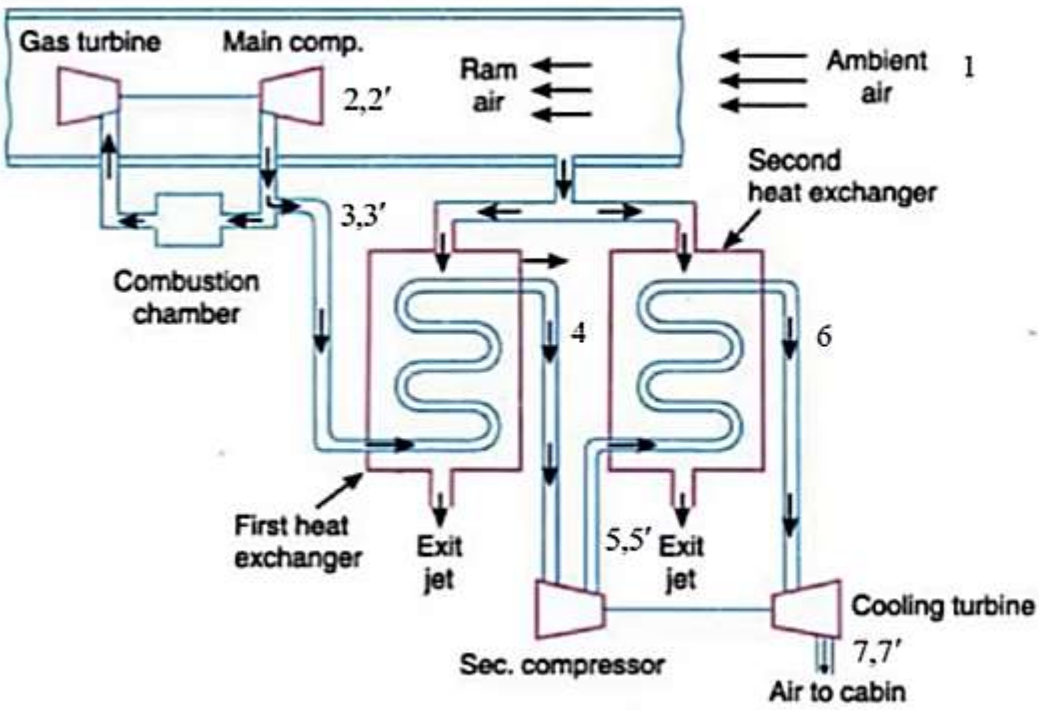
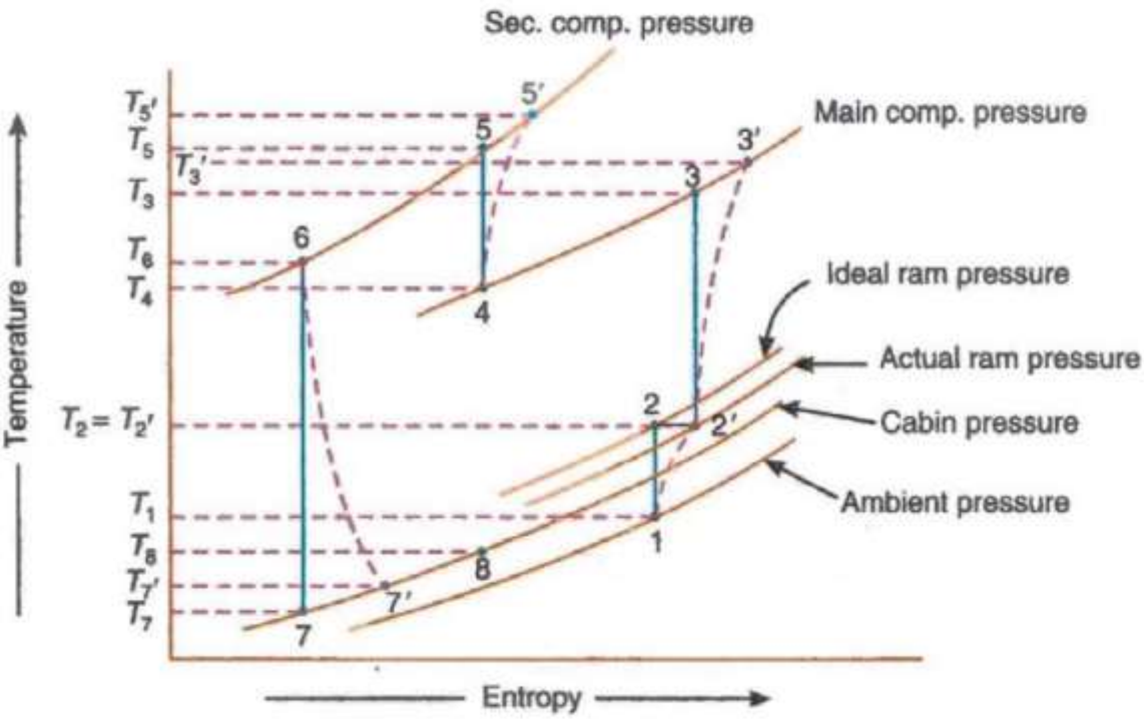


Fig. 3.11. Boot-strap air cooling system.

The *T-s* diagram for a boot-strap air cycle cooling system is shown in Fig. 3.15. The various processes are as follows :

1. The process 1– 2 represents the isentropic ramming of ambient air from pressure p_1 and temperature T_1 to pressure p_2 and temperature T_2. The process 1– 2′ represents the actual ramming process because of internal friction due to irreversibilities.
2. The process 2′– 3 represents the isentropic compression of air in the main compressor and the process 2′– 3′ represents the actual compression of air because of internal friction due to irreversibilities.
3. The process 3′–4 represents the cooling by ram air in the first heat exchanger. The pressure drop in the heat exchanger is neglected.
4. The process 4 – 5 represents the isentropic compression of cooled air, from first heat exchanger, in the secondary compressor. The process 4 – 5′ represents the actual compression process because of internal friction due to irreversibilities.
5. The process 5′– 6 represents the cooling by ram air in the second heat exchanger. The pressure drop in the heat exchanger in neglected.
6. The process 6 – 7 represents the isentropic expansion of cooled air in the cooling turbine upto the cabin pressure. The process 6 – 7′ represents actual expansion of the cooled air in the cooling turbine.
7. The process 7′– 8 represents the heating of air upto the cabin temperature T_8.



If Q tonnes of refrigeration is the cooling load in the cabin, then the quantity of air required for the refrigeration purpose will be

$$m_a = \frac{210\,Q}{c_p(T_8 - T_{7'})}\ \text{kg/min}$$

Power required for the refrigerating system,

$$P = \frac{m_a c_p (T_{3'} - T_{2'})}{60}\ \text{kW}$$

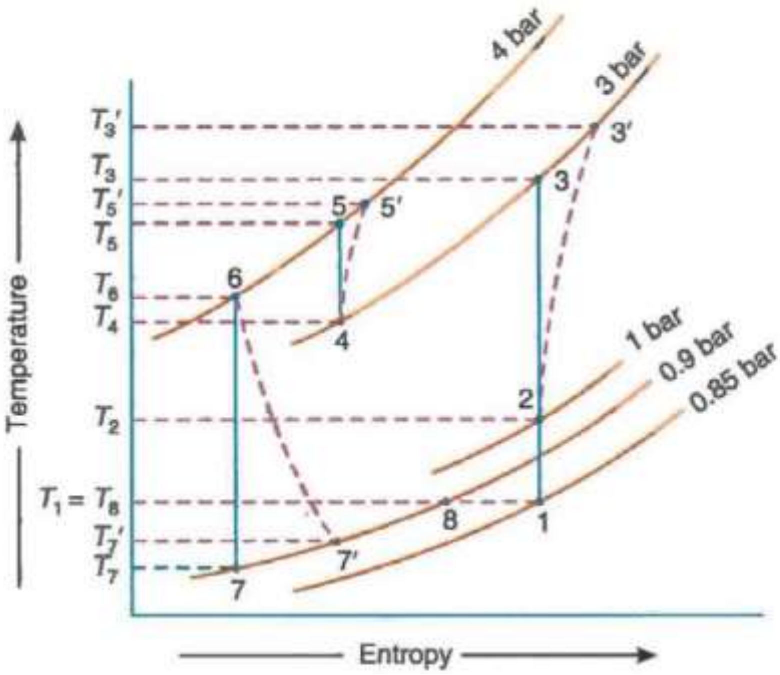
and C.O.P. of the refrigerating system

$$= \frac{210\,Q}{m_a c_p (T_{3'} - T_{2'})} = \frac{210\,Q}{P \times 60}$$

Problem 1: 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. power required to operate the system; and
2. The C.O.P. of the system.
3. Draw the schematic and temperature - entropy diagram of the system. Take specific heat ratio = 1.4 and cP = I kl/kg K.

Solution. Given : $Q = 10$ TR ; $T_1 = 20°\text{C} = 20 + 273 = 293$ 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 ; $T_8 = 20°\text{C} = 20 + 273 = 293$ K ; $\gamma = 1.4$; $c_p = 1$ kJ/kg K



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,

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

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

We know that isentropic efficiency of the auxiliary compressor,

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

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

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

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,

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

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

We know that turbine efficiency,

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

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

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

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,

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

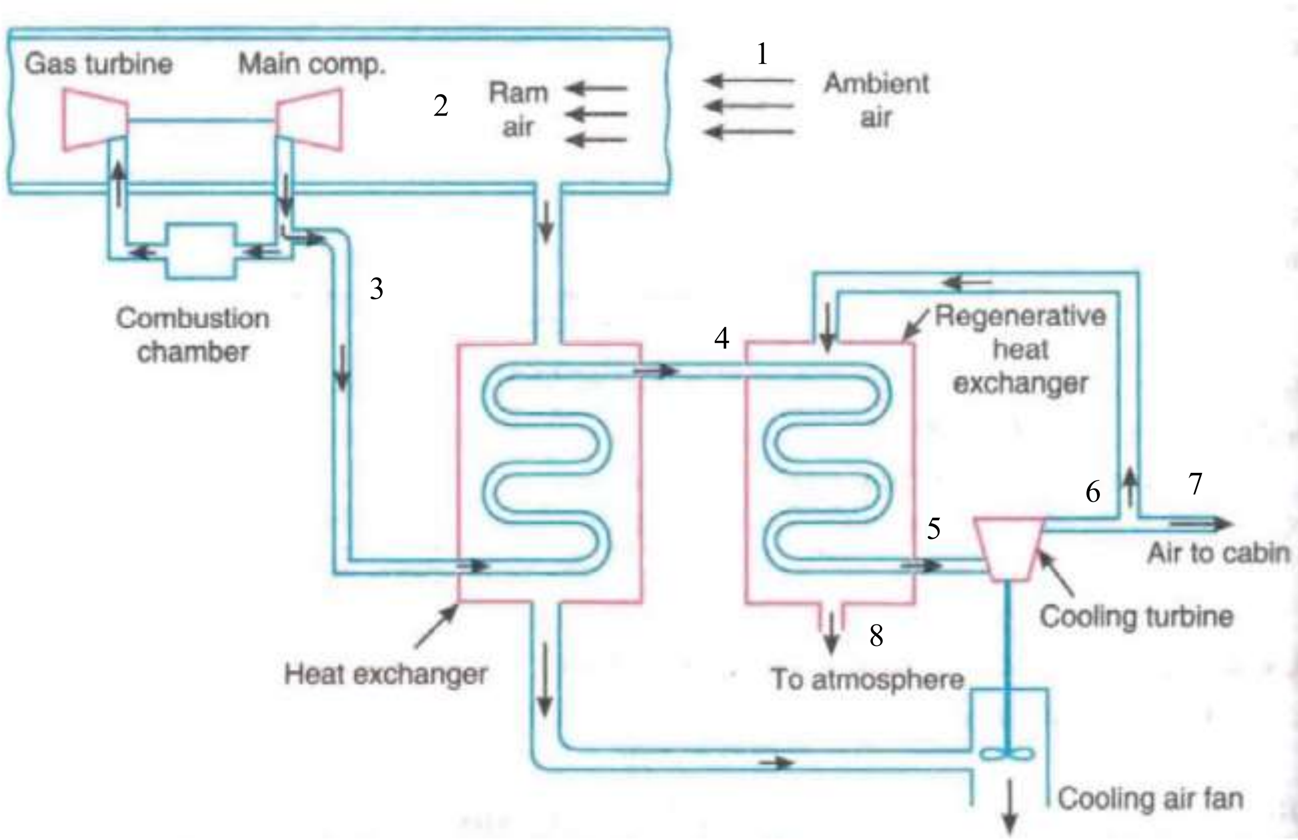
2. C.O.P. of the system

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

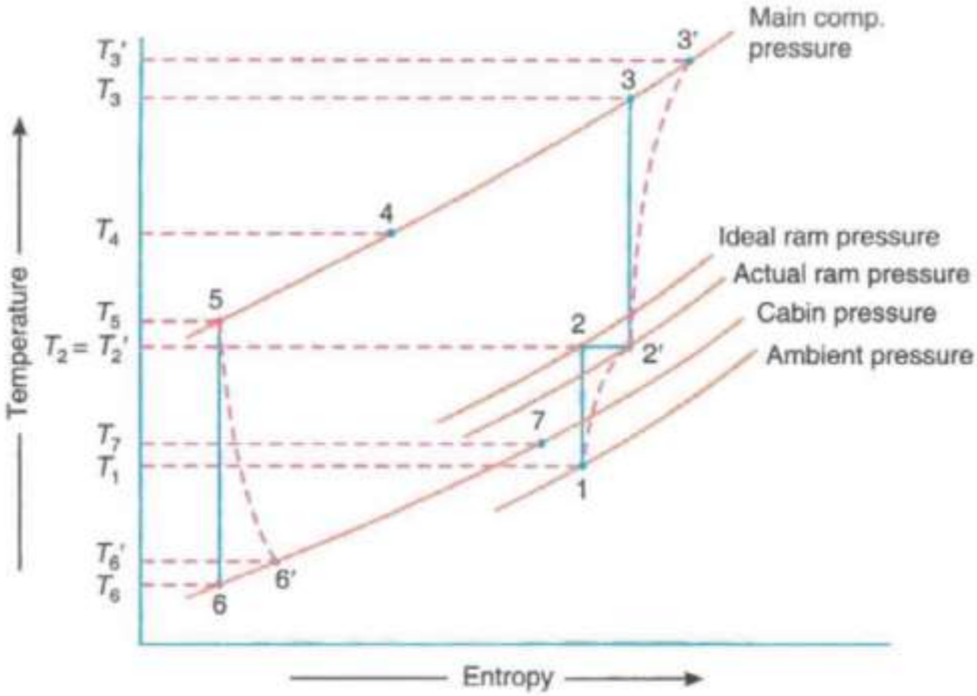
$$= \frac{210\,Q}{m_a c_p (T_{3'} - T_2)} = \frac{210 \times 10}{55 \times 1\,(448.7 - 306.8)} = 0.27 \quad \textbf{Ans.}$$

The regenerative air cooling system

The regenerative air cooling system is shown in Figure inserted below. It is a modification of a simple air cooling system with the addition of a regenerative heat exchanger. The high pressure and high temperature air from the main compressor is first cooled by the ram air in the heat exchanger. The air is further cooled in the regenerative heat exchanger with a portion of the air bled after expansion in the cooling turbine. This type of cooling system is used for supersonic aircrafts and rockets.



The T-s diagram for the regenerative air cooling system is shown in Figure inserted below. The various processes are as follows:



1. The process 1–2 represents isentropic ramming of air and process 1– 2′ represents actual ramming of air because of internal friction due to irreversibilities.

2. The process 2′–3 represents isentropic compression of air in the main compressor and the process 2′–3′ represents actual compression of air because of internal friction due to irreversibilities.
3. The process 3′–4 represents cooling of compressed air by ram air in the heat exchanger.
4. The process 4–5 represents cooling of air in the regenerative heat exchanger.
5. The process 5–6 represents isentropic expansion of air in the cooling turbine upto the cabin pressure and the process 5–6′ represents actual expansion of air in the cooling turbine.
6. The process 6′–7 represents heating of air upto the cabin temperature T_7.

If Q tonnes of refrigeration is the cooling load in the cabin, then the quantity of air required for the refrigeration purpose will be

$$m_a = \frac{210\,Q}{c_p(T_7 - T_{6'})} \text{ kg / min}$$

Let 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.

For the energy balance of regenerative heat exchanger, we have

$$m_2 c_p (T_8 - T_{6'}) = m_1 c_p (T_4 - T_5)$$

$$\therefore \quad m_2 = \frac{m_1(T_4 - T_5)}{(T_8 - T_{6'})}$$

where T_8 = Temperature of air leaving to atmosphere from the regenerative heat exchanger.

Power required for the refrigeration system,

$$P = \frac{m_1 c_p (T_{3'} - T_{2'})}{60} \text{ kW}$$

and C.O.P. of the refrigerating system

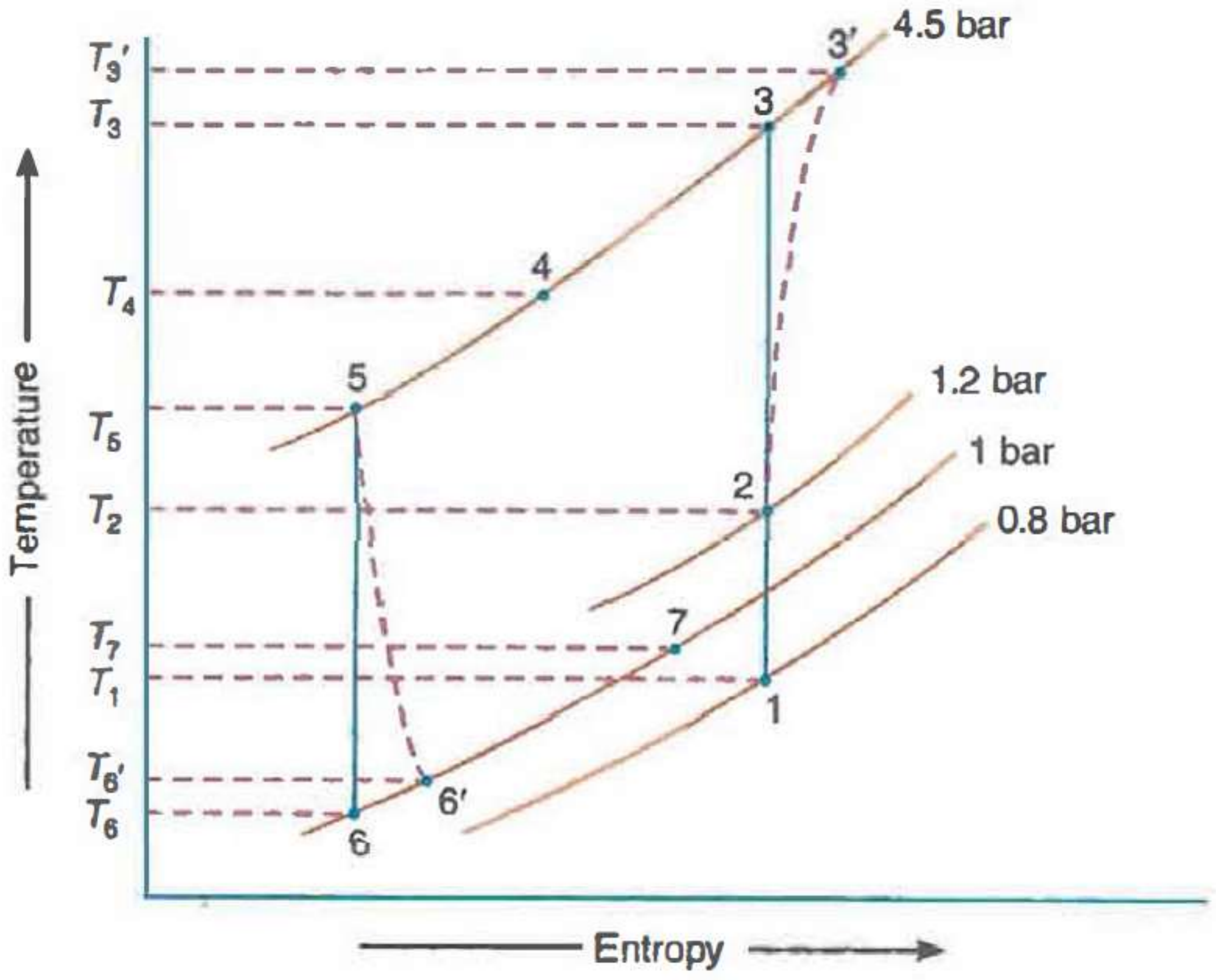
$$= \frac{210\,Q}{m_1 c_p (T_{3'} - T_{2'})} = \frac{210\,Q}{P \times 60}$$

Problem 2: 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



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),

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

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

and for the isentropic compression process 2–3,

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

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

Isentropic efficiency of the compressor,

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

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

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

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

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

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

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

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

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

and isentropic efficiency of the cooling turbine,

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

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

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

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,

$$m_a = m_1 - m_2$$

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

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.**