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.

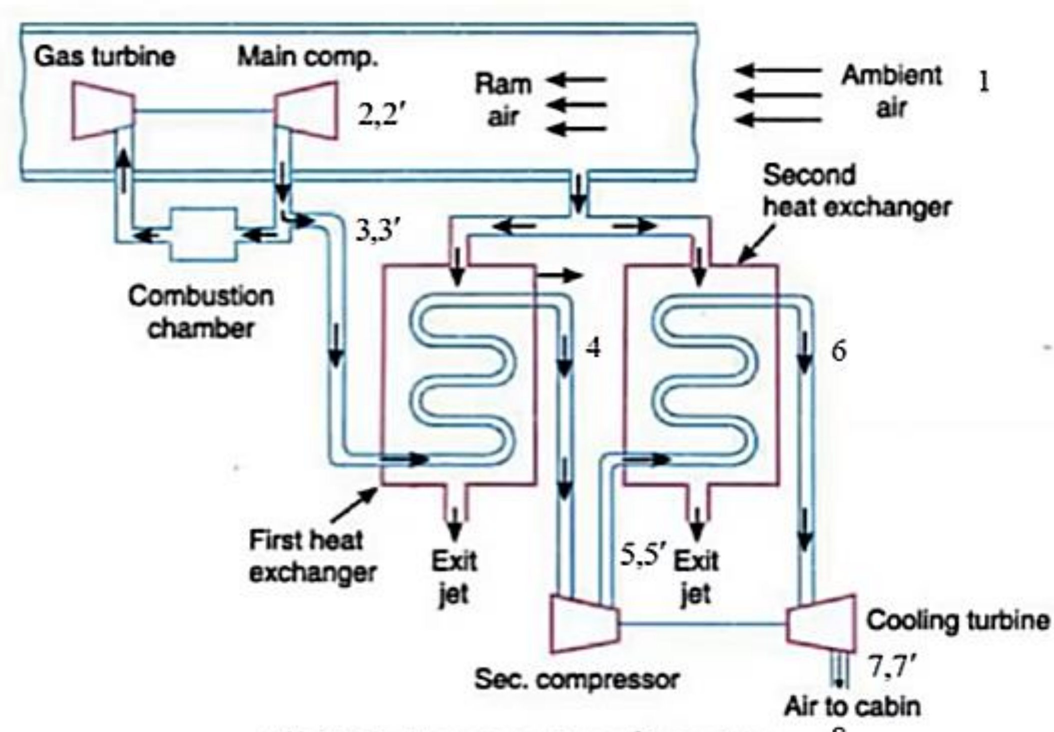
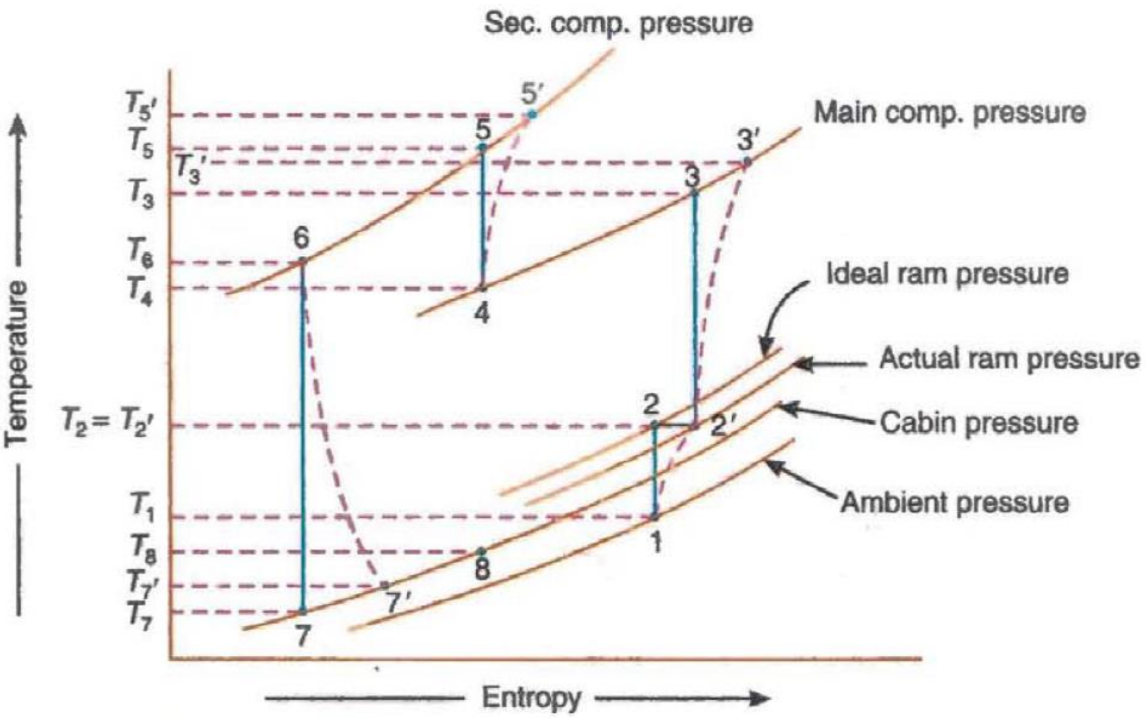


Fig. 3.11. Boot-strap air cooling system.

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,

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

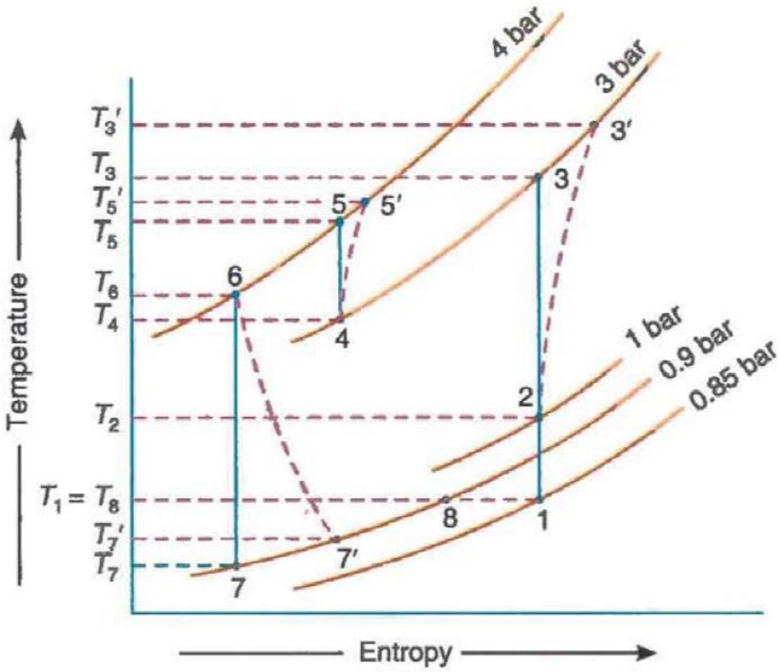
and C.O.P. of the refrigerating system

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

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°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 ; η_T = 85% = 0.85 ; $p_7 = p_{7'} = p_8$ = 0.9 bar ; T_8 = 20°C = 20 + 273 = 293 K ; γ = 1.4 ; c_p = 1 kJ/kg K


4 bar
3 bar
1 bar
0.9 bar
0.85 bar
T_3'
T_3
T_5'
T_5
T_6
T_4
T_2
$T_1 = T_8$
T_7'
T_7
1
2
3
3'
4
5
5'
6
7
7'
8
Temperature
Entropy

We know that for isentropic ramming process 1-2,

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

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

Now for isentropic process 2-3,

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

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

We know that isentropic efficiency of the compressor,

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

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

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

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,

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

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