CHAPTER EIGTH

Air Refrigeration Systems

Merits and demerits of air refrigeration systems explained

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.

Methods of air refrigeration systems

The various methods of air refrigeration systems used for aircrafts these days are as follows

1. Simple air cooling system,
2. Simple air evaporative cooling system,
3. Boot strap air cooling system,
4. Boot strap air evaporative cooling system,
5. Reduced ambient air cooling system, and
6. Regenerative air cooling system.

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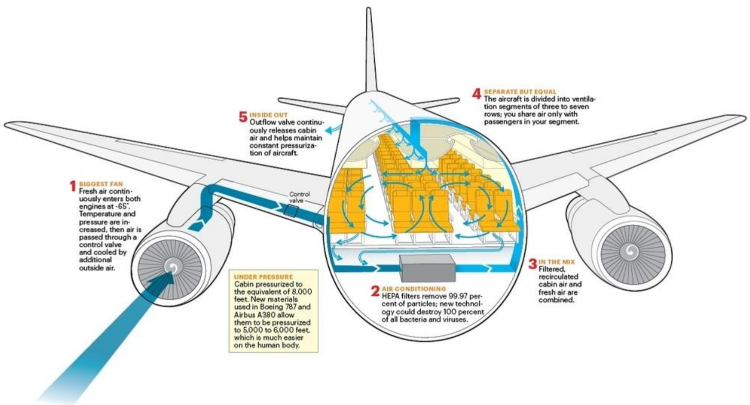
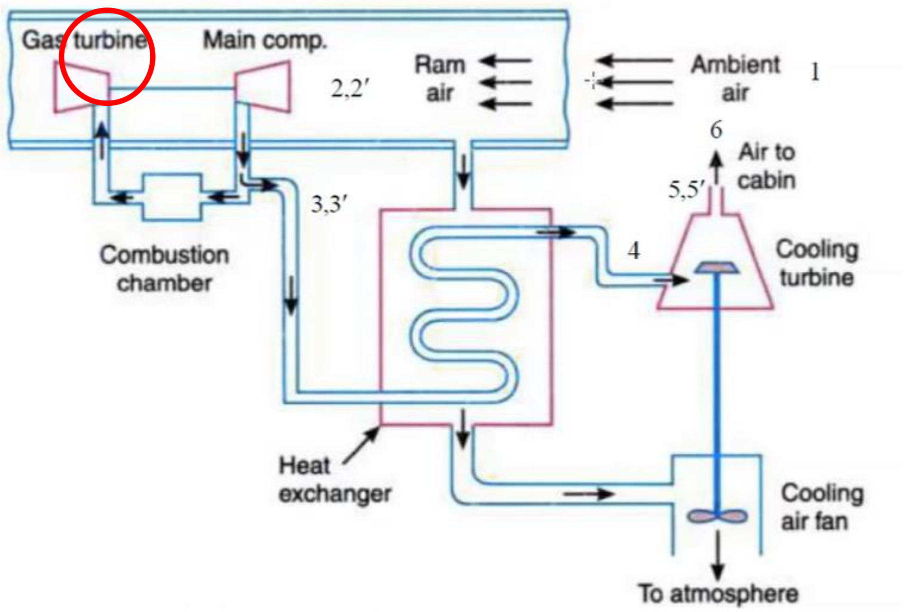
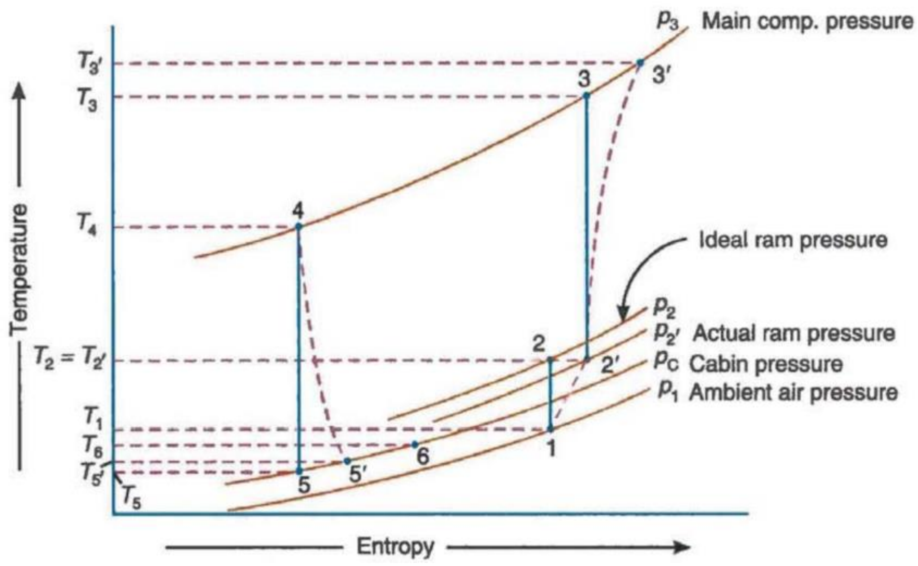
Now, let us discuss mathematically the above mentioned systems from **thermodynamics** view;

Simple air cooling systems

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.







1. Ramming Process

$$\frac{T_2}{T_1} = \frac{T_{2'}}{T_1} = 1 + \frac{V^2(\gamma - 1)}{2\gamma R T_1}$$

$$= 1 + \frac{V^2(\gamma - 1)}{2a^2}$$

where a = Local sonic or acoustic velocity at the ambient air conditions.

$= \sqrt{\gamma R T_1}$, where R is in J/kg K.

The equation (*iv*) may further be written as

$$\frac{T_2}{T_1} = \frac{T_{2'}}{T_1} = 1 + \frac{\gamma - 1}{2} \times M^2$$

M = Mach number of the flight. It is defined as the ratio of air craft velocity (V) to the local sonic velocity (a).

The temperature $T_2 = T_{2'}$ is called the *stagnation temperature* of the ambient air entering the main compressor. The stagnation pressure after isentropic compression (p_2) is given by

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\eta_R = \frac{\text{Actual rise in pressure}}{\text{Isentropic rise in pressure}} = \frac{p_{2'} - p_1}{p_2 - p_1}$$

2. **Compression process**

$$W_C = m_a\, c_p (T_{3'} - T_{2'})$$

m_a = Mass of air bled from the main compressor for refrigeration purposes.

3. **Cooling process**

$$Q_R = m_a c_p (T_{3'} - T_4)$$

4. **Expansion process**

$$W_T = m_a c_p (T_4 - T_{5'})$$

5. **Refrigeration process**

$$R_E = m_a c_p (T_6 - T_{5'})$$

where T_6 = Inside temperature of cabin.

$T_{5'}$ = Exit temperature of cooling turbine.

We know that C.O.P. of the air cycle

$$= \frac{\text{Refrigerating effect produced}}{\text{Work done}}$$

$$= \frac{m_a c_p (T_6 - T_{5'})}{m_a c_p (T_{3'} - T_{2'})} = \frac{T_6 - T_{5'}}{T_{3'} - T_{2'}}$$

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

$$m_a = \frac{210\,Q}{c_p(T_6 - T_{5'})} \text{ kg / min}$$

Power required for the refrigeration system,

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

and C.O.P. of the refrigerating system

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

Note : 1. We have discussed above that C.O.P. of the air cycle

$$= \frac{m_a c_p (T_6 - T_{5'})}{m_a c_p (T_{3'} - T_{2'})} = \frac{T_6 - T_{5'}}{T_{3'} - T_{2'}}$$

Problem. 1: 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 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
2. C.O.P. of the system. Assume that all the expansions and compressions are isentropic. The pressure of 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

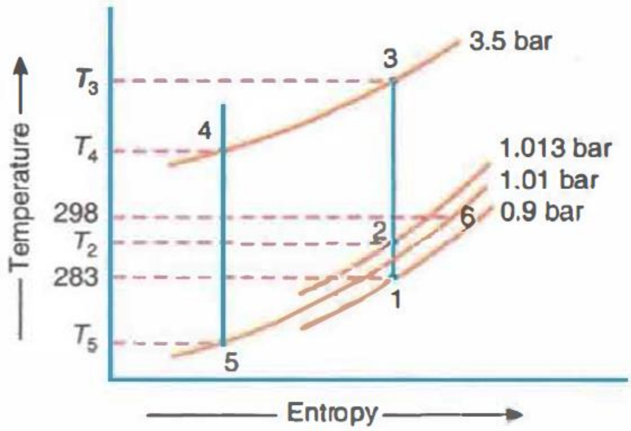
First of all, let us find the mass of air (m_a) required for the refrigeration purpose. Since the compressions and expansions are isentropic, therefore the various processes on the *T-s* diagram are as shown in Fig. 3.4.

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

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

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

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

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

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

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.**

C.O.P. of the system

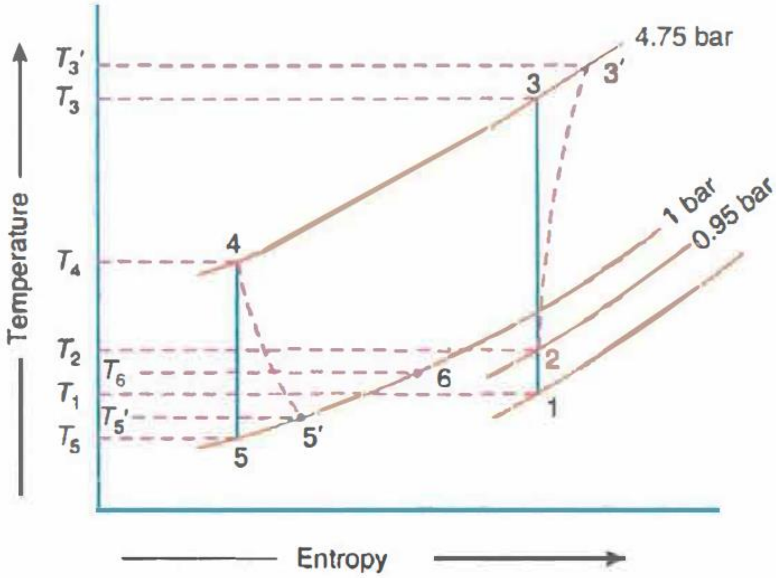
We know that C.O.P. of the system

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

Problem. 2: 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 an. 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.



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,

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

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

and isentropic efficiency of the compressor,

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

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

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

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,

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

C.O.P.

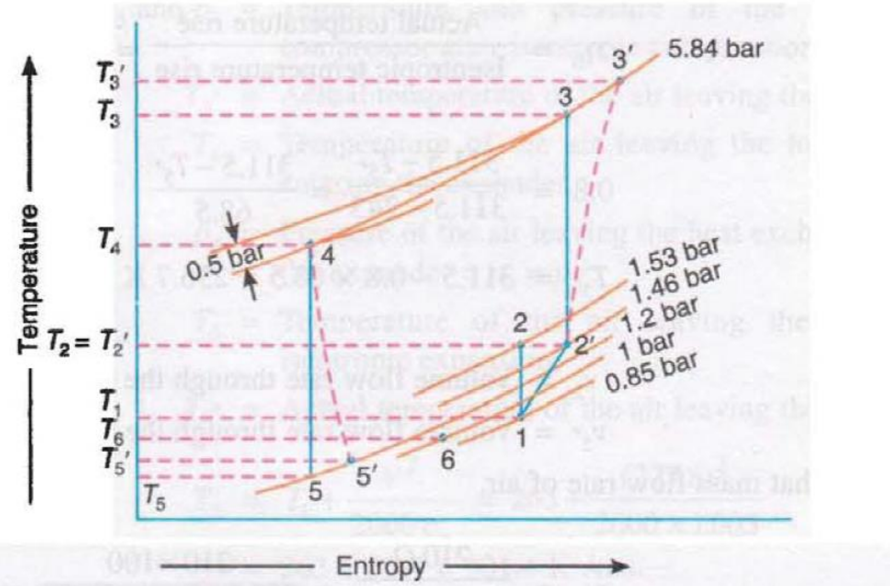
We know that $\quad \text{C.O.P.} = \frac{210\,Q}{m_a c_p (T_{3'} - T_2)} = \frac{210 \times 30}{89.64 \times 1.004\,(499.7 - 303)} = 0.356 \quad$ **Ans.**

Problem. 3: the cockpit of a jet plane flying at a speed of 1200 km/h is to be cooled by a simple air cooling system. The cock pit is to be maintained at 25°C and the pressure in the cock pet is 1 bar. The ambient air pressure and temperature are 0.85 bar and 30°C. The other data available is as follows:

Cock-pit cooling load= 10 TR; Main compressor pressure ratio = 4; Ram efficiency=90%. Temperature of air leaving the heat exchanger and entering the cooling turbine = 60 °C: pressure drop in the heat exchanger = 0.5 bar; Pressure loss between the cooler turbine and cockpit = 0.2 bar.

Assuming the isentropic efficiencies of main compressor and cooler turbine as 80%, find the quantity of air passed through the cooling turbine and C.0.P. of the system. Take $\gamma = 1.4$ and C_p=1 kJ/kg.K

Solution. Given : $V = 1200$ km / h = 333.3 m / s ; $T_6 = 25°C = 25 + 273 = 298$ K ; $p_6 = 1$ bar ; $p_1 = 0.85$ bar ; $T_1 = 30°C = 30 + 273 = 303$ K ; $Q = 10$ TR ; $p_3 / p_{2'} = 4$; $\eta_R = 90\% = 0.9$; $T_4 = 60°C = 60 + 273 = 333$ K ; $p_4 = (p_{3'} - 0.5)$ bar ; $p_5 = p_{5'} = p_6 + 0.2 = 1 + 0.2 = 1.2$ bar ; $\eta_C = \eta_T = 80\% = 0.8$; $\gamma = 1.4$; $c_p = 1$ kJ/kg K



Let $T_{2'}$ = Stagnation temperature of the ambient air entering the main compressor = T_2,

p_2 = Pressure of air after isentropic ramming, and

$p_{2'}$ = Stagnation pressure of air entering the main compressor.

We know that

$$T_2 = T_{2'} = T_1 + \frac{V^2}{2000\,c_p} = 303 + \frac{(333.3)^2}{2000 \times 1}$$

$$= 303 + 55.5 = 358.5 \text{ K}$$

and

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{358.5}{303}\right)^{\frac{1.4}{1.4-1}} = (1.183)^{3.5} = 1.8$$

$\therefore$ $p_2 = p_1 \times 1.8 = 0.85 \times 1.8 = 1.53$ bar

We know that ram efficiency,

$$\eta_R = \frac{\text{Actual pressure rise}}{\text{Isentropic pressure rise}} = \frac{p_{2'} - p_1}{p_2 - p_1}$$

$$0.9 = \frac{p_{2'} - 0.85}{1.53 - 0.85} = \frac{p_{2'} - 0.85}{0.68}$$

$\therefore$ $p_{2'} = 0.9 \times 0.68 + 0.85 = 1.46$ bar

Now for the isentropic process 2′– 3,

$$\frac{T_3}{T_{2'}} = \left(\frac{p_3}{p_{2'}}\right)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}} = (4)^{0.286} = 1.486$$

$\therefore$ $T_3 = T_{2'} \times 1.486 = 358.5 \times 1.486 = 532.7$ K

and isentropic efficiency of the compressor,

$$\eta_C = \frac{\text{Isentropic temperature rise}}{\text{Actual temperature rise}} = \frac{T_3 - T_{2'}}{T_{3'} - T_{2'}}$$

$$0.8 = \frac{532.7 - 358.5}{T_{3'} - 358.5} = \frac{174.2}{T_{3'} - 358.5}$$

$\therefore$ $$T_{3'} = \frac{174.2}{0.8} + 358.5 = 576 \text{ K}$$