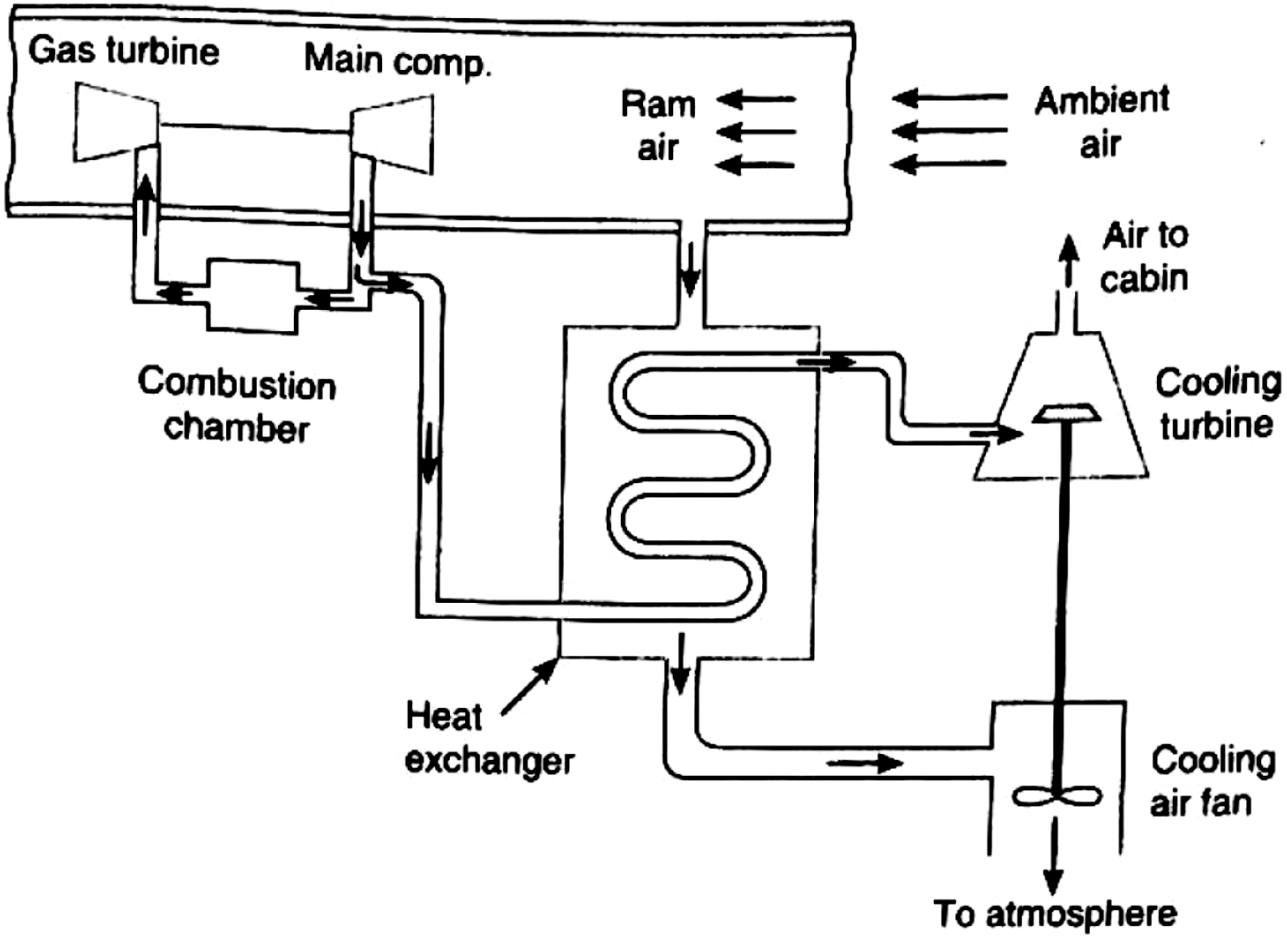
Refrigeration

7: Simple Air Refrigeration Cycles

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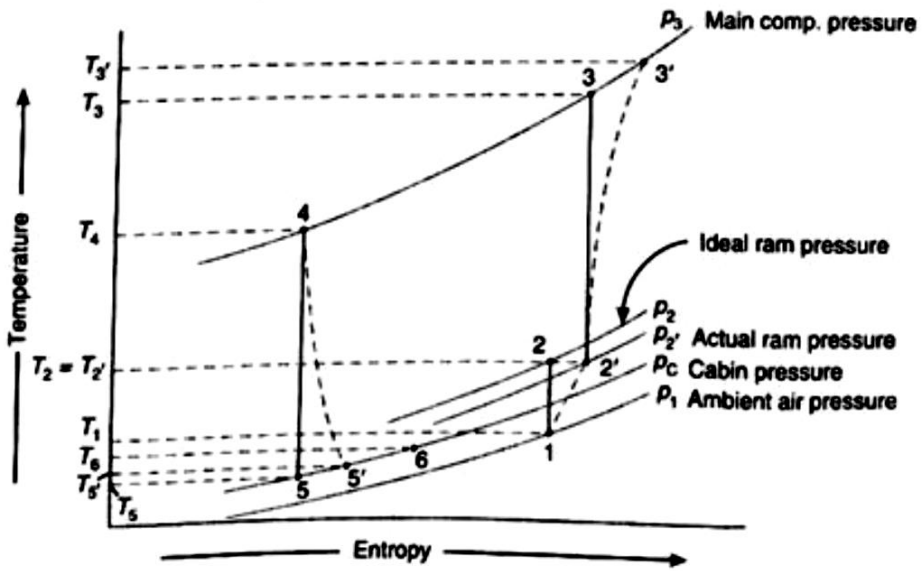
Simple air-cooling system

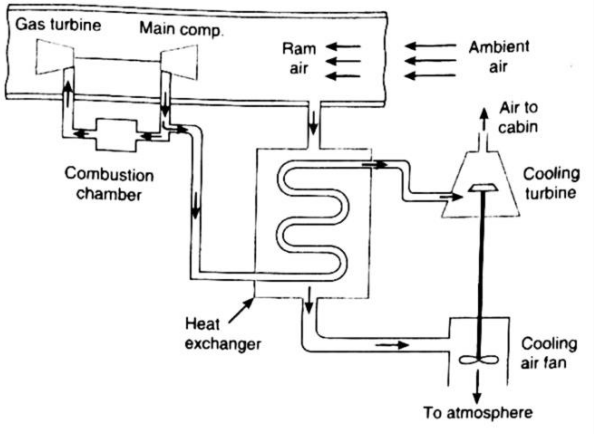
A simple air-cooling system for aircrafts is shown in Fig. The main components of this system are the main compressor driven by a gas turbine, a heat exchanger, a cooling turbine and a cooling air fan.



Simple air cooling system

Ramming process. Let the pressure and temperature of ambient air is P_1 and T_1 respectively. The ambient air is rammed isentropically from pressure P_1 and temperature T_1 to the pressure P_2 and temperature T_2. This ideal ramming action is shown by the vertical line 1-2 in Fig. 3.2. In actual practice, because of internal friction due to irreversibilities, the temperature of the rammed air is more than T_2. Thus, the actual ramming process is shown by the curve 1-2' which is adiabatic but not isentropic due to friction. The pressure and temperature of the rammed air is now p_2' and T_2' respectively. During the ideal or actual ramming process, the total energy or enthalpy remains constant i.e. $h_2 = h_2$' and $T_2 = T_2$'





If V is the aircraft velocity or the velocity of air relative to the aircraft in metres per second, then kinetic energy of outside air relative to aircraft,

$$\text{K.E.} = \frac{V^2}{2000} \text{ kJ/kg} \qquad \ldots (i)$$

Simple air cooling system

From the energy equation, we know that

$$h_2 - h_1 = \frac{V^2}{2000}$$

$$c_p \cdot T_2 - c_p \cdot T_1 = \frac{V^2}{2000}$$

$$\therefore \quad T_2 = T_1 + \frac{V^2}{2000\, c_p}$$

or

$$\frac{T_2}{T_1} = 1 + \frac{V^2}{2000\, c_p T_1}$$

and

$$\frac{T_{2'}}{T_1} = 1 + \frac{V^2}{2000\, c_p T_1} \qquad \ldots (\because T_2 = T_{2'}) \qquad \ldots (ii)$$

We know that, $c_p - c_v = R$

or

$$c_p\left[1 - \frac{c_v}{c_p}\right] = R \quad \text{or} \quad c_p\left[1 - \frac{1}{\gamma}\right] = R \qquad \ldots (\because c_p / c_v = \gamma)$$

$$\therefore \quad c_p = \frac{\gamma R}{\gamma - 1}$$

Simple air cooling system

Substituting the value of c_p in equation (*ii*), we have

$$\frac{T_2}{T_1} = \frac{T_{2'}}{T_1} = 1 + \frac{V^2(\gamma - 1)}{2000\,\gamma R T_1} = 1 + \frac{V^2(\gamma - 1)}{2\gamma(1000R)T_1} \quad \text{(when } R \text{ is in kJ/kgK)} \ldots (iii)$$

It may be noted that when R is in J/kg K, then equation (*iii*) may be written as follows:

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

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

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

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

Simple air cooling system

where M = Mach number of the flight. It is defined as the ratio of aircraft 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 ram compressor. The stagnation pressure after isentropic compression (P_2) is given by

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

Due to the irreversible compression in the ram, the air reaches point 2′ instead of point 2 at the same stagnation temperature but at a reduced stagnation pressure p_2'. The pressure p_2' may be obtained from the expression of ram efficiency (η_R) which is given as

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

2. *Compression process.* The isentropic compression of air in the main compressor is represented by the line 2′– 3. In actual practice, because of internal friction, due to irreversiblities, the actual compression is represented by the curve 2′– 3′. The work done during this compression process is given by

$$W_C = m_a\, c_p\, (T_3' - T_2')$$

where

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

Simple air cooling system

3. *Cooling process.* The compressed air is cooled by the ram air in the heat exchanger. This process is shown by the curve 3′– 4 in Fig. 3.2. In actual practice, there is a pressure drop in the heat exchanger which is not shown in the figure. The temperature of air decreases from $T_{3'}$ to T_4. The heat rejected in the heat exchanger during the cooling process is given by

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

4. *Expansion process.* The cooled air is now expanded isentropically in the cooling turbine as shown by the curve 4 – 5. In actual practice, because of internal friction due to irreversibilities, the actual expansion in the cooling turbine is shown by the curve 4 – 5′. The work done by the cooling turbine during this expansion process is given by

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

The work of this turbine is used to drive the cooling air fan which draws cooling air from the heat exchanger.

5. *Refrigeration process.* The air from the cooling turbine (*i.e.* after expansion) is sent to the cabin and cock pit where it gets heated by the heat of equipment and occupancy. This process is shown by the curve 5′– 6 in Fig. 3.2. The refrigerating effect produced or heat absorbed is given by

Simple air cooling system

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

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

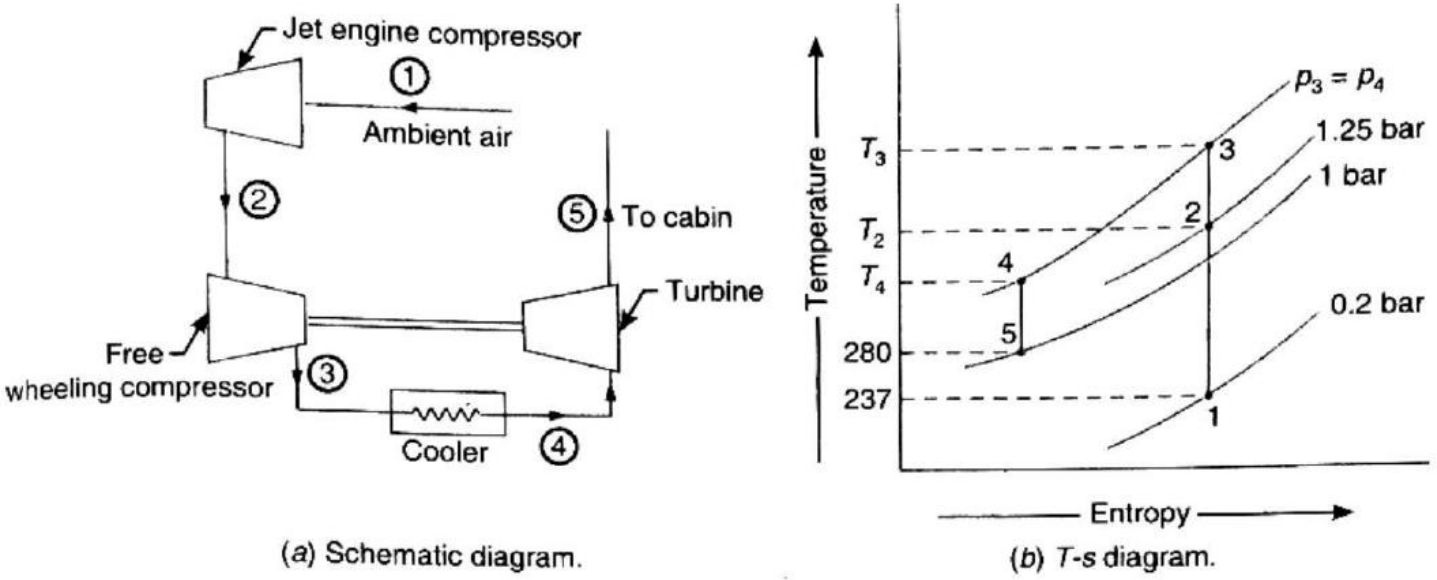
$$= \frac{m_a c_p (T_6 - T_{5'})}{m_a c_p (T_{3'} - T_{2'})} = \frac{T_6 - T_{5'}}{T_{3'} - T_{2'}}$$

Simple air-cooling system

Example: free-wheeling conditioning system unit of a pressurized aircraft receives its air from the jet engine compressor at a pressure of 1.25 bar. The ambient pressure and temperature are 0.2bar and 237 K respectively. The air-conditioning unit consists of a free-wheeling compressor and turbine mounted on one shaft. The work produced by the turbine is sufficient to drive the compressor. The compressed air is then cooled in the cooler at constant pressure and then expanded in the turbine to the cabin pressure of 1 bar and temperature of 280 K. Calculate the compressor discharge pressure and the cooler exit temperature.

Solution: Given : P_2= 1.25 bar ; P_1 = 0.2 bar; T_1 = 237 K ; p5 = 1 bar ; T_5 = 280 K

The schematic diagram and T-s diagram of the given air-conditioning system is shown in Fig. 3.3 (a) and (b) respectively.



(a) Schematic diagram.

(b) T-s diagram.

Simple air cooling system

Compressor discharge pressure

Let p_3 = Compressor discharge pressure in bar,

T_2 = Temperature of air leaving the jet engine compressor or entering the free wheeling compressor, and

T_3 = Temperature of air leaving the free wheeling compressor.

We know that $$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.25}{0.2}\right)^{\frac{1.4-1}{1.4}} = (6.25)^{0.286} = 1.69$$

... (Taking γ for air = 1.4)

$\therefore$ $$T_2 = T_1 \times 1.69 = 237 \times 1.69 = 400 \text{ K}$$

Work done by the free wheeling compressor in compressing the air,

$$W_C = c_p(T_3 - T_2)$$

and work done by the turbine is expanding the air,

$$W_T = c_p(T_4 - T_5)$$

Since the work produced by the turbine is sufficient to drive the compressor, therefore $W_T = W_C$, or

Simple air-cooling system

$$T_4 - T_5 = T_3 - T_2$$

$$T_5\left[\frac{T_4}{T_5} - 1\right] = T_2\left[\frac{T_3}{T_2} - 1\right]$$

$$T_5\left[\left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] = T_2\left[\left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$280\left[\left(\frac{p_3}{1}\right)^{\frac{1.4-1}{1.4}} - 1\right] = 400\left[\left(\frac{p_3}{1.25}\right)^{\frac{1.4-1}{1.4}} - 1\right]$$

$$(p_3)^{0.286} - 1 = \frac{400}{280}\left[\frac{(p_3)^{0.286}}{1.066} - 1\right] = 1.34(p_3)^{0.286} - 1.428$$

$$0.34\,(p_3)^{0.286} = 0.428 \quad \text{or} \quad (p_3)^{0.286} = 1.26$$

$$p_3 = (1.26)^{1/0.286} = 2.245 \text{ bar Ans.}$$

Cooler exit temperature

Let T_4 = Cooler exit temperature.

We know that $$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{2.245}{1}\right)^{\frac{1.4-1}{1.4}} = (2.245)^{0.286} = 1.26$$

$\therefore$ $T_4 = T_5 \times 1.26 = 280 \times 1.26 = 352.8$ K Ans.

Simple air cooling system

Example: A simple air-cooled system is used for an aero plane 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; 2.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

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.

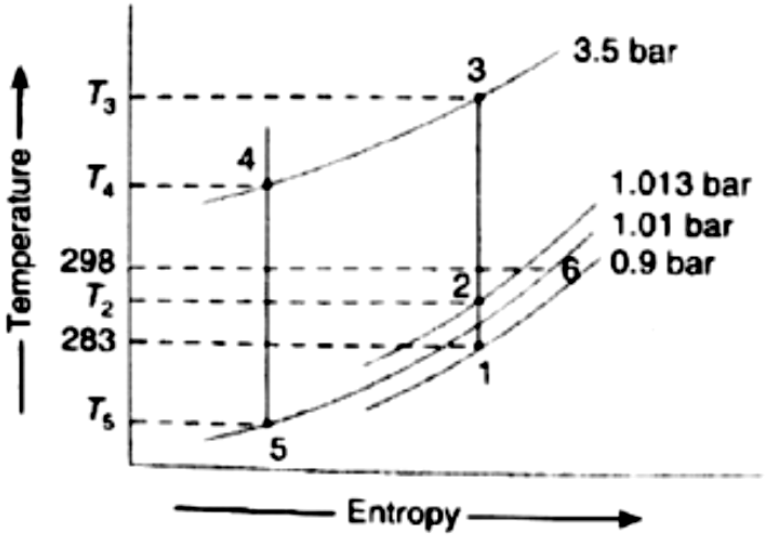
Let T_2 = Temperature of air at the end of ramming or entering the ram compressor

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.

Simple air cooling system



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

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

Simple air cooling system

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

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

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,

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

2. *C.O.P. of the system*

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

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

Next: Multistage Refrigeration cycles

Thank you