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LECTURE NOTES

ON

REFRIGERATION & A/C

CE C471 / ME C461

AIR [GAS]CYCLE REFRIGERATION

PART-2

BY

DR.A.M.SURENDRA KUMAR

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INTRODUCTION

- Air is used as working fluid.
- No change of phase through out.
- Heat carrying capacity/kg of air is very small compared with other refrigerant systems.
- High pressure air readily available in the Aircraft .
- Low equipment weight.

- **Basic elements**:

  1. Compressor 2. Heat exchanger 3. Expander 4. Refrigerator

  Open system : The air used in the refrigerator is thrown into the atmosphere.

  Closed system: Air used is recirculated

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- To increase C.O.P., T_2 should kept low.
- But cannot be reduced below 25°C –Atmospheric Temp.
- T_1 should be kept high.
- But cannot be increased above 0^0 C.
- It is the required temperature.

If say $T_1 = 0°C$ which is the required temperature for the production of ice then

$$T_1 \text{ in winter} < T_2 \text{ in summer}$$

so that for the same required temperature, Carnot refrigerator works more efficiently in winter than in summer because

C.O.P. in winter > C.O.P. in summer.

Assuming 40°C and 20°C are the average temperatures in summer and winter, then

$$\frac{0+273}{20-0} > \frac{0+273}{40-0}$$

$$\text{(C.O.P. in winter) } \frac{273}{20} > \text{(C.O.P. in summer) } \frac{273}{40}$$

This explains the effect of atmospheric temperature on C.O.P. of Carnot refrigerator used for particular purpose.

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Example:

If Carnot Refrigerator is used for making ice, (Required temp is 0^0C) and for A/C plant (required temp. to be maintained is 20^0C) in summer when the atmospheric temp. is 40^0C, then the Carnot refrigerator used for A/c plant works more efficiently than the Carnot refrigerator used for making ice because C.O.P of Carnot refrigerator used for making ice

$$\frac{20+273}{40-20} > \frac{0+273}{40-0}$$

$$\frac{293}{20} > \frac{273}{40} \text{ as } \frac{586}{40} > \frac{273}{40}$$

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ADVANTAGES OF AIR –REFRIGERATION SYSTEMS

- 1. As the air is easily available compared with the other refrigerant, it is cheap.
- 2. The air used is non-flammable, so there is no danger of fire as in NH_3 machine.
- 3. The weight of the air refrigeration system / T.R is quite low compared with the other refrigeration systems which is one of the major causes selecting this system in air craft.

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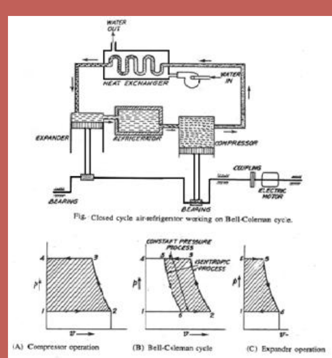
BELL-COLEMAN REFRIGERATOR



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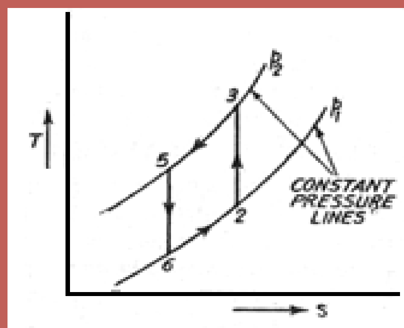
REPRESENTATION OF AIR- REFRIGERATION CYCLE ON T-S DIAGRAM



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ACTUAL BELL-COLMAN CYCLE

Actual analysis of Bell-Coleman-cycle. The actual cycle of operation differs from the theoretical in following respects :

(1) The compression and expansion processes do not follow isentropic law due to the internal friction, therefore, the processes can be considered as irreversible adiabatic (increase in entropy).

(2) The pressure drop takes place in the cooler due to the fluid friction particularly when the velocity of flow is considerably large.

(3) The pressure drop also takes place in the refrigerator, therefore, the pressure at the outlet of the expansion cylinder (or turbine) is greater than the pressure in the refrigerator.

These effects on the operating cycle are shown on *p-v* and *T-s* diagrams in Figs. (*a*) and (*b*).

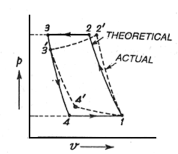

Fig. (*a*)

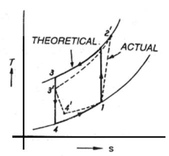

Fig. (*b*)

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NECESSISTY OF COOLING THE AEROPLANE

- Temperature is low at higher altitude.
- But many external & internal heat sources – Add the heat in the Cabin
- For comfort feeling, temperature of air should not exceed above 22^0C – maintain this temp. in the cabin
- -5^0C is required for preservation of food & drinks

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EXTERNAL HEAT SOURCES

(1) Sun pours heavy quantity of heat in the passenger cabin through the windows and also heats the top surface of the plane which further transfers the heat to the cabin.

(2) The pressure required in the passenger cabin is atmospheric pressure at sea level so that it is necessary to compress the ambient air from the ambient pressure to the cabin pressure because the pressure of the atmosphere decreases with an increase in altitude. Due to this compression, the temperature of the air entering the cabin will be higher than the ambient temperature.

(3) When the fast moving plane passes through air, it compresses a layer of air and raises its temperature. Owing to the skin friction, this compression occurs all over the aircraft and high temperature air layer will be always in contact with the external surface of the aircraft, so that, the heat will flow from the surface of the air-plane to the cabin.

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$V_1 = V_a$ = Speed of Aeroplane or speed of air in opposite direction

h_1 = Enthalpy of air before compression

h_2 = Enthalpy of air after compression

V_2 = Velocity of stagnant air.

Applying steady flow energy equation to the flowing air

$$\frac{V_1^2}{2} + h_1 = \frac{V_2^2}{2} + h_2$$

As $V_2 = 0$

$$\therefore \quad (h_2 - h_1) = C_p\,(T_2 - T_1) = \frac{V_1^2}{2}$$

$$\therefore \quad \Delta T = (T_2 - T_1) = \text{Rise in temperature} = \frac{V_1^2}{2C_p}$$

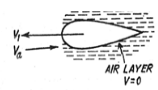

Fig. Air stagnation on aeroplane surface.

The actual rise in temperature will be 80 to 90% of the rise calculated theoretically because of heat transfer from hot compressed air to the colder surrounding.

An aeroplane moving with 1000 km/hour will experience 50°C rise in temperature of the surface.

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INTERNAL HEAT SOURCES

Internal Sources. (1) Human body continuously generates heat at a rate of 400 kJ per hour at rest and this heat is dissipated to the surroundings or to the cabin air. The passengers and pilot give off the heat to the cabin air.

(2) The electrical and electronic equipments used for the control system generate heat and this heat should be taken out for the efficient working of the control system. An aeroplane of 3000 KW capacity carrying 50 – 75 passengers requires control equipments of 10 kW capacity and it requires nearly 3 tons of refrigeration or cooling capacity.

(3) The engine parts of the aeroplane are subjected to a high temperature throughout the flight and heat from these parts comes to the cabin through conduction, convection and radiation.

All the above sources which are adding heat to the cabin will increase the cabin temperature and it becomes uncomfortable for the passengers. In the actual design, proper care is taken to reduce the heat flow from different sources mentioned above. Nowadays, it has become a common trend to equip the aeroplane with the refrigeration plant as the man requires more comfort.

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The advantages of air refrigeration for aeroplane are summarised as follows :

(1) As the compressed air is already available, there is no necessity to install a separate compression equipment for the system.

(2) Weight per ton of refrigeration capacity is least.

(3) Space and volume required per ton to set the plant is less compared with other systems.

(4) Air being non-flammable, there is no danger of fire.

(5) Leakage problem does not arise in air-refrigeration system which is the serious problem in vapour compression system.

(6) Maintenance cost is low.

(7) Any part of the air refrigeration system can be removed and repaired easily

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TYPES OF AIR REFRIGERATION SYSTEM

- 1. Simple cooling cycle system
- 2. Evaporative cooling system.
- 3. Boot strap air cycle refrigeration system
- 4. Regenerative cooling system.
- 5. Reduced ambient type cooling system

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SIMPLE EVAPORATIVE COOLING TYPE A/C SYSTEM

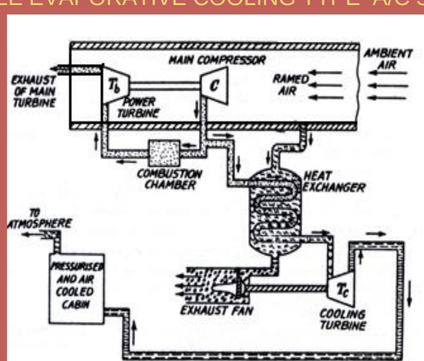

Fig. (a) Simple cooling cycle.

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The initial compression of the ambient air due to ram effect and a simple aircraft refrigeration cycle are shown in Fig. 11.5. The ram effect is shown by the line 1-2. Point 2′ denotes the state after isentropic diffusion to pressure p'_2 and temperature T_2'.
The energy equation for the process of diffusion is

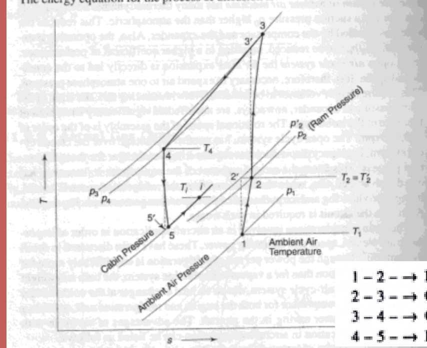

Fig. 11.5 Simple Aircraft Refrigeration Cycle

1 – 2 – → Ramming action.
2 – 3 – → Compression in main compressor.
3 – 4 – → Cooling in heat exchanger.
4 – 5 – → Expansion in the cooling turbine.

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Power required for the refrigeration system = m_a(kg/s) x Δ h(kJ/kg)
(to run the compressor)

= m_a Cp ($T_3 - T_2$) kW

C.O.P of the system = refrigerating effect / Work for compressor

$$= \frac{\text{Refrigerating capacity (in kW)}}{\text{Power (in kW for Running compressor)}}$$

$$= \frac{3.5\,TR}{\text{Power required for compressor}}$$

Where TR = tonn of refrigeration = 210 kJ/ minute = 3.5 kW

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BOOT STRAP AIR CYCLE REFRIGERATION SYSTEM

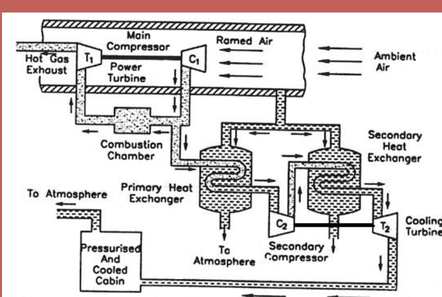

Fig. (a) Boot-Strap air-cycle Refrigeration System.

This cannot be used for ground cooling.

To provide an additional cooling capacity when the primary source does not have sufficient pressure to provide the amount of cooling required.

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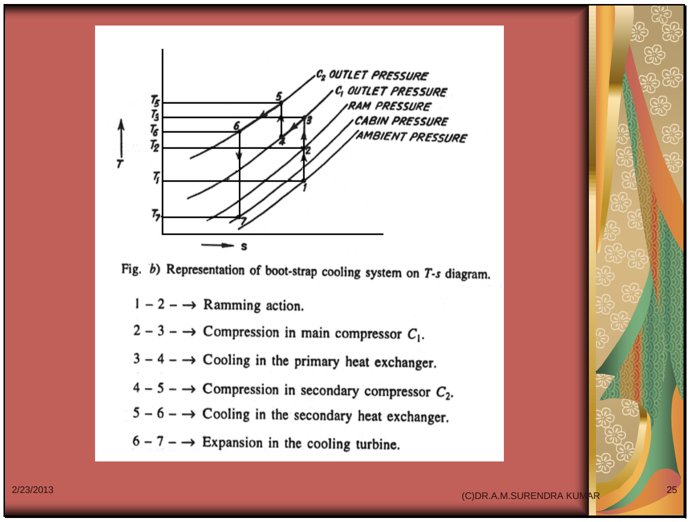

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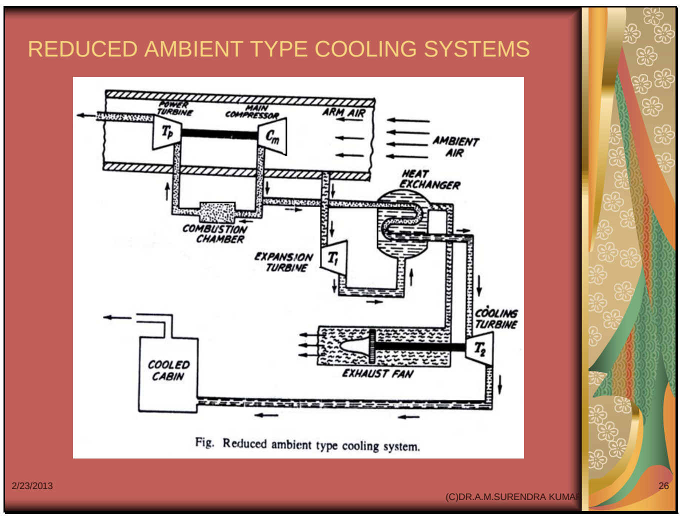

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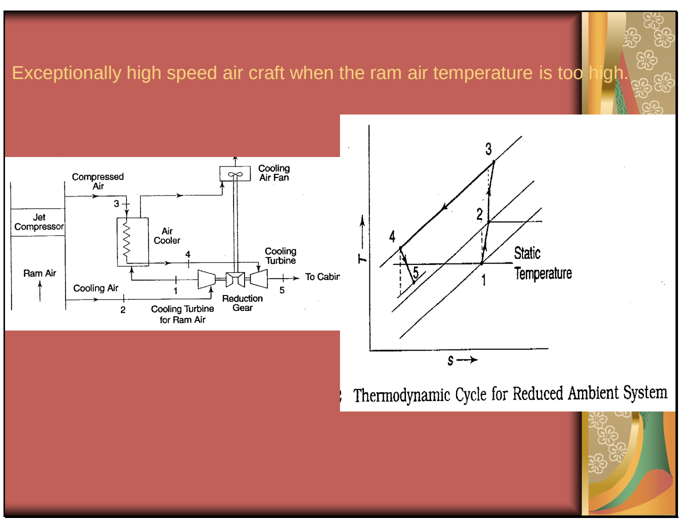

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DRY AIR RATED TEMPERATURE [DART]

A comparison of the different types of air-refrigeration systems is made in terms of *dry air rated temperature* (DART). This is the temperature of the discharge air from the expander if there is no condensed moisture present.

The rating of the aircraft units is given in terms of kg of air per unit time at the design DART. Thus the capacity of the machine giving $\dot{m}$ kg/s of air at a DART of t_0 to maintain a cabin at temperature t_i is

$$\dot{Q}_0 = \dot{m} C_p (t_i - t_0)$$

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COMPARISON OF DIFFERENT AIR COOLING SYSTEM USED IN AIR CRAFT

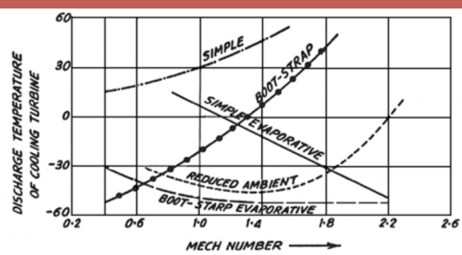

Fig. Air cycle cooling system performance curves (approximate).

(i) The simple system is preferable at low speeds.

(ii) Above a speed of 1000 kmph, the regenerative system is necessary. The Bootstrap system is also used.

(iii) Reduced ambient system may be useful for supersonic aircrafts and rockets.

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ACTUAL AIR-CONDITIONING SYSTEM WITH CONTROLLS

- In an automatic control Air-conditioning system, the following three controls are generally incorporated for the efficient working of the A/C system.

- 1. Temperature control in the Cabin
- 2. Air flow(quantity) control in the Cabin.
- 3. Water separator and anti-ice control

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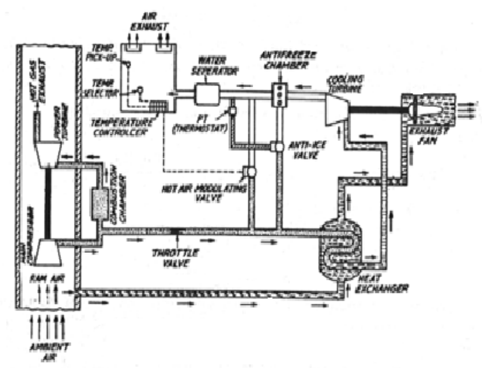

Fig. Air conditioning system of aeroplane with controls.

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Example 1

An air-cycle unit operating on the simple system is designed for the following conditions. 7.5 kg/min of air entering the turbine at 4.4 bar, cabin pressure 1 bar, dry air rated discharge temperature of -6 ^{0}C and a turbine efficiency of 80 %.

- (a) At what temperature does the air enter the turbine ?
- (b) How much power does the turbine supply to the fan ?

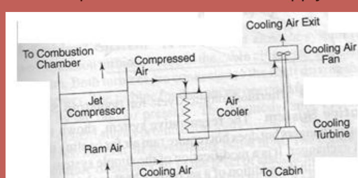

Fig. Simple System

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- In this system, the compressed air after cooling in air cooler (H.E) is passed through a cooling turbine. The work of this turbine is to drive a fan which draws cooling air through the H.E. This fan is put on the down stream side thus avoiding the additional temperature.

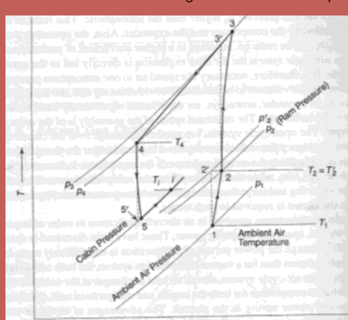

Fig. 11.5 Simple Aircraft Refrigeration Cycle

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- Given , $\dot{m}$ = 7.5 k/min, P_4 = 4.4 bar, P_5 = 1 bar, $ή_{turbine}$ = 80%
- T_5 = - 6^0C = 267 ^{0}K Find T_4 = ? & Turbine power = ?

$$\frac{T_4}{T_5^{\,I}} = \left(\frac{P_4}{P_5^{\,I}}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.4}{1}\right)^{\frac{1.4-1}{1.4}}$$

$$= 1.52$$

$$T_4 = 1.52 T_5^{\,I}$$

$$\eta_{turbine} = \frac{\Delta h_{ACTUAL}}{\Delta h_{ISENTROPIC}} = \frac{h_4 - h_5}{h_4 - h_{5^I}^{\,I}} = \frac{T_4 - T_5}{T_4 - T_5^{\,I}}$$

$$0.80 = \frac{1.52 T_{5^I}^{\,I} - 267}{1.52 T_5^{\,I} - T_5^{\,I}}$$

- $T_5^{\,I}$ = 241.84 K

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$$T_4 = 1.52 T_5^{\,I}$$
$$= 1.52 \times 241.84$$
$$= 367 \text{ K}$$

- Turbine work = m x cp x (T_4 - T_5)
- = (7.5/60) X 1.005 (367.60- 267)
- = 12.63 kW

a) The temperature does the air enter the turbine T_4= 367.60K = 94.6 ^{0}C

a) Turbine power supply to the fan = 12.63 kW