THERMODYNAMIC ANALYSIS OF VAPOR COMPRESSION REFRIGERATION SYSTEM FOR AIRCRAFT WITH REFRIGERANT R134a

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Abstract

The Environmental Control System (ECS) for a typical fighter aircraft is used for cabin cooling and pressurization, demisting operations, and for avionics cooling. Most of the passenger and fighter aircrafts use Bleed-Air Cycle for ECS. In this paper a new ECS called All Electric Environmental Control System (AEECS) is presented which works on Vapor Compression Refrigeration System using ram air as medium. It is called a power optimized system. The sizing of the system is based on the heat load calculations of the cabin and avionics for different flight conditions. A generalized software program is developed for evaluating system performance which includes key results regarding air compressor capacity, thermodynamic properties of refrigerants and Vapor Compression Refrigeration System. The AEECS is found to reduce the power requirement of the system to 80 kW compared to the Bleed Air Cycle ECS which requires a power of 0.8 MW to run the system. The results are presented in the form of graphs.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>m</th>
<th>m_c</th>
<th>m_a</th>
<th>m_t</th>
<th>P_amb</th>
<th>P_ca</th>
<th>P_com</th>
<th>P_ram</th>
<th>P_ret</th>
<th>PR_c</th>
<th>PR_ret</th>
<th>P_1</th>
<th>P_2</th>
<th>Q</th>
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<td>C_c = Heat capacity rate of ram air which is used in the cold side of the heat exchanger</td>
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<td>C_p = Specific heat of ambient air in kJ/kg. K</td>
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<td>L_ret = Load on refrigerant compressor in kW</td>
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<td>h_1 = Enthalpy of vapor refrigerant after evaporation in kJ/kg</td>
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<td>h_2 = Enthalpy of vapor refrigerant after compression in kJ/kg</td>
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<td>h_3 = Enthalpy of liquid refrigerant after condensation in kJ/kg</td>
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<td>h_4 = Enthalpy of liquid refrigerant after expansion in kJ/kg</td>
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\(Q_c\) = Heat load inside cabin in kW
\(Q_e\) = Heat load on the evaporator in kW
\(Q_{re}\) = Heat rejected by refrigerant inside condenser in kW
\(T_{amb}\) = Temperature of ambient air in °C
\(T_{ci}\) = Temperature inside cabin in °C
\(T_{cm}\) = Cabin mean temperature in °C
\(T_{co}\) = Temperature outside cabin in °C
\(T_{ei}\) = Temperature at the inlet of evaporator in °C
\(T_{eo}\) = Temperature at the outlet of evaporator in °C
\(T_{ram}\) = Temperature of ram air in °C
\(T_1\) = Temperature of the refrigerant at the outlet of evaporator in °C
\(T_2\) = Temperature of the refrigerant at the outlet of compressor in °C
\(\Delta P_h\) = Pressure drop in Primary Heat Exchanger in bar
\(\Delta P_p\) = Pressure drop in Piping
\(\Delta T\) = Temperature difference in °C
\(\zeta_c\) = Efficiency of air compressor
\(\zeta_{rc}\) = Efficiency of refrigerant compressor
\(\zeta\) = Effectiveness of Primary Heat Exchanger

**Greek Symbols**

\(\gamma\) = Heat Capacity Ratio
\(\Delta h\) = Difference in enthalpy in kJ/kg
\(\Delta P_{cv}\) = Pressure drop in cabin valves in bar
\(\Delta P_c\) = Pressure drop in evaporator in bar
\(\Delta P_h\) = Pressure drop in Primary Heat Exchanger in bar

**Introduction**

The Environmental Control System for a typical fighter aircraft is used for cabin cooling and pressurization, demisting operations, and avionics cooling. Presently most of the Fighter and Passenger Aircrafts ECS are using conventional Bleed-Air Cycle System as ECS which consists of an Air Cycle Machine (ACM) along with a High Pressure Water Separator (HPWS). The Bleed-Air Cycle System uses the high pressure and high temperature bleed-air drawn from the high pressure compressor of the engine as a medium. This bleed air is cooled by passing through a series of compact heat exchangers and a Cold Air Unit (CAU). The amount of the energy wasted due to the cooling of this high pressure and high temperature air is very high. The main disadvantage in this system is the decrease in the thrust produced by the engine and increase in fuel consumption due to drawing of bleed air from the compressor of the engine. Also the high temperature air needs to travel long distances from engine making it necessary to use high temperature materials, seals and fire safety system which may lead to fire hazards in case of leakage or breakdown of insulation. This further increases the service and maintenance cost of the system.

With the advanced technology, the trend is currently to use more electricity in Aircraft, this is called "All Electric Aircraft", in which part or all the systems are electrically driven [1]. To overcome these problems All Electric Environmental Control System (AEECS) has been chosen which works on Vapor Compression Refrigeration System. The use of AEECS is a very recent trend to which world aircraft industries are switching over due to the extensive developments in environmental control system and development of user friendly refrigerants. The refrigerants (which are the main source of heat transfer in any Vapor Compression Refrigeration System) have high COP and heat transfer rates compared to air. In this system no bleed air is drawn from the engine and therefore the efficiency of the engine is kept to its maximum. In this system, ram air is chosen as medium for cooling and pressurizing the cabin, demisting operations and avionics cooling. A generalized software program has been developed as per the flow chart shown in Fig.1 to calculate the cabin heat loads at different flight cases by taking the refrigerant properties [2-3] and calculation methodology [1]. World aircraft development industries are switching over to age old Vapour Compression Systems due to extensive developments in environmental control system and user friendly refrigerants. PC 12 (Passenger Aircraft) and PC 21 (Swiss air force trainer) developed by PILATUS Aircraft Industries Switzerland, has developed the Vapour Cycle System (VCS) system for aircraft and the systems are operational.

**All Electric Environmental Control System (AEECS)**

The general schematic diagram of the AEECS is shown in Fig.2. In this system, the compressed air is generated from the variable speed centrifugal compressors which are electrically driven and the compressed air is cooled by passing it through a primary heat exchanger.
Traces of moisture present in the air are removed by passing the air through a low pressure water separator. The air is further cooled by passing it through the Vapor Compression Refrigeration System to attain the required cabin temperature. The conditioned air is now passed through the air manifold for distribution to cabin and avionics. The Cooling Pack Temperature Control Valve (CPTCV) is used to by-pass the air without passing it to the Vapor Compression Refrigeration System if the temperature of air is equal to the required cabin temperature; heater is required to heat the air before sending it to the cabin at higher altitudes.

Among the refrigerants, the R134a is chosen as the refrigerant for the Vapor Compression Refrigeration System of AEECS since it is a single HFC compound with no chlorine content. The Fluorine atom in the molecule of R134a makes the substances physiologically more favorable [4]. The depletion of ozone layer in the upper atmosphere (stratosphere) with the leakage of these substances is zero. Ozone Depletion Potential (ODP=0) and Modest Global Warming Potential (GWP=1300) [5] of R134a, more practical, eco-friendly and is ready for commercial use.

Methodology

The design of the AEECS is completely based on the temperature and pressure to be maintained inside the cockpit and heat loads present inside the cockpit. The mean temperature which is to be maintained inside the cabin can be within the range of 22°C to 29°C and the pressure to be maintained inside the cabin ranges from 0.4 bar to 1 bar depending on the altitude and mach number of the flight.

Heat Loads inside Cabin and Avionics

The heat loads present include cabin heat loads and avionics heat loads. Avionics heat loads are the loads produced by the electronic equipment and therefore they do not change with varying altitude and mach number. But the cabin heat loads keep changing with different flight conditions as they are the function of altitude, mach number and heat loads due to conduction and convection. Various points from the flight cycle are selected to see the effect of all corners of flight envelop for estimation of heat loads for air compressor and refrigerant compressor. It will help to design the proper air compressor as well as refrigerant compressor. The heat loads due to conduction and convection include heat load due to convection from external insulated walls, non-insulated external wall, insulated bulk head walls, non-insulated bulk head walls, non-insulated structural projections, of the cabin, heat load due to solar radiation through transparencies (which include canopy and windscreen), heat load due to conduction and convection through the transparencies, metabolic heat load of the pilot, electrical heat load and mechanical heat load [6]. These heat loads are used to calculate the mass flow rate of air required to be circulated inside the cabin to maintain a comfortable temperature and pressure inside the cabin. The cabin mean temperature shall be estimated using empirical relation given below.

$$T_{cm} = 0.25T_{ci} + 0.75T_{co}$$  \hspace{1cm} (1)

The above equation is globally fighter aircraft industries are using for calculating cabin mean temperature based on cabin volume. However the same has been validated experimentally for fighter aircraft.

The mass flow rate can be calculated using the equation

$$m = \frac{Q}{C_p \Delta T} \text{ kg/min}$$  \hspace{1cm} (2)

Where, \(\Delta T = T_{co} - T_{ci}\) and \(Q = Q_c + Q_a\)

Air Cycle

The required air in terms of mass flow rate of the air is obtained by drawing the air from the surrounding atmosphere through the "Ram Air Duct", which is a small scoop generally located on the "wing to body fairing", and compressed through the air compressor. The shape of the duct is responsible for the ramming action of the air which results in the increase of the temperature and pressure of the atmospheric air. The temperature and pressure of ram air is calculated as

$$T_{ram} = T_{amb} \left(1 + \frac{\gamma - 1}{2} M^2 R\right)$$  \hspace{1cm} (3)

$$P_{ram} = P_{amb} R \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$  \hspace{1cm} (4)

Where, \(R\) is Recovery factor

The air is compressed to the required pressure \(P_{com}\) which, depends on the pressure required inside the cabin
and the pressure losses in the heat exchanger, evaporator, piping’s and valves inside the cabin.

\[ P_{\text{com}} = P_{ca} + \Delta P_h + \Delta P_e + \Delta P_p + \Delta P_{cv} \]  

(5)

\[ PR = \frac{P_{\text{com}}}{P_{\text{ram}}} \]  

(6)

The compressed ram air is cooled to the required cabin temperature and pressure by passing it through primary heat exchanger and evaporator. The design of the air compressor is based on the pressure ratio and compressor load values obtained during different flight conditions. Load on the air compressor is calculated by using the equation.

\[ L_c = \frac{m C_{pr} T_{\text{ram}}}{\eta_c} \left( \left( \frac{PR}{\gamma} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right) (kW) \]  

(7)

Where, \( \eta_c = \text{Efficiency of Air Compressor} \).

The heat exchanger which is used here is a compact heat exchanger. It is an air to air heat exchanger which uses ambient air to cool the compressed air. The temperature at the outlet of the heat exchanger is calculated using the equation.

\[ \epsilon = \frac{C_h T_{\text{hi}} - T_{\text{ho}}}{C_{\text{min}} T_{\text{hi}} - T_{ci}} \]  

(8)

Where, \( \epsilon = \text{effectiveness of heat exchanger} \),

\[ C_h = m C_{\text{ph}}, C_c = m C_{\text{pc}} \text{ and } C_{\text{min}} = \min \left( C_h, C_c \right) \]

**Vapor Compression Refrigeration System**

The cooling of the compressed ram air after the primary heat exchanger is done in evaporator of the vapor compression refrigeration system. The air is cooled by using the refrigerant R 134a which is an eco friendly refrigerant. The heat load on the evaporator is calculated using the equation.

\[ Q_e = m C_p \Delta T (kW) \]  

(9)

Where, \( \Delta T = (T_{ei} - T_{eo}) \)

This is the amount of heat that is to be removed by the evaporator in order to supply the air to the cabin with required temperature. The Tonnage of refrigerant to be used to remove the heat load is given by the equation:

\[ \text{Tonnage of Refrigerant} = \frac{Q_e}{3.5176} T_R \]  

(10)

The operating temperature of the refrigerant in the evaporator is -20°C. The mass flow of the refrigerant required to cool the air is calculated by using the equation is

\[ m_r = \frac{Q_e}{\Delta h} (kg/min) \]  

(11)

The required mass flow of the refrigerant to cool the air is obtained by compressing the super heated refrigerant in the refrigerant compressor. The pressure ratio required to compress the refrigerant inside the refrigerant compressor is obtained by using the equation

\[ \frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} \]  

(12)

The design of the refrigerant compressor is based on the pressure ratio and the loads acting on the compressor during different flight conditions. The load on the refrigerant compressor is calculated by using the equation

\[ L_{rc} = \frac{m C_{pr} T_{\text{ram}}}{\eta_{rc}} \left( \left( \frac{PR}{\gamma} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right) (kW) \]  

(13)

Where, \( \eta_{rc} = \text{Efficiency of refrigerant compressor} \).

The compressed refrigerant is condensed to liquid refrigerant in the air cooled compact heat exchanger as condenser at constant temperature and pressure. The amount of heat rejected from the condenser is calculated using the equation

\[ Q_{re} = m_r (h_2 - h_3) \]  

(14)

The complete phase change of the refrigerant from vapor to liquid is achieved in the expansion valve where the high temperature and pressure refrigerant is expanded to the temperature and pressure of refrigerant required inside the evaporator to cool the air. The heat absorbed by
the refrigerant during the evaporation is calculated by using the equation.

$$Q_{ab} = m_r (h_1 - h_4)$$ (15)

**Results and Discussions**

The variation of cabin heat loads with varying altitude can be observed from Fig.3, which shows that with increase in Altitude (at a constant Mach number) the cabin heat loads decrease. The variation of cabin heat loads with Mach number can be seen from Fig.4 and Fig.5, which shows that with increase in Mach number (at a constant Altitude) the cabin heat loads increase. The decrease in cabin heat loads with increase in altitude is due to the decrease in the ambient air temperature with increasing altitude. The increase in cabin heat loads is due to the increase in external skin temperature ($T_s$), floor temperature ($T_f$), and bulkhead wall temperature ($T_b$) with increasing Mach number.

The variation of air compressor load with varying Altitude and Mach number is shown in Fig.6 to Fig.10. From the Fig.6 to Fig.9, it can be clearly seen that the Load on Air Compressor decreases with increase in Mach number (at a constant altitude) and from Fig.10, it can be seen that with increase in Altitude (at constant Mach number) the load on air compressor increases. With increase in Mach number the velocity with which the ambient air enters into the "Ram Air Duct" increases. This high velocity air undergoes ramming in the ram air duct resulting in a ram air with temperature and pressure as high as the compressed ram air. Therefore, the load on air compressor decreases with increase in Mach number. The temperature and pressure of the air decreases with increase in altitude and therefore the air compressor has to compress the ram air with a high pressure ratio resulting in the increase of load on air compressor.

The variation of refrigerant compressor load with altitude is shown in Fig.11 and Fig.12, which shows that the load on refrigerant compressor decreases with increase in Mach number (at a constant altitude). This is due to ram effect and kinetic heating as the Mach number increases at a constant altitude.

The variation of load on refrigerant compressor with Mach number is shown in Fig.13 in which decrease in the load on refrigerant compressor with increase in Altitude (at constant Mach). The load on refrigerant compressor decreases with increase in Mach number because the increasing Mach number increases the pressure and temperature of ram air which results in the increase in the heat load on evaporator and thereby increasing the load on the refrigerant compressor to supply more refrigerant to cool the air. The decrease in the load on refrigerant compressor with increase in altitude is due to the decrease in the temperature and pressure of the ambient air with increasing altitude which results in the decrease in heat load on evaporator and the refrigerant compressor and the vapor compression refrigeration system.

**Conclusions**

The following conclusions have been drawn from the above results. The cabin heat loads are decreases with increase in Altitude at a constant Mach number is due to the decrease in ambient air temperature with increasing altitude. The cabin heat loads are maximum at sea level due to high kinetic heating and solar heating. The cabin heat loads increases due to the increase in external skin temperature, floor temperature and bulkhead wall temperature with increasing Mach number. The load on air compressor is found to be very less when the aircraft is at sea-level with a Mach number of 0.9. The load on air compressor is highest when the aircraft is flying at an altitude of 15 km with a mach number of 0.6 (~80kW). This shows that the air compressor has to be designed for a load of 80 kW. The load on refrigerant compressor is found to be maximum at sea-level when the aircraft is flying with 0.9 Mach (~6kW) and is minimum at an altitude of 3 km from where there is no requirement of cooling the air by using the vapor compression refrigeration system. This shows that the refrigerant compressor has to be designed for a load of 6 kW.

The secondary power system which is used to power the AEECS is an electric power system which is designed in such a way that it provides the system with right amount of power and can be switched on and off as and when needed, thus conserving power. The losses in electrical cabling are lower than those in pneumatic systems used to power the conventional bleed air ECS. The use of ram air as a medium to cool the cabin avoids the use of high pressure and high temperature sealing materials thereby reducing the maintenance and servicing cost of the system and also avoids the chance of fire hazards due to the leakage of sealing materials.

The use of ram air as a medium to cool the cabin and avionics reduces the number of components to be used in the system resulting in the considerable decrease of the
total power requirement of the system compared to the conventional Bleed air System. The use of refrigerant to cool the compressed air results in high heat transfer rates.

Finally, the engine thrust has to be maintained to its maximum value by removing the need to use bleed air drawn from the engine for cooling of cabin and avionics. This results in attaining the maximum efficiency of the engine.

Acknowledgements

The authors wish to acknowledge Aeronautical Development Agency to publish this paper.

References


Fig. 2 Schematic Diagram of All Electric Environmental Control System Using Vapor Compression Refrigeration System
Fig. 1 Flow Chart of AEECS
Fig. 3 Variation of Cabin Heat Load with Altitude (at 0.9 Mach)

Fig. 4 Variation of Cabin Heat Load with Mach Number at Sea-level

Fig. 5 Variation of Cabin Heat Load with Mach Number at an Altitude of 15 km

Fig. 6 Variation of Load on Air Compressor with Mach Number at Sea-level

Fig. 7 Variation of Load on Air Compressor with Mach Number at an Altitude of 6 km

Fig. 8 Variation of Load on Air Compressor with Mach Number at an Altitude of 12 km
Fig. 9 Variation of Load on Air Compressor with Mach Number at an Altitude of 15 km

Fig. 10 Variation of Load on Air Compressor with Altitude (at 0.9 Mach)

Fig. 11 Variation of Refrigerant Compressor Load with Mach Number at Sea-level

Fig. 12 Variation of Load on Refrigerant Compressor with Mach Number at an Altitude of 3 km

Fig. 13 Variation of Load on Refrigerant Compressor with Altitude (at 0.9 Mach)