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THINKING OF THE WORLD

Analysis of Air Conditioning Systems in Commercial Airliners

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Abstract

The following project details the analysis of air conditioning systems in commercial airliners. The system uses air passed in by the turbo-prop compressors and heats it up with rammed air to be supplied to the cabin for cooling. The analysis entails the observation of relations between cooling loads, cooling air mass flows, and overall cooling capabilities of the system.

Introduction

Commercial airliners use Environmental Control Systems which provide fresh air to the airliner by bleeding air from compressors inside the jet engines. Airliners cruise optimally at 893 km/hr and operate at an altitude of 11,000 m. A schematic of the cooling system is as follows:

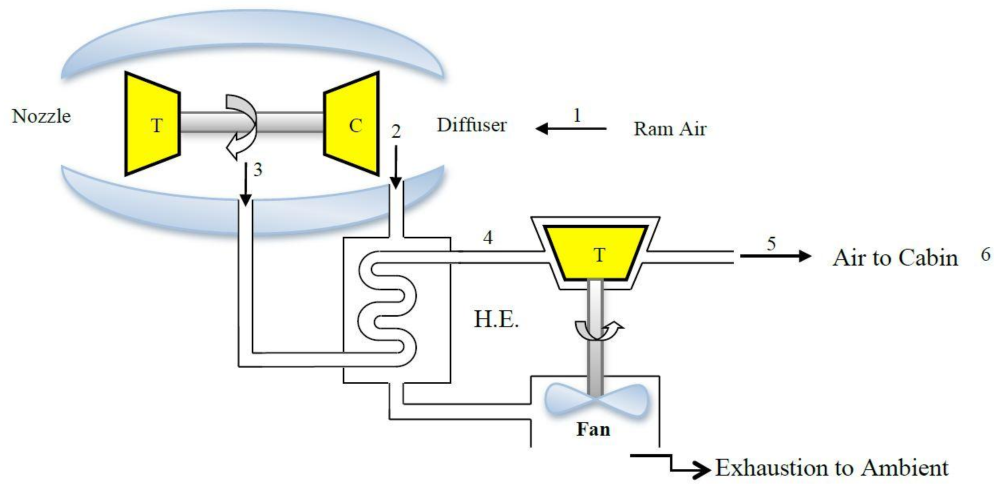


Figure 1. Schematic of aircraft air conditioning system, courtesy of Dr. M. Bahrami, S.F.U.[1]

Air at point 1 is rammed into the engine, where it reaches stagnation, leading to a sudden increase in the temperature of the air. The compressor works on this heated air, during this operation, the air gains pressure while losing temperature. From stage 3 to 4, air bled from the compressor is heated using the air being bled from stage 2. The air from stage 4 which is still at too high of a pressure to be useful, is passed through a turbine. Then the air is passed to the circulation system at stage 5, where it mixes with the cabin air while providing for the cooling.

The cooling system achieves three important objectives; it continuously replaces the cabin air with fresh air, while providing for cooling, and also pressuring it for cabin use.

The ideal operation of the process described above is given in figure 2.

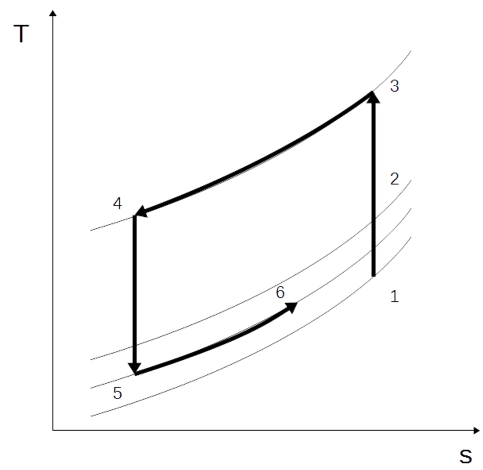


Figure 2. Ideal T-s diagram of air conditioning system.

Analysis

Figure 2 gives the T-s diagram for an ideal system, where the stages 1 to 2 to 3, and 4 to 5 are isentropic. For the sake of analysis we will consider the non-ideal behavior of the compressor and the turbine. Thus being non-isentropic the qualitative behavior of the system will be as given in figure 3.

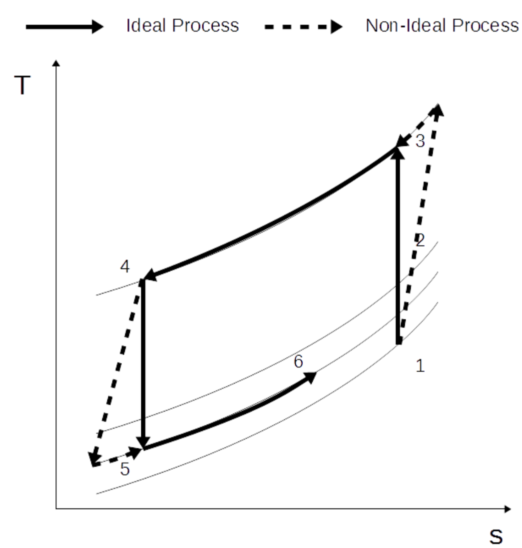


Figure 3. T-s diagram for non-ideal air conditioning system.

Our simplifying assumptions stand on the basis of ideal gases, as the operating temperatures and pressure for air inside the air conditioning system will be much higher than critical point. Thus for air being approximated as ideal gas:

$$Pv = RT$$

Where,

$$P, Pressure\ of\ the\ gas$$

$$v, volume\ per\ mass$$

$$R, is\ the\ gas\ constant, 0.287\ kJ/kg.K\ for\ air$$

$$T, Temperature\ of\ gas$$

Under isentropic conditions for an ideal gas:

$$P_{2s} = P_1 \left(\frac{T_{2s}}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

Where,

$$PV^{\gamma} = Constant$$

Further assumptions involve neglecting the drop in K.E. and P.E. while the gas travels through the air conditioning system, hence for each element in the system $\Delta KE = \Delta PE = 0$, thus owing to this the change in enthalpy will be directly related to the change in Temperature.

In order to void considering a completely idealized process, and to make our calculations more accurate we will consider non-deal behavior for the ram effect, compressor, heat exchanger, and the turbine. For each of the elements the non-ideality will be given as follows:

$$Ram\ efficiency = \eta_{Ram} = \frac{P_2 - P_1}{P_{2s} - P_1}$$

$$Isentropic\ efficiency\ of\ compressor = \eta_C = \frac{T_{3s} - T_2}{T_3 - T_2}$$

$$Isentropic\ efficiency\ of\ turbine = \eta_T = \frac{T_4 - T_5}{T_4 - T_{5s}}$$

$$Effectiveness\ of\ heat\ exchanger = \varepsilon = \frac{(\dot{m}C_p)_{3-4}(T_3 - T_4)}{(\dot{m}C_p)_{min}(T_3 - T_2)}$$

For the primary analysis, the state of air conditioning systems was fixed as:

$$Inlet\ Cabin\ Air: 24^o\ C, 1\ bar$$

$$Ambient\ Air: 27^o C, 0.86\ bar$$

$$Cooling\ Load: 20.14000\ kJ/hr$$

$$P_3 = 4.5P_2$$

$$\eta_{Ram} = 88\%$$

$$P_4 = P_3 - 0.51\ bar$$

$$\varepsilon = 0.9$$

$$P_5 = Cabin\ Pressure + 0.1\ bar$$

$$\eta_C = \eta_T = 82\%$$

$$For\ air: C_p = 1\frac{kJ}{kg.K}, \gamma = 1.4$$

Further simplifying the analysis of the heat exchanger let us assume:

$$\left(\dot{m}C_p\right)_{min} = \left(\dot{m}C_p\right)_{3-4}$$

Given the relations above, the state of the constitutive elements can be found by progressively solving the following equations:

$$T_{2s} = T_2 = T_1 + \frac{V^2}{2C_p}$$

$$P_{2s} = P_1\left(\frac{T_{2s}}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$P_2 = \eta_{Ram}.(P_{2s} - P_1) + P_1$$

$$P_{3s} = P_3 = 4.5P_2$$

$$T_{3s} = T_2\left(\frac{P_{3s}}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_3 = \frac{T_{3s} - T_2}{\eta_C} + T_2$$

$$P_4 = P_3 - 0.51\ bar$$

$$T_4 = T_3 - \varepsilon.(T_3 - T_2)$$

$$P_{5s} = P_5 = Cabin\ Pressure + 0.1\ bar$$

$$T_{5s} = T_4\left(\frac{P_{5s}}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_5 = T_4 - \eta_T.(T_4 - T_{5s})$$

After calculating the state temperatures and pressures, to calculate the air mass flow, we can consider the fact that the cooling takes place between stage 5 and 6, and as $\Delta KE = \Delta PE = 0$,

$$Q = \dot{m}C_p\Delta T$$

Thus,

$$\dot{m} = \frac{Cooling\ Load}{C_p.(T_6 - T_5)}$$

Further, the work required by the compressor will be:

$$W = \dot{m}C_p(T_3 - T_2) - Q_{lost}$$

$$Q_{lost} = \dot{m}.[C_p.\log\left(\frac{T_3}{T_2}\right) - R.\log\left(\frac{P_3}{P_2}\right)].(Ambient\ Air\ Temperature)$$

Hence, COP for the system can be calculated as

$$COP = \frac{Cooling\ Load}{Compressor\ Work}$$

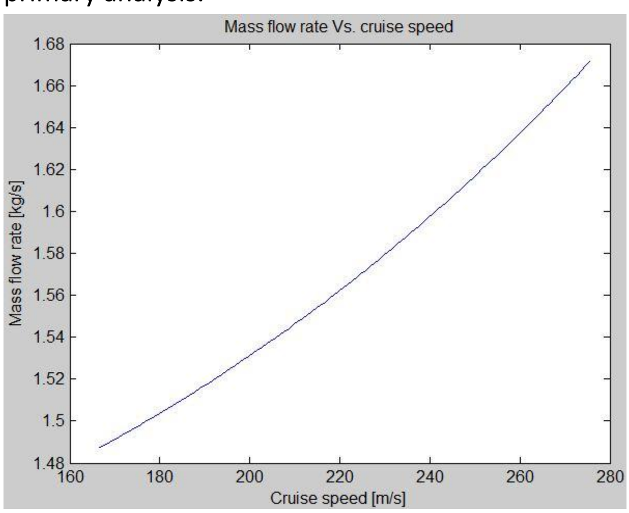
Results & Discussion

The values for the primary analysis are given as follows:

$Mass\ air\ flow = \dot{m}, [kg/s]$	COP	$Compressor\ Power\ used\ for\ cooling\ [kW]$	$Propulsion\ Power\ [kW]$	$Cooling\ to\ Propulsion\ Power\ Ratio$
1.613	0.2473	314	221,110	0.0014

Table 1. Data set from primary analysis

To check the dependency of the interested data sets on input variables, the mass air flow, and COP were compared against the airplane cruise speed, temperature of the ambient air, and cooling load. Only one of the inputs was varied at a time while all other parameters were held at the values given in the primary analysis.



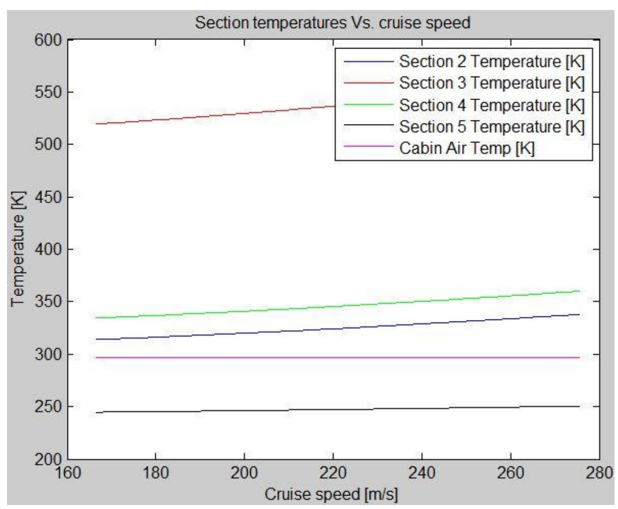


Figure 4. Mass Flow Rate and Section Temperatures Vs. Cruise Speed.

As seen in figure 4,the cruise speed increases the temperature after ramming stage, as the air has more KE, but while subsequently going through the system , the effect fades away, and we can see that section 5 Temperature does not respond as fast as section 2 to cruise speed, as such the mass flow rate does not display drastic change. Although we can see that mass flow rate looks exponentialy dependent on the cruise speed. The converse is true for COP, as temperate at section 3 rises faster than that at section 2, the work done by the compressor is also increasing, again as the difference does not change drastically, COP only changes by about 19% for 42% change in the cruise speed.

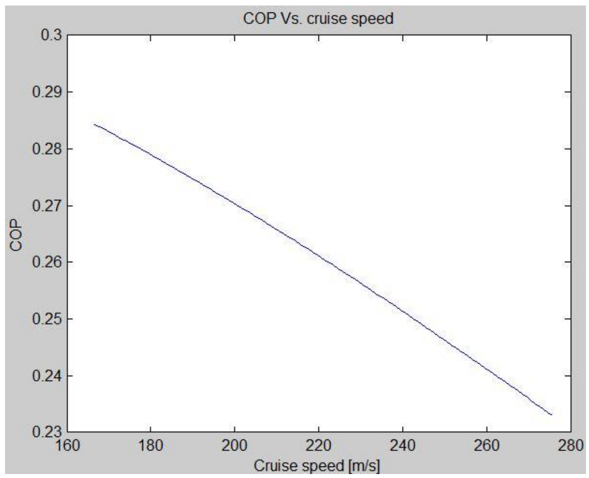
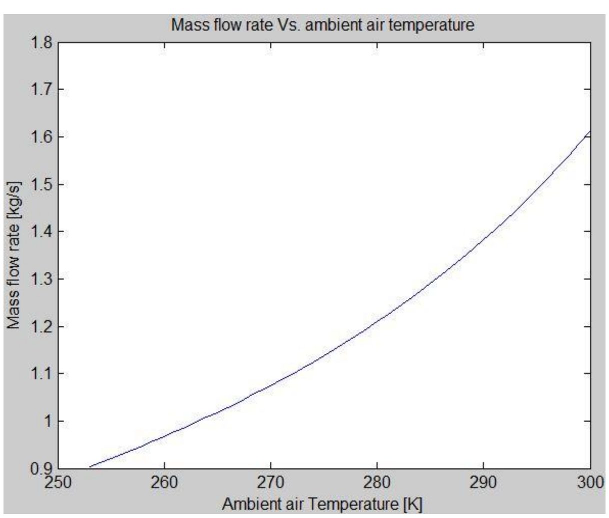


Figure 5. COP Vs. Cruise Speed.

For the ambient temperature, we can see that the section temperatures can be approximated as direct linear functions, as such the difference between temperature at Section 5 and that of Cabin, closes up quickly with increase in air temperature, thus leading to a high rise in the mass flow rate. Again for COP the result is expected, as Section 2 temperature rises slower than Section 3, more work is done by compressor at higher ambient air temperatures, thus leading to a decrease in the COP.



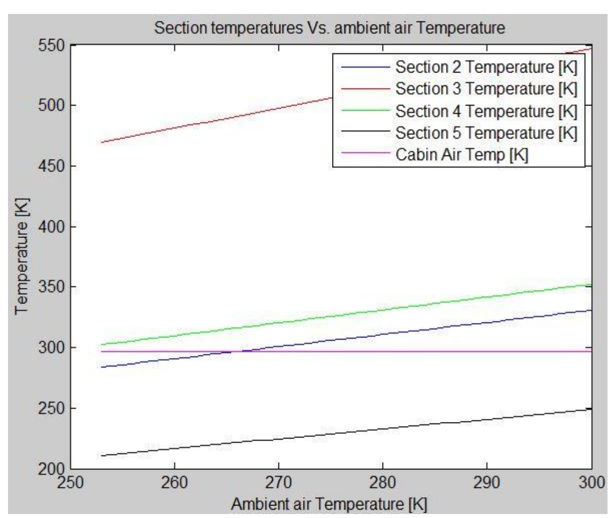


Figure 6. Mass Flow Rate and Section Temperatures Vs. Ambient Air Temperature.

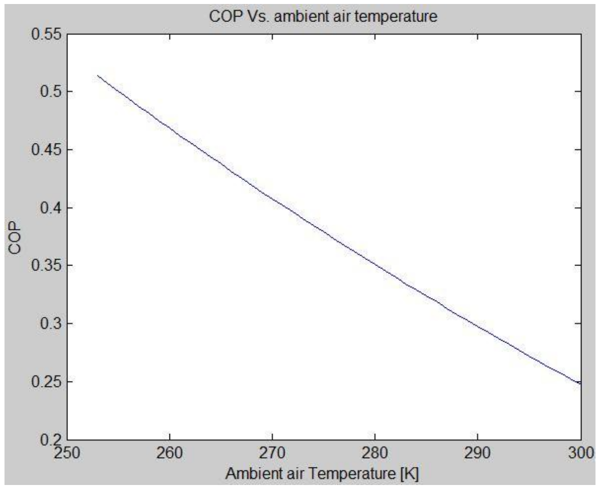


Figure 6. COP Vs Ambient Air Temperature.

Lastly for the cooling load, as it does not impact any of the section temperatures, the mass flow rate becomes its linear function. COP does not get impacted, as the work done by the compressor is now linearly dependent on the mass flow rate.

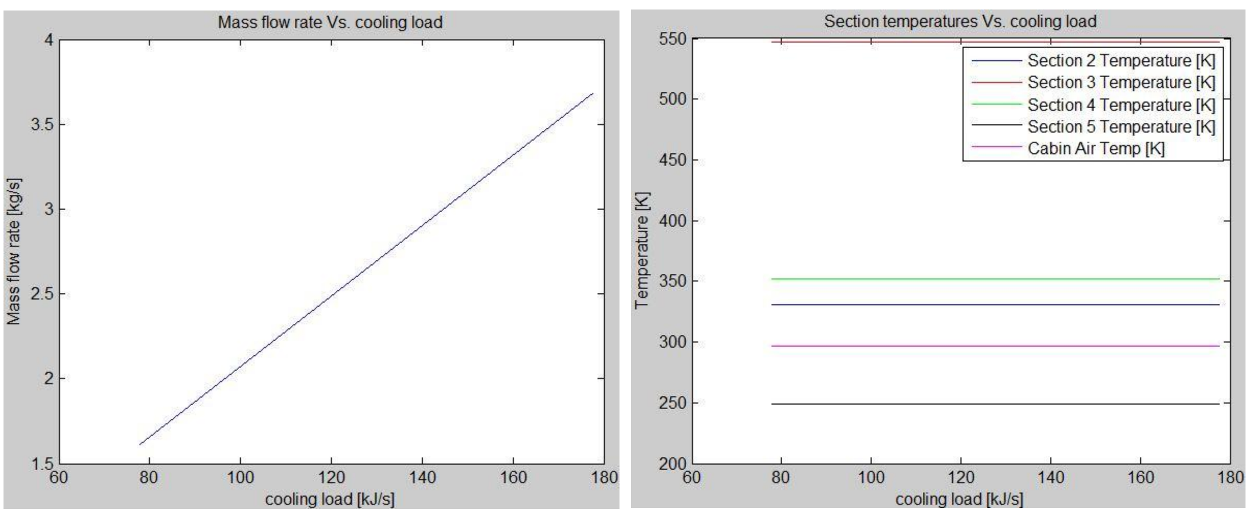


Figure 7. Mass Flow Rate and Section Temperatures Vs. Cooling Load.

From the above data we can safely say that mass flow rate and COP of the air conditioning system are most sensitive to the ambient air temperature, given that higher altitude variations in air temperature are not very volatile means that optimization of air conditioning system will not be highly dependent on the temperature. The same can be said about the cooling load, as it is a direct linear function and hence easiest to adapt for. Although the cruise speed is a controllable parameter, and a judicious choice will save power being spent on the air conditioning, as the ratio of power used for cooling to propulsion is really small, but nevertheless at higher altitudes, due to low drag, power saved on cooling would mean more economic flights.

Thus the optimized working conditions for the air conditioning system are dictated by low cruise velocity, low ambient temperature, while it is not really dependent on the cooling load.

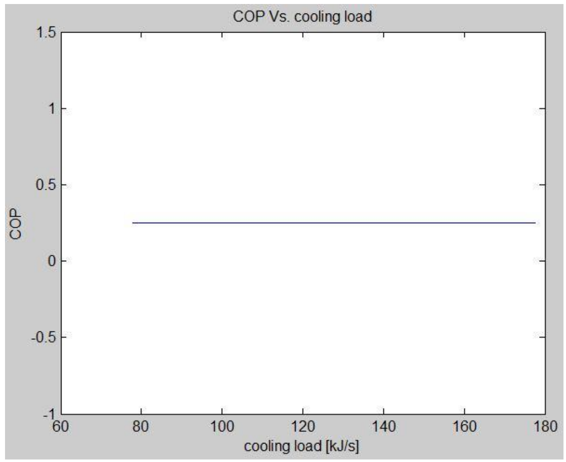


Figure 4. COP Vs. Cooling Load.

Conclusion

Air conditioning systems in airliners are designed to refresh, cool, and pressure the cabin. They do so by bleeding the air rammed into the propulsion compressors. The air is cooled by using air from ramming section of the jet. Data analysis shows that the mass rate of air flowing through the system increases with increase in air speed, ambient air temperature, and cooling load inside the cabin. While the COP of the conditioning system decreases with increase in cruise speed, and ambient air temperature, and is independent of the cooling load.

The optimized condition for the system can be achieved by balancing the COP with the mass flow rate these two parameters behave oppositely to each other with respect to the studied parameters. Since among the given parameters only cooling load and cruise speed are controllable, cruise speed of 883 km/hr seems optimized to balance the mass flow rate through the air conditioning system to the COP.

References

[1]http://www.sfu.ca/~mbahrami/ENSC%20388/Lab/Experimrnt%202/Vapor%20Compression%20Refrigeration%20Cycle.pdf

[2] http://www.boeing.com/boeing/commercial/cabinair/

[3] http://en.wikipedia.org/wiki/Environmental_control_system_%28aircraft%29