A THERMODYNAMIC STUDY OF AN AIRCRAFT AIR-CONDITIONING AIR CYCLE MACHINE

Cláudia Regina de Andrade
Instituto Tecnológico de Aeronáutica, IEM, Pça Marechal Eduardo Gomes, 50 - 12228-900 - São José dos Campos, SP, Brasil, claudia@mec.ita.br

Edson Luiz Zaparoli
Instituto Tecnológico de Aeronáutica, IEM, Pça Marechal Eduardo Gomes, 50 - 12228-900 - São José dos Campos, SP, Brasil, zaparoli@mec.ita.br

Abstract. *At this work a thermodynamic study of an air-conditioning aircraft air cycle machine (ACM) is performed. This ACM configuration includes mainly two compact heat exchangers, a compressor and an expander. The energy to drive this machine comes from the compressed air bleed from the compressor of the aircraft propulsion turbine. Some design features that affect the ACM performance will be studied in this work: aircraft Mach number, cabin altitude, cabin temperature and the percentage of the turbine work absorbed by the exhaust fan. Results obtained shows that the implemented computational tool that solves the ACM mathematical model allows an understanding of the ACM performance when flight aircraft and cabin human comfort parameters are changed to attain an optimized ECS configuration design.*

Keywords: *air conditioning, air cycle machine (ACM), environmental control system (ECS), coefficient of performance (COP).*

1. INTRODUCTION

Environmental control system (ECS) is a generic term used in the aircraft industry for the systems and equipment associated with the ventilation, heating, cooling, humidity/contamination control, and pressurization in the occupied compartments, cargo compartments, and electronic equipment bays. (ASHRAE, 1997).

The primary function of the cabin air conditioning and pressurization system is to maintain an aircraft environment that will ensure the safety and comfort of the passengers and crew during all fly operational conditions and provide adequate avionics cooling. This includes a supply of conditioned air for heating and cooling the cockpit and cabin spaces. Air cycle refrigeration is a tried and tested technology that has long been the basis of aircraft cabin cooling. Air cycle machine is an attractive process since air is free, safe and harmless to the environment. The use of air as a refrigerant is based on the principle that when a gas expands isentropically from a given temperature, its final temperature at the new pressure is much lower. The resulting cold gas can then be used as a refrigerant, either directly in an open system, or indirectly by means of a heat exchanger in a closed system. The efficiency of such systems is limited to a great extent by the efficiencies of compression and expansion, as well as those of the heat exchangers employed.

Until now the low energy efficiency and high cost of air cycle systems have prevented their use in stationary applications (buildings, automobiles). The air cycle machine has evolved as a widely used means of providing cooling for aircraft and helicopters. Compressed air extracted from one or more stages of the engine compressor expands through a turbine with the power extracted used to drive a fan (simple cycle), a compressor (bootstrap cycle), or both (simple/bootstrap cycle).

The power extraction and expansion of the compressor air across the turbine results in a significant temperature decrease. This air provides cooling of the aircraft occupied compartments and avionics. The present day gas turbine aircrafts have very high cooling loads because of their large occupancy, electronic equipment and high velocity with consequent heat generation due to skin friction. The main considerations involved in an aircraft application in order of importance are weight, space and operating power, since weight and space results in severe fuel penalties. Though the power per refrigerating effect unit is considerably more for air cycle refrigeration than for a vapor-compression system (lower COP), the bulk and weight advantages of the air open cycle machine, due to no heat exchanger at the cold end (low pressure/temperature) and a common turbo compressor for both the propulsion turbine and refrigeration plant, result in a greater overall power saving in the aircraft.

Some additional advantages of an air cycle with regard to its application in aircraft refrigeration can be listed as follows (Arora, 1988): (a) high ventilation rate necessary for the pressurized aircraft cabin; (b) high flow rate of compressed air for cabin pressurization; (c) part of compression work can be attributed to cabin pressurization (also necessary if other refrigeration cycle is used); (d) one equipment for cooling/heating load (an independent heating equipment is necessary for another refrigeration cycle); (e) the cabin air-conditioning/pressurization integration.

At this context, the present work focuses on the numerical simulation of the air cycle machine changing some aircraft flight and human comfort parameters as Mach number, cabin altitude and cabin temperature. Results obtained from the numerical simulations allowed to understanding the influence of these parameters on the ACM performance and to provide an ECS optimized configuration design.

2. MATHEMATICAL FORMULATION

Cabin altitude and pressure changes are much smaller in magnitude on today's high altitude pressurized jets than they were during past flights. Although the percentage of oxygen in cabin air remains virtually unchanged (21 percent) at all normal flight altitudes compared to sea level, the partial pressure of oxygen decreases with increasing altitude. This is because with increasing altitude air is less densely packed, resulting in fewer molecules of oxygen available for each occupant breathing cycle (Hunt and Space, 1994). At a maximum cabin altitude of 8,000 feet, the partial pressure of oxygen is about 74 percent of the sea level value requiring an adequate pressurization system to maintain a suitable comfort level to the passengers and crew. A typical flight will cruise at 35,000 to 39,000 feet, resulting in a cabin altitude of 8,000 feet. Figure 1 shows a typical cabin altitude schedule.

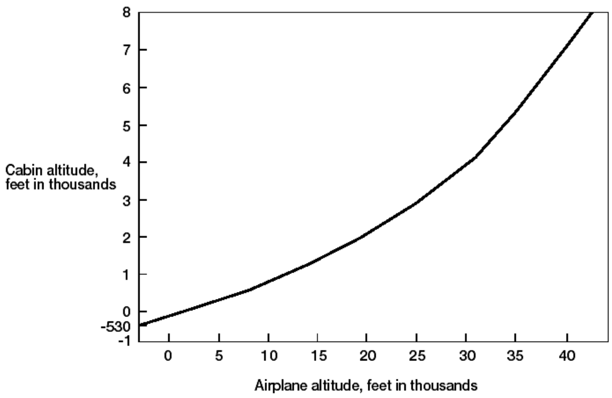


Figure 1 - A typical cabin altitude schedule.

An air-conditioning pack is an air cycle refrigeration system that uses the air passing through and into the airplane as the refrigerant. This is accomplished by a combined turbine and compressor machine, valves for temperature and flow control, and heat exchangers using outside air to dispense waste heat. The ACM must provide essentially dry, sterile, and dust free conditioned air to the airplane cabin at the proper temperature, flow rate, and pressure to satisfy pressurization and temperature control requirements (Hunt et al., 1995). There are three basic configurations of ACM where compressed air extracted from one or more stages of the propulsion turbine compressor is cooled (by one or more heat exchangers) and expanded through a turbine. The power supplied by the ACM turbine may be used to drive a fan (simple cycle, Fig. (2a)); a compressor (bootstrap cycle, Fig. (2b)); or both (simple/bootstrap cycle, Fig. (2c)).

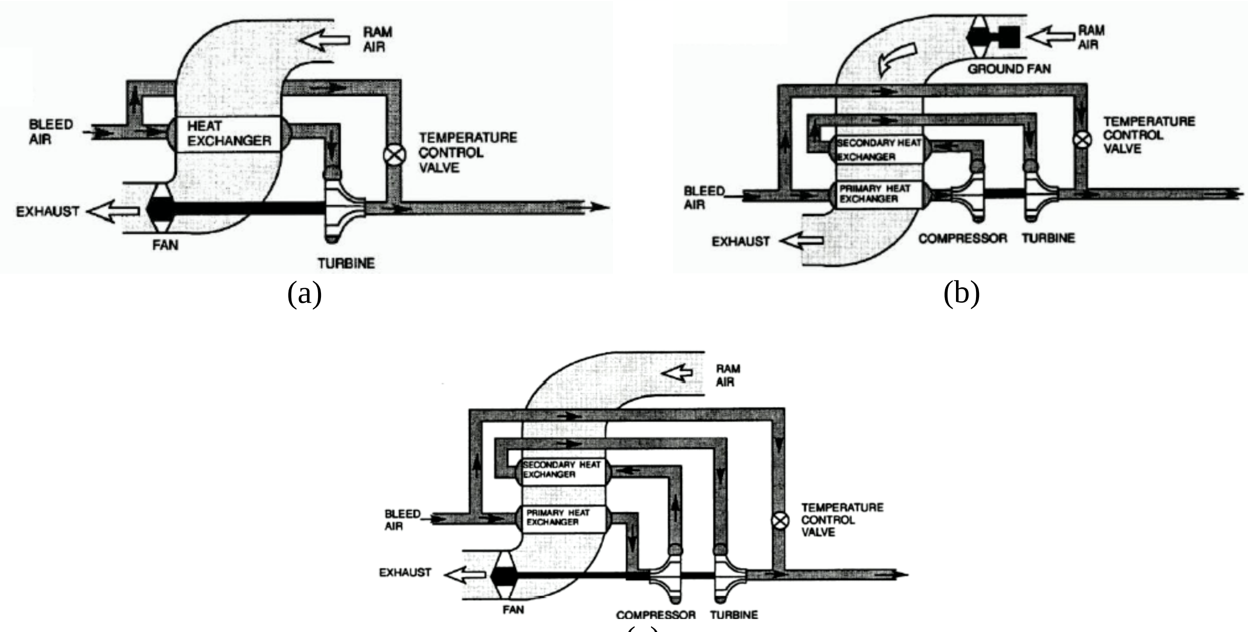
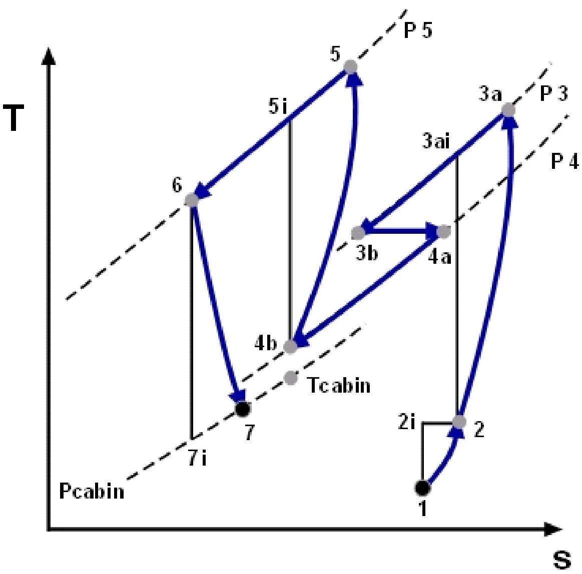


Figure 2 - Air cycle machines: (a) simple cycle; (b) bootstrap cycle; (c) simple/bootstrap cycle.

In the simple cycle, all the ACM turbine work is consumed by the heat exchanger exhaust fan while in the full boostrap cycle this work is used only to drive the ACM compressor. Mixed configurations (simple/bootstrap) can be simulated distributing part of the ACM turbine useful work between the ACM compressor and the exhaust fan. A typical open bootstrap air cycle machine process (1-7) is schematized by the temperature x entropy diagram in Fig. (3).



Where:

1	**ambient static conditions;**
2	**state after ram air compression;**
3a	**propulsion turbine compressor (primary compressor) exit;**
3b	**bleed pre-cooler (heat exchanger) exit;**
4a	**bleed pressure control valve exit;**
4b	**ACM primary heat exchanger exit;**
5	**ACM compressor (secondary compressor) exit;**
6	**ACM secondary heat exchanger exit;**
7	**ACM turbine exit;**
i	**isentropic process exit;**
cabin	**aircraft cabin conditions.**

Figure 3 – Open bootstrap gas cycle applied in an aircraft.

When the aircraft is flying, the initial compression of the ambient air is due to ram effect. The ram effect is shown by line 1-2. Point 1 represents the static temperature and pressure of external ambient air, while point 2i denotes the state after isentropic compression to pressure P_{2i} and temperature T_{2i} so that we have from the energy equation:

$$h_2 = h_1 + \frac{V_1^2}{2} \qquad \text{Eq. 1}$$

where:

h_1 = static air enthalpy.

V_1 = aircraft velocity.

Assuming air as a perfect gas with constant specific heat, from Eq. (1), the following result is obtained:

$$T_2 = T_{2i} = T_1 + \frac{V_1^2}{2Cp} \qquad \text{Eq. 2}$$

The above relation can be modified such that the Mach number appears:

$$\frac{T_2}{T_1} = 1 + \frac{(k-1)M^2}{2} \qquad \text{Eq. 3}$$

where:

k = Cp/Cv = specific heat relation: constant pressure to constant volume;

M = Mach number of the aircraft flight = V_1/a;

a = sound velocity.

The stagnation pressure after isentropic compression P_{2i}, is given by the relation:

$$\frac{P_{2i}}{P_1} = \left(\frac{T_{2i}}{T_1}\right)^{\frac{k}{k-1}} \qquad \text{Eq. 4}$$

The irreversible ram compression, however, results in air reaching point 2 instead of point 2i, that is, at the same stagnation temperature but at a reduced stagnation pressure P_2 which is obtained from the knowledge of the ram efficiency (η_r) defined by:

$$\eta_r = \frac{P_2 - P_1}{P_{2i} - P_1} = \frac{\text{actual pressure recovery}}{\text{ideal pressure recovery}} \qquad \text{Eq. 5}$$

The ram work (W_r) which is obtained directly from the engine (drag penalty) is evaluated by:

$$W_r = \dot{m}Cp\,(T_2 - T_1) \qquad \text{Eq. 6}$$

$\dot{m}$ = mass flow rate.

The rest of compression occurs at the propulsion turbine compressor, process 2-3a. For the ideal isentropic process 2-3i the temperature at the point 3i is calculated as:

$$\frac{T_{3ai}}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{k-1}{k}} \qquad \text{Eq. 7}$$

Where P_3 = compressor bleed port pressure.

The temperature at the point 3a (primary compressor bleed port) is determined with the value of the primary compressor isentropic efficiency (η_{pc}), defined by:

$$\eta_{pc} = \frac{T_{3ai} - T_2}{T_{3a} - T_2} = \frac{\text{ideal primary compressor work}}{\text{actual primary compressor work}} \qquad \text{Eq. 8}$$

The actual primary compressor work can be calculated by:

$$W_{pc} = \dot{m}Cp\,(T_{3a} - T_2) = \frac{\dot{m}CpT_2}{\eta_{pc}}\left[\left(\frac{P_3}{P_2}\right)^{\frac{k-1}{k}} - 1\right] \qquad \text{Eq. 9}$$

The aircraft bleed system controls the temperature and pressure of the compressed air. The state of compressed air supplied to the air cycle machine is represented by point 4a in T x s diagram shown in Fig. (3). The temperature drop in the pneumatic system pre-cooler (3a-3b) doesn't represent a performance penalty but the pressure reduction through the pneumatic pressure control valve (3b-4a) causes a lost in the cooling effect.

In the process 4a-4b the working fluid (air) is cooled by the ACM primary heat exchanger. Pressure P_{4a} is equal to P_{4b} if the fluid friction process is neglected. The amount of heat rejected in the ACM primary heat exchanger (Q_{phx}) is:

$$Q_{phx} = \dot{m}Cp\,(T_{4a} - T_{4b}) \qquad \text{Eq. 10}$$

Where T_{4b} is calculated taking account the primary heat exchanger effectiveness (ε_{phx}) given by:

$$\varepsilon_{phx} = \frac{T_{4a} - T_{4b}}{T_{4a} - T_2} \qquad \text{Eq. 11}$$

assuming that the heat sink (ram air) temperature of the primary heat exchanger is equal to T_2.

The temperature after the cooling process 4a-4b must be higher than the stagnation temperature T_2 of the ambient air. It implies that the working fluid cannot be cooled by heat exchange to a temperature bellow T_2.

Temperature at the point 5i, after the isentropic compression through the ACM secondary compressor, is calculated as:

$$\frac{T_{5i}}{T_{4b}} = \left(\frac{P_5}{P_{4b}}\right)^{\frac{k-1}{k}} \qquad \text{Eq. 12}$$

Given the value of the secondary compressor isentropic efficiency, the temperature at the point 5 can be determined as:

$$\eta_{sc} = \frac{T_{5i} - T_{4b}}{T_5 - T_{4b}} = \frac{\text{ideal secondary compressor work}}{\text{actual secondary compressor work}} \qquad \text{Eq. 13}$$

The actual secondary compressor work can be calculated by:

$$W_{sc} = \dot{m}Cp\,(T_5 - T_{4b}) = \frac{\dot{m}CpT_{4b}}{\eta_{sc}}\left[\left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}} - 1\right] \qquad \text{Eq. 14}$$

In the process 5-6 the working fluid (air) is cooled by the ACM secondary heat exchanger. If the fluid friction process is neglected, pressure P_5 is equal to P_6. The amount of heat rejected in the ACM secondary heat exchanger (Q_{shx}) is:

$$Q_{shx} = \dot{m}Cp\,(T_5 - T_6) \qquad \text{Eq. 15}$$

Where T_6 is calculated taking account the secondary heat exchanger effectiveness (ε_{shx}) given by:

$$\varepsilon_{shx} = \frac{T_5 - T_6}{T_5 - T_2} \qquad \text{Eq. 16}$$

assuming that the minimum attainable temperature for the working fluid is the ram air temperature.

The largest temperature drop occurs when the air expands in the turbine (expander) of the air cycle machine. In the isentropic process the state at the end of expansion process is represented by point 7i in T x s diagram, Fig. (3). For the actual conditions, the pressure $P_{7i} = P_7$ is slightly above the pressure of aircraft pressurized cabin (P_{cabin}) that is higher than the external ambient pressure. At the present work, it is assumed that $P_7 = P_{cabin}$, neglecting the pressure drop in the air distribution ducts.

Pressure P_5 (= P_6) is determined solving the implicit equation obtained from the ACM work balancing: the ACM turbine work is equal to the sum of the secondary compressor work and the exhaust fan work.

Temperature T_{7i} can be calculated by the isentropic relation:

$$\frac{T_{7i}}{T_6} = \left(\frac{P_7}{P_6}\right)^{\frac{k-1}{k}} \qquad \text{Eq. 17}$$

Due to expansion irreversibilities, temperature T_7 is greater than T_{7i} reducing the expander temperature drop. The temperature T_7 at the end of the actual expansion process can be calculated knowing the turbine isentropic efficiency (η_t):

$$\eta_t = \frac{T_6 - T_7}{T_6 - T_{7i}} = \frac{\text{actual turbine work}}{\text{isentropic turbine work}} \qquad \text{Eq. 18}$$

The ACM turbine useful work is calculated as:

$$W_t = \dot{m}Cp\,(T_6 - T_7) = \dot{m}CpT_6 \left[1 - \left(\frac{P_7}{P_5}\right)^{\frac{k-1}{k}}\right]\eta_t \qquad \text{Eq. 19}$$

The implicit equation resultant from the ACM work balance is given by:

$$W_{sc} = \alpha\,(W_t) \qquad \text{Eq. 20}$$

Where α indicates the percentage of the ACM turbine work absorbed by the secondary compressor. The available work to drive the heat exchanger exhaust fan is equal to (1 - α) W_t .

Inserting Eq. (14) and Eq. (19) in the Eq. (20), the implicit equation that provides the P_5 value is obtained:

$$\frac{\dot{m}CpT_{4b}}{\eta_{sc}}\left[\left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}} - 1\right] - \alpha\left\{\dot{m}CpT_6\left[1 - \left(\frac{P_7}{P_5}\right)^{\frac{k-1}{k}}\right]\eta_t\right\} = 0 \qquad \text{Eq. 21}$$

When $\alpha = 0$, the exhaust fan uses all the ACM turbine work (simple cycle) and for $\alpha = 1$, the secondary compressor absorbs the whole turbine work (bootstrap cycle).

The air circulated through the air cycle machine is insufflated in the aircraft cabin with temperature T_7, that should be lower than the inside air temperature T_{cabin}. The cooling effect of the air cycle machine (Q_c) is calculated by:

$$Q_c = \dot{m}Cp\,(T_{cabin} - T_7) \qquad \text{Eq. 22}$$

A portion of the primary compressor work must be attributed to the cabin pressurization system This work is used to increase the external air pressure to an adequate value that satisfies the human breathing requirements attaining a desirable occupants comfort level (usually a pressure value in the 8,000 feet level in the standard atmosphere, Fig. (1)). The pressurization work (W_p) can be calculated by:

$$W_p = \frac{\dot{m}CpT_2}{\eta_{pc}}\left[\left(\frac{P_7}{P_2}\right)^{\frac{k-1}{k}} - 1\right] + W_r \qquad \text{Eq. 23}$$

The coefficient of performance (COP_p) for the simple/bootstrap cycle, including the pressurization work, can be evaluated as:

$$COP_p = \frac{Q_c}{W_r + W_{pc}} \qquad \text{Eq. 24}$$

Excluding the pressurization work, Eq. (23), the coefficient of performance (COP) for the simple/bootstrap cycle is calculated by:

$$COP = \frac{Q_c}{W_r + W_{pc} - W_p} \qquad \text{Eq. 25}$$

The equation set, Eq. (1) to Eq. (25), modeling the simple/bootstrap cycle represented in Fig. (3) and it was implemented in a mathematical software with a visual development environment (Mathcad, 1999). The obtained results will be discussed in the next item of this study.

3. RESULTS AND DISCUSSION

At the present work the influence on the COP air cycle of the Mach number, exhaust fan power, cabin pressure and cabin temperature was analyzed. Numerical values used in each simulation are presented in Tab. (1).

Table 1 – Numerical simulations which the COP was calculated.

	A test	B test	C test	D test
Mach number	Range: 0.47 to 1.18	Constant (= 0.47)	Constant (= 0.47)	Constant (= 0.47)
Exhaust fan power	Constant (α = 1)	$0 \leq \alpha \leq 1$	Constant (α = 1)	Constant (α = 1)
Cabin pressure	Constant (= 8,000 feet)	Constant (= 8,000 feet)	Range: 6,000 to 12,000 feet	Constant (= 8,000 feet)
Cabin temperature	Constant (= 24°C)	Constant (= 24°C)	Constant (= 24°C)	Range: 18 to 30°C

The ambient static conditions, (point 1 in Fig. (3)), were maintained constant as shown in Tab. (2). Also, the ACM turbine and compressors efficiencies, the ram air compression efficiency, the bleed port (point 3a, in Fig. (3)) pressure and temperature values and the heat exchangers effectiveness were simulated with constant values, Tab. (2).

Table 2 – Numerical values maintained as constant parameters in the simulations.

T_1 = -57°C	P_1 = 20 kPa	P_3 = 250 kPa	P_4 = 200 kPa	$T_{3b} = T_{4a}$ = 200°C
$\eta_t = 0.77$	$\eta_r = 0.84$	$\eta_{pc} = \eta_{sc} = 0.82$	$\varepsilon_{phx} = \varepsilon_{shx} = 0.80$	

Figure (4) shows the "A test" results, Tab. (1), for the Mach number effect on the ACM performance. The increase in the Mach number reduces both coefficients of performance above defined COP_p (Eq. (24)) and COP (Eq. (25)). When the flight velocity elevates the stagnation temperature T_2 increases, that is, the minimum heat sink fluid temperature. This fact reduces the amount of rejected heat in the ACM heat exchangers.

The influence of the percentage of the ACM turbine power absorbed by the exhaust fan on the coefficients of performance is presented in Fig. (5), corresponding to the "B test" in Tab. (1). As the exhaust fan power consumption increases, the power available to the secondary compressor decreases lowering the temperature and pressure at the point 5, Fig. (3). Consequently, the rejected heat in the secondary heat exchanger is diminished and the pressure difference available to the turbine expansion is lower. This implies in a reduction of the both coefficients of performance as can be seen in Fig. (5).

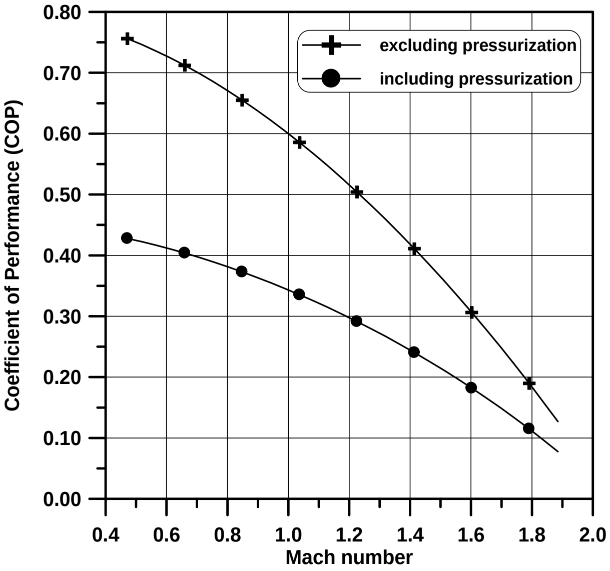


Figure 4 – Coefficient of Performance as a function of the aircraft Mach number.

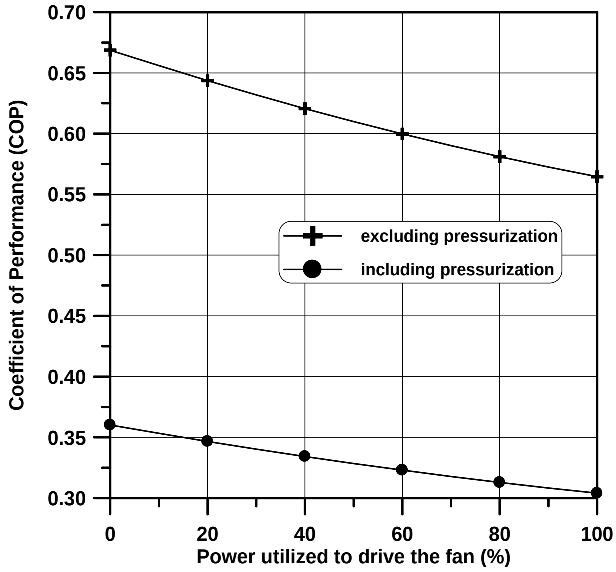


Figure 5 – Coefficient of Performance as a function of the power required to drive the fan.

Figure (6) illustrates the "C test" results, Tab. (1), for the cabin pressure effect on the ACM performance. Higher values of cabin altitude (lower cabin pressure) increase the ACM turbine power. When this power is used by the secondary compressor, an elevation in the temperature and pressure of the state 5 occurs, Fig. (3). This implies in an increase in the amount of rejected heat in the secondary heat exchanger causing a temperature T_7 reduction. So, the cooling effect increases the Eq. (24) numerator, also affecting the COP_p value.

On the other hand, the coefficient of performance excluding the pressurization work presents a decrease because the Eq. (25) denominator increases with the cabin altitude elevation (W_{pc} = constant and W_p decreases when the cabin altitude increases, as shown in Fig. (7)). Then, this effect exceeds the numerator increase previously above discussed.

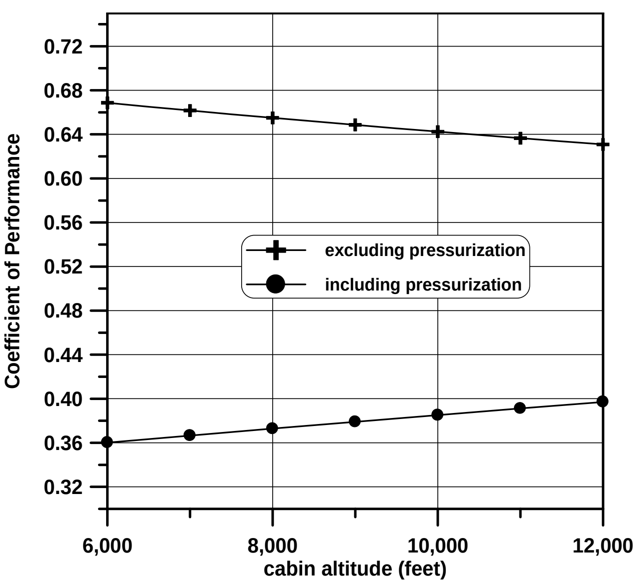


Figure 6 – Coefficient of Performance as a function of the aircraft cabin altitude.

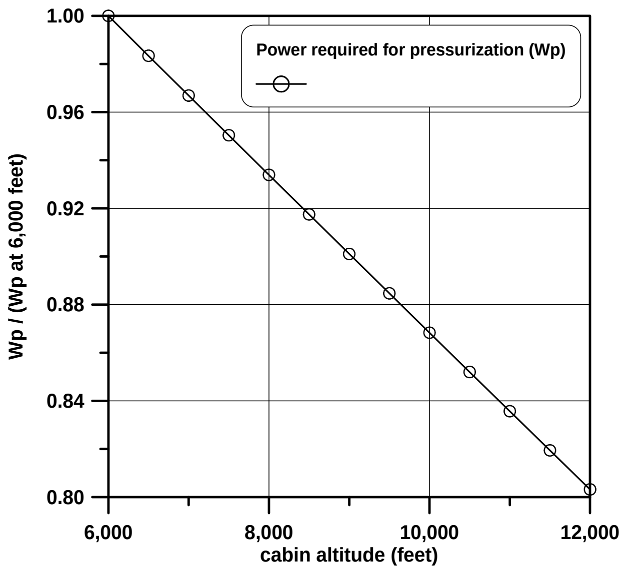


Figure 7 – Power required for the aircraft pressurization as a function of the aircraft cabin altitude.

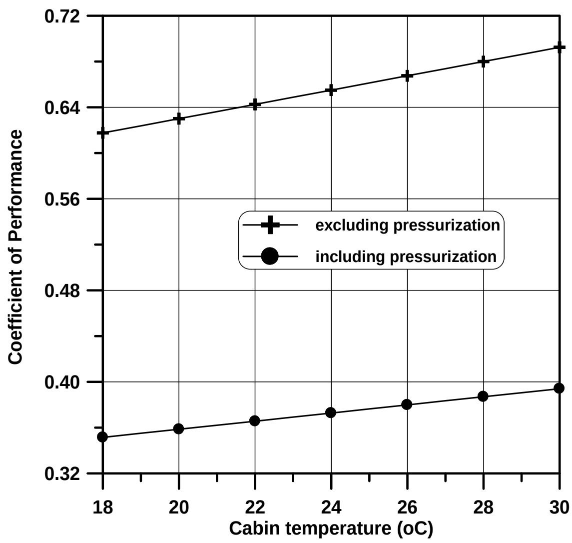


Figure 8 – Coefficient of Performance as a function of the aircraft cabin temperature.

The cabin temperature influence on the ACM performance is shown in Fig. (8). When others cycle parameters don't change ("D test" in Tab (1)), the increase in the T_{cabin} value causes an elevation in the cooling effect (Eq. (22)) and, consequently elevates both coefficients of performance. Future studies could also investigate the effect of the ambient static conditions (pressure and temperature) in the air-cycle machine performance.

Results obtained in this work shows that the computational tool that solves the ACM mathematical model (thermodynamic cycle analysis) allows an understanding of the ACM performance when flight aircraft and cabin human comfort parameters are changed to attain a optimized ECS configuration design.

4. REFERENCES

Arora, C. P., 1988, "Refrigeration and Air Conditioning", Tata McGraw-Hill Publishing Company Limited, New Delhi, India, 726 p.

ASHRAE Handbook, 1997, "Fundamentals Volume", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Hunt, E.H. and Space, D.R., 1994, The Airplane Cabin Environment, "International In-flight Service Management Organization Conference", Montreal, Canada.

Hunt, E.H., Reid, D.H., Space, D.R. and Tilton, F.E., 1995, Commercial Airliner Environmental Control System, "Aerospace Medical Association Annual Meeting", Anaheim, California.

Mathcad, 1999, "Reference Manual", MathSoft Inc, Cambridge, MA, USA.