NUMERICAL ANALYSYS OF TIPICAL AIRCRAFT AIR-CONDITIONING AIR CYCLE MACHINES

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Abstract. *The aircraft air-conditioning system is designed to provide a comfortable cabin temperature, acceptable ventilation, good airflow distribution across the cabin width, and sufficient airflow to maintain cabin pressurization requirements. The outside air supplied to the cabin aircraft is provided by the engine compressors, cooled by air conditioning packs located under the wing center section, and mixed with an equal quantity of filtered recirculated air. Approximately 20 liters/seconds of air per passenger is provided, of which half is filtered recirculated air and half is outside air. This results in a complete cabin air exchange every two to three minutes (20 to 30 air changes per hour). The high air exchange rate is necessary to control temperature gradients, prevent stagnant cold areas, maintain air quality and dissipate smoke and odors in the cabin environment. This mentioned task in commercial transport aircrafts is performed by an air cycle machine (ACM) that 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 herein studied as the influence of the turbine and compressors efficiencies and heat exchangers effectiveness. Results show that the implemented computational tool that solves the ACM mathematical model allows an understanding of its performance when flight aircraft and ACM components parameters are changed to attain an optimized configuration design.*

Keywords*: aircraft air-conditioning system; conditioning air cycle machines; efficiencies; effectiveness*

1. INTRODUCTION

The Federal Aviation Administration (FAA) regulates the design of transport category aircraft for operation in the United States under Federal Aviation Regulation (FAR) Part 25. ECS (Environmental Control System) equipment and systems must meet these requirements, which are primarily related to health and safety of the occupants. The ECS is designed to provide a comfortable cabin temperature, acceptable ventilation, good airflow distribution across the cabin width, and sufficient bleed airflow to maintain cabin pressurization. The term ECS often encompasses other functions such as windshield defog, airfoil anti-ice, oxygen systems, and other pneumatic demands, (ASHRAE, 1997).

We have become accustomed to thinking of air conditioning as the cooling of air, but actually it means much more than just this. A complete air-conditioning system for an aircraft should control both the temperature and humidity of the air, heating or cooling it as is necessary. It should provide adequate movement of the air for ventilation, and there should be provision for the removal of cabin odors, (Garrett, 1991).

In a typical commercial transport aircraft, the compressed air required by the air conditioning and pressurization systems is originally provided by the outside air, as shown in Fig. 1. This airflow is primarily compressed in the engine compressors (point 1) cooled by the two air conditioning packs (point 1) located under the wing center section, and mixed with an equal quantity of filtered recirculated air (point 2). Approximately 0.01 m^3/s (10 l/s) of air per passenger is provided, of which half is filtered recirculated air and half is outside air. This results in a complete cabin air exchange every two to three minutes (20 to 30 air changes per hour).

The high air exchange rate is necessary to control temperature gradients, prevent stagnant cold areas, maintain air quality and dissipate smoke and odors in the cabin. High outside airflow rates are also necessary to maintain overall cabin temperature control and cabin pressurization. Due to the large quantity of air entering the relatively small volume of the cabin, as compared to a building, precise control of the airflow patterns is required to give comfort without draftiness (point 3).

The ECS also includes a Cabin Pressure Control System (CPCS) that continuously monitors ground and flight modes, altitude, climb, cruise or descent modes, as well as the aircraft's holding patterns at various altitudes. It uses this information to position the cabin pressure outflow valve (point 4, in Fig. 1) to maintain cabin internal pressure as close to sea level as practical, without exceeding a pre-established cabin-to-outside pressure differential (determined by fuselage structural resistance characteristics). At a 12,000 m (37,000 ft) typical cruise altitude, the external ambient pressure is 20 kPa (nearly 1/5 of its sea level value, as shown in Fig. 2). However due to human physiological requirements, the cabin pressure must be maintained as lower as possible to satisfy the respiratory process (minimum oxygen partial pressure). Usually, the internal cabin pressure is equivalent to 11,278 m (8,000 ft) or a pressure of 79 kPa as depicted in Fig. 3. Some executive transport aircrafts can maintain a more reduced cruise internal pressure around 1,829 m (6,000 ft) that implies in a more comfortable cabin pressure.

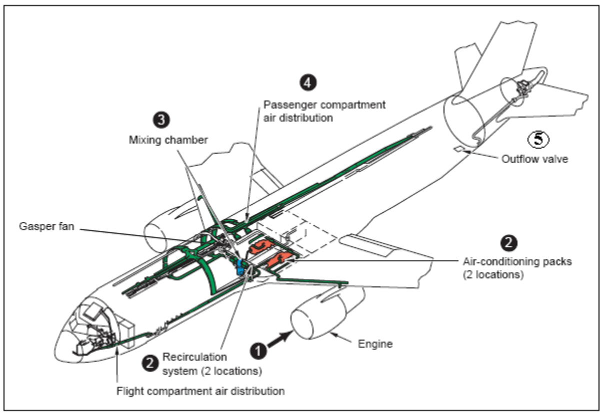


Figure 1 – Typical aircraft ECS system (Hunt and Space, 1994).

During a typical flight mission, the outflow valve repositions itself to allow more or less air to escape as the aircraft changes altitude. The resulting cabin altitude is consistent with aircraft altitude within the constraints of keeping pressure changes comfortable for crew and passengers. Normal pressure limit change rates are 1.8 kPa per minute ascending and 1.1 kPa per minute descending.

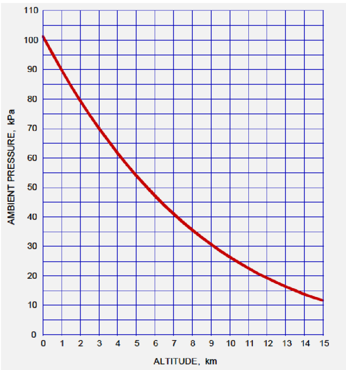


Figure 2 – Variation of external ambient pressure with altitude at ISA conditions (ASHRAE, 1997).

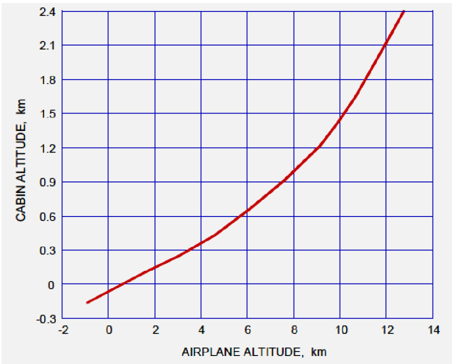


Figure 3 – Typical cabin altitude schedule (ASHRAE, 1997).

Besides satisfying the pressurization needs, the air-conditioning pack must also provides essentially dry, sterile, and dust free conditioned air to the aircraft cabin at the proper temperature, flow rate, and pressure to satisfy pressurization and temperature control requirements. Air-cycle refrigeration is the predominant means of air conditioning for commercial and military aircraft. The use of air cycle is one of these, offering a benign substitute for CFC refrigerants (usually employed in vapor-cycle refrigeration) as well as reduced energy consumption and capital costs for targeted applications.

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, 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, Arora (1988).

Some additional advantages of an air cycle with regard to its application in aircraft refrigeration can be listed:

i. high ventilation rate necessary for the pressurized aircraft cabin.
ii. high flow rate of compressed air for cabin pressurization.
iii. part of compression work can be attributed to cabin pressurization
iv. one equipment for cooling/heating load (an independent heating equipment is necessary for another refrigeration cycle).
v. the cabin air-conditioning/pressurization integration.

The thermodynamic study of air-cycle machines (ACM) is an important tool to determine its coefficient of performance (COP) depending on aircraft operational parameters and/or ACM components (compressor, expansor, heat exchanger) efficiencies. Andrade and Zaparoli (2004) performed a numerical study and analyzed the ACM performance as a function of the aircraft Mach number, cabin altitude, cabin temperature and the percentage of the turbine work absorbed by the exhaust fan. Authors confirmed that the bootstrap cycle provides an increase in the ACM overall performance in comparison with simple and combined (simple/bootstrap) architectures.

Conceição et al. (2006) studied the three and four-wheel air-cycle machines configurations using a computational approach. Results showed that the turbine expansion second-stage provides an increase in the thermodynamic cycle efficiency. Cruise and ground conditions were simulated showing that the numerical tool could be useful in the preliminary design of ACM configurations.

At the present work, a numerical simulation of the ACM thermodynamic performance is carried out to evaluate the influence of its components efficiency and effectiveness in the machine COP during the cruise mode. A typical flight mission (climb, cruise and descent modes) is also simulated showing the COP variation as a function of the cabin and external pressures (or equivalent altitudes) changes.

2. AIR-CYCLE MACHINE CONFIGURATIONS

An air-cycle machine (ACM) consist of two main units, the expansion turbine, and the air-to-air heat exchanged. The ACM essentially does the opposite of a turbocompressor; the turbocompressor causes the air to compress and heat; the ACM causes air to expand and cool, (Lombardo, 1993).

Air cycle refrigeration works on the reverse Brayton or Joule cycle. The conventional air cycle ACM for aeronautical applications operates in an open-loop Brayton refrigeration cycle similar to the Brayton power cycle of gas turbine engines; the difference between the two cycles is that for the power cycle heat is added by burning fuel while for the refrigeration cycle heat is removed in a ram air heat exchanger.

In an air cycle machine, compression of the ambient air by the gas turbine engine compressor provides the power input. The heat of compression is removed by two heat exchangers (items 3 and 4 in Figure 4) using ambient ram air as the heat sink, as indicated in Figure 4 (item 8). This cooled air is refrigerated by expansion across a turbine powered by the compressed bleed air. The turbine energy resulting from the isentropic expansion is absorbed by a second rotor, which is either a ram air fan, bleed air compressor, or both.

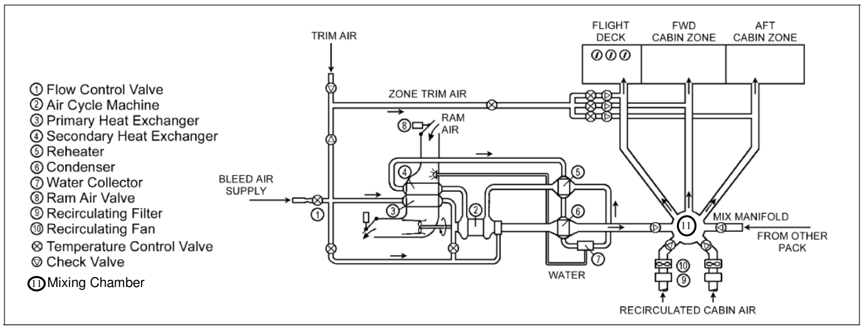
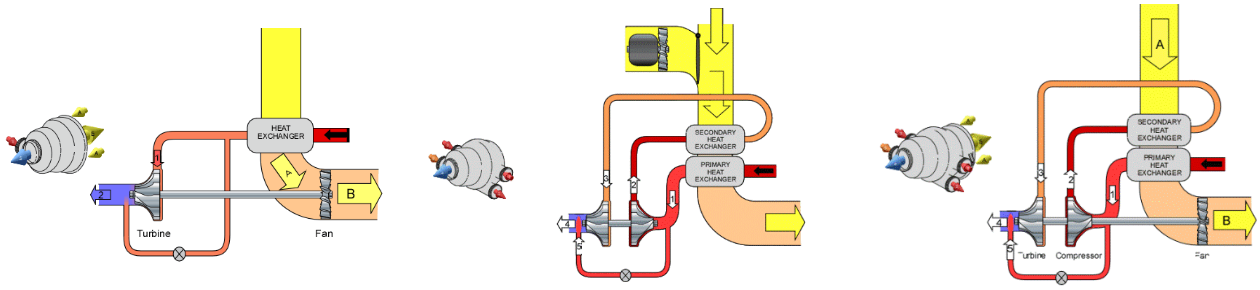


Figure 4 - Typical Aircraft Air-Conditioning Schematic (ASHRAE, 1997).

Most aircraft use two or three air-cycle packs (as depicted by point 2 in Fig. 1) operating in parallel to compensate for failures during flight and to allow the aircraft to be dispatched with certain failures. In the mixing chamber (point 3 in Figure 1 or item 11 in Figure 4), the recirculated cabin air is mixed with equal quantity of cold air (discharged by the ACM turbine) supplied by the right and left air conditioning packs.

When the turbine work is absorbed entirely by a fan the ACM is named simple cycle (Fig. 4a). In the bootstrap cycle (Fig. 4b), all the turbine work is utilized to drive a compressor while in the three-wheel configuration the drive extracted from the turbine is divided between the fan and the compressor, as shown in Fig. 4c.

The two-wheel or bootstrap cycle (Figure 5b), provides a significant increase in cycle efficiency over the simple cycle (Figure 5a) at the expense of additional system complexity. It does this by providing an additional stage of compression of the bleed air supply by replacing the ACM fan with a compressor rotor. This increases the inlet pressure at the cooling turbine resulting in increased turbine power. However, this necessitates an additional heat exchanger (intercooler) to remove the added heat of compression.



(a) The simple cycle consists of a turbine and fan on a common shaft.

(b) The two wheel Bootstrap consists of a turbine and compressor on a common shaft.

(c) The three wheel bootstrap consists of a turbine, compressor and fan on a common shaft

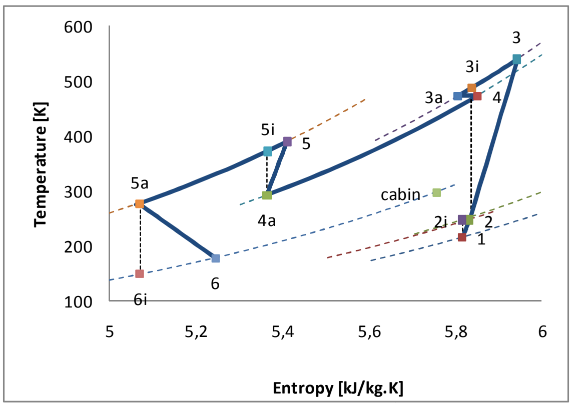
Figure 5 – Air cycle machine configurations: (a) Simple; (b) Bootstrap and (c) Combined (Simple/Bootstrap).

The three-wheel or combined cycle (Figure 5c), utilizes the simple with the bootstrap cycle architectures by incorporating both the simple cycle fan and the bootstrap compressor on the same shaft as the cooling turbine. Combined cycle efficiency presents an intermediary value between the simple and bootstrap COPs. Most of the turbine power (~85%) is absorbed by the compressor; while the heat exchanger cooling airflow requirement is satisfied by the fan, using the remaining turbine power.

The efficiency of such systems is limited to a great extent by the efficiencies of compression and expansion, as well as the heat exchanger effectiveness. Originally, slow speed reciprocating compressors and expanders were used. The poor efficiency and reliability of such machinery were major factors in the replacement of such systems with vapour compression equipment. However, the development of rotary compressors and expanders (such as in car turbochargers) greatly improved the isentropic efficiency and reliability of the air cycle. Advances in turbine technology, together with the development of air bearings and ceramic components offer further efficiency improvements. Combining these advances with newly available, compact heat exchangers, which have greatly improved heat transfer characteristics, makes competition with many existing vapor compression quite feasible.

3. THERMODYNAMIC ANALYSIS OF THE AIR-CYCLE MACHINE

The thermodynamic processes included in a typical ACM for aeronautical applications are shown in Figure 6. The pressure at the turbine discharge is fixed by desired cabin pressure the pre-established value.



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

Figure 6 – Diagram temperature-entropy for an 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 i denotes the state after isentropic compression to pressure Pi and temperature Ti 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:

$$T_2 = T_i = T_1 + \frac{V_1^2}{2C_p} \qquad \text{Eq. 2}$$

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 = C_p/C_v = 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 Pi, is given by the relation:

$$\frac{P_i}{P_1} = \left(\frac{T_i}{T_1}\right)^{\frac{k}{k-1}} \qquad \text{Eq. 4}$$

The irreversible ram compression, however, results in air reaching point 2 instead of point i, 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:

$$\eta_r = \frac{P_2 - P_1}{P_i - P_1} = \frac{real\ pressure\ recovery}{ideal\ pressure\ recovery} \qquad \text{Eq. 5}$$

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

$$W_r = \dot{m} C_p (T_2 - T_1)\ ,\ \dot{m} = \text{mass flow rate} \qquad \text{Eq. 6}$$

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

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

Where P_3 = compressor bleed port pressure.

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

$$\eta_{pc} = \frac{T_{3i} - T_2}{T_3 - T_2} = \frac{ideal\ pressure\ recovery}{actual\ pressure\ recovery} \qquad \text{Eq. 8}$$

The actual primary compressor work can be calculated by:

$$W_{pc} = \dot{m} C_p (T_3 - T_2) = \frac{\dot{m} C_p T_2}{\eta_{pc}} \left[\left(\frac{P_3}{P_2}\right)^{\frac{k-1}{k}} - 1 \right] \qquad \text{Eq. 9}$$

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 4 in T x s diagram shown in Fig. 3. The temperature drop in the pneumatic system pre-cooler (3-3a) doesn’t represent a performance penalty but the pressure reduction through the pneumatic pressure control valve (3a-4) causes a lost in the cooling effect.

In the process 4-4a the working fluid (air) is cooled by the ACM primary heat exchanger. Pressure P_4 is equal to P_{4a} if the fluid friction process is neglected. The amount of heat rejected in the ACM primary heat exchanger (Q_{phx}) is:

$$Q_{phx} = \dot{m}C_p(T_4 - T_{4a})$$ Eq. 10

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

$$\varepsilon_{phx} = \frac{T_4 - T_{4a}}{T_4 - T_2}$$ 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:

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

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

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

The actual secondary compressor work can be calculated by:

$$W_{sc} = \dot{m}C_p(T_5 - T_{4a}) = \frac{\dot{m}C_p T_{4a}}{\eta_{sc}}\left[\left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}} - 1\right]$$ 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_{5a}. The amount of heat rejected in the ACM secondary heat exchanger (Q_{shx}) is:

$$Q_{shx} = \dot{m}C_p(T_5 - T_{5a})$$ Eq. 15

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

$$\varepsilon_{shx} = \frac{T_5 - T_{5a}}{T_5 - T_2}$$ 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 6i in the temperature-entropy diagram, Fig. 6. For actual conditions, the pressure $P_{6i} = P_6$ 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 $P_6 = P_{cabin}$, neglecting the pressure drop in the air distribution ducts.

Pressure P_5 (= P_{5a}) 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_{6i} can be calculated by the isentropic relation:

$$\frac{T_{6i}}{T_{5a}} = \left(\frac{P_6}{P_{5a}}\right)^{\frac{k-1}{k}}$$ Eq. 17

Due to expansion irreversibility, temperature T_6 is greater than T_{6i} reducing the expander temperature drop. The temperature T_6 at the end of the actual expansion process can be calculated knowing the turbine isentropic efficiency (η_t):

$$\eta_t = \frac{T_{5a} - T_6}{T_{5a} - T_{6i}} = \frac{real\ turbine\ work}{isentropic\ turbine\ work}$$ Eq. 18

The ACM turbine useful work is calculated as:

$$W_t = \dot{m}C_p(T_{5a} - T_6) = \dot{m}C_p T_{5a}\left[1 - \left(\frac{P_6}{P_5}\right)^{\frac{k-1}{k}}\right]\eta_t$$ Eq. 19

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

$$W_{sc} = \alpha . W_t$$ 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) Wt.

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

$$\frac{\dot{m}C_p T_{4a}}{\eta_{sc}}\left[\left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}}\right] - \alpha\left\{\dot{m}C_p T_{5a}\left[\left(1 - \left(\frac{P_6}{P_5}\right)^{\frac{k-1}{k}}\right)\right]\eta_t\right\} = 0$$ Eq. 21

When α = 0, the exhaust fan uses all the ACM turbine work (simple cycle) and for α = 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:

$$Q_c = \dot{m}C_p(T_{cabin} - T_6)$$ 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 occupant's 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:

$$W_p = \frac{\dot{m}C_p T_2}{\eta_{pc}}\left[\left(\frac{P_6}{P_2}\right)^{\frac{k-1}{k}} - 1\right] + W_r$$ Eq. 23

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

$$COPP = \frac{Q_c}{\left(W_r + W_{pc} + W_{sc}\right) - W_t}$$ Eq. 24

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

$$COP = \frac{Q_c}{\left(W_r + W_{pc} + W_{sc}\right) - \left(W_t + W_p\right)}$$ Eq. 25

The equation set, Eq. (1) to Eq. (25), modeling the simple/bootstrap cycle represented in Fig. 6, and it was implemented in a mathematical software with a visual development environment (EES, 2002).

At the bootstrap cycle, all the turbine work is absorbed by the secondary compressor. So, the COP and COPP expressions can be reduced to:

$$COPP = \frac{Q_c}{W_r + W_{pc}}$$ and $$COP = \frac{Q_c}{W_r + W_{pc} - W_p}$$ Eq. 26

4. RESULTS

4.1 Effect of the ACM components efficiency and/or effectiveness on its COP

To validate the computational tool developed in the present work, results are compared with Conceição (2006) study. Using the same input data (Tab. 2), the COP values are identical and equal to 0.68. After, an analysis of the efficiency (expansor, secondary compressor) and effectiveness (primary and secondary heat exchangers) on the ACM performance (COP) is carried out. Results are presented for bootstrap air-cycle (α =1, Eq. 21). In each studied case, the ACM parameters vary in the 70-100% range as shown in Tab. 1. Some parameters as the ambient external and cabin conditions are maintained constant (see Tab.2). The state of compressed air supplied to the air cycle machine is (point 4 in Fig. 6) is also pre-established and doesn't vary.

Table 1 – Studied cases with changed parameters

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
η_r	0.7-1.0	0.84	0.84	0.84	0.84
η_{sc}	0.82	0.7-1.0	0.82	0.82	0.82
η_t	0.77	0.77	0.7-1.0	0.77	0.77
ε_{phx}	0.8	0.8	0.8	0.7-1.0	0.8
ε_{shx}	0.8	0.8	0.8	0.8	0.7-1.0

Table 2 – Fixed parameters

T_1 = -57°C	P_1 = 20kPa	P3 = 250 kPa
P4 = 200 kPa	T3a = T4 200°C	Ma = 0.8465
P_{cabin}=81,199Pa	T_{cabin}=24°C	η_{pc} = 0.82

Figure 7 to Fig. 11 presents the bootstrap air-cycle machine performance evaluation as a function of its components efficiency and/or effectiveness. Both COP (Eq.25) and COPP (Eq.24) curves are plotted. Note that in all cases, the COP and COPP curves present the same behavior (as a shift procedure) but the COP values are higher because the cabin pressurization work was excluded in the calculation.

The turbine and secondary compressor effects are depicted in Fig. 7 and Fig. 8. Both COP and COPP values increases when the components efficiency elevates. It is verified that for turbine, a 30% variation in the efficiency values has an effect of around 30% on the COP. This influence is less pronounced by the secondary compressor efficiency variation leading to an 8.5 % in the COP variation as illustrated in Tab. 3.

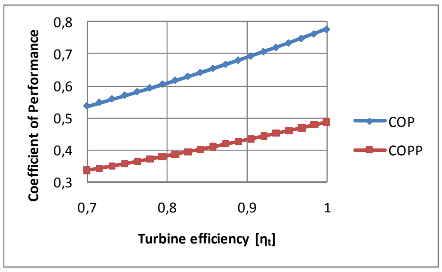


Figure 7. Coefficient of Performance as a function of the Turbine Efficiency

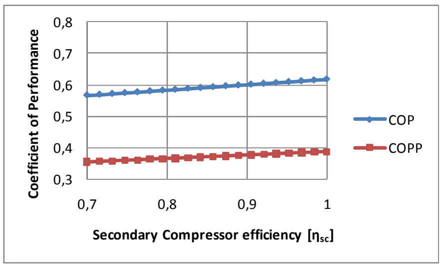


Figure 8. Coefficient of Performance as a function of the Secondary Compressor Efficiency

On the other hand, Fig. 9 shows that the ram efficiency variation has little effect on the air-cycle machine performance, reaching 0.75 independently of the η_r analyzed range. Note in Tab. 3 that when a 30% variation occurs, the COP and COPP vary only 3% and 6%, respectively.

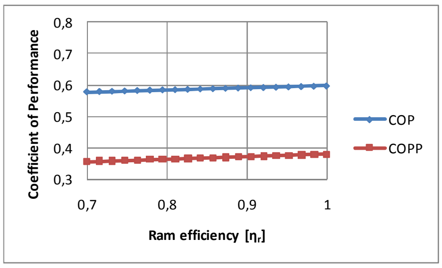


Figure 9. Coefficient of Performance as a function of the Ram Efficiency

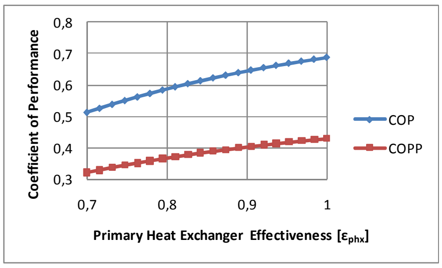


Figure 10. Coefficient of Performance as a function of the Primary Heat Exchanger Effectiveness

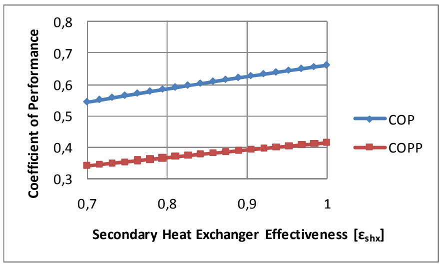


Figure 11. Coefficient of Performance as a function of the Secondary Heat Exchanger Effectiveness

Table 3 – ACM performance as a function of the its components variation

η_t	COP	COPP
0.7-1.0	0.5371-0.7782	0.3364-0.4874
30%	*30.98%*	*30,98%*
η_{pc}	**COP**	**COPP**
0.7-1.0	0.5011-0.7159	0.3183-0.4391
30%	*30.0%*	*27.51%*
η_{sc}	**COP**	**COPP**
0.7-1.0	0.566-0.6184	0.3575-0.3874
30%	*8.47*	*8.49*
η_r	**COP**	**COPP**
0.7-1.0	0.5775-0,5974	0.3568-0.3799
30%	*3,33%*	*6.08%*
ε_{phx}	**COP**	**COPP**
0.7-1.0	0.513-0.6868	0.3213-0.4302
30%	25,31%	25,31%
ε_{shx}	**COP**	**COPP**
0.7-1.0	0.5442-0.6628	0.335-0.4256
30%	*17.89%*	*17.89%*

Figure 10 and Fig. 11 present the ACM performance as a function of the primary and secondary heat exchangers, respectively. The COP varies 25% (both COP and COPP in Tab. 3) when the the primary heat exchanger effectiveness varies 30%. For the secondary heat exchanger, the COP and COPP values reach 0.66 and 0.43, respectively when $\varepsilon_{sc} = 1$ but its impact is of almost 18% as shown in Tab. 3. The three air-cycle machine components that impacts more significantly in its performance are in order of relevance: turbine/ compressor efficiencies and primary heat exchanger effectiveness.

4.2. Results for the COP variation in a scheduled typical flight mission

In the previous section, the influence of the bootstrap air-cycle machine components was separately studied. At the present section, the COP evaluation is analyzed for a complete flight mission (with climb, cruise and descent modes totalizing 4000 seconds as indicated in Fig. 12). Note that the cabin and external pressures profiles vary along the flight duration but while the aircraft cruise pressure is equivalent to the pressure in the 11,200 m altitude, the internal cabin cruise is close to the 1,800 m altitude. This pressure differential is typical of a commercial transport aircraft and is determined by combining the fuselage structural restrictions and cabin comfort requirements. Simulations were carried out using the fixed parameters listed in Tab. 2 and the following values for the remaining components: η_t = 0.77; η_{pc} = 0.82; η_{sc} =0.82; η_r = 0.84; ε_{phx} = 0.8 and ε_{shx} = 0.8.

During the flight mission, the external temperature follows the ISA atmosphere profile as shown in Fig. 13.

Figure 14 shows W_p, W_{pc}, W_r and Q_c distribution along the flight mission duration. Note that the ram work has less magnitude in comparison with the others parameters and little variation during the time-evolution. The cooling effect of the air cycle machine (Q_c) is also almost constant during the aircraft flight. The cabin pressurization work (W_p) curve follows the altitude profile (Fig. 12), reaching maximum values during the cruise mode. The primary compressor work (W_{pc}) curve present a opposite behavior in relation to the altitude profile, decreasing during the climb mode, constant at the cruise altitude and increasing when the aircraft descends. Even at the cruise mode (when the W_{pc} value is minimum), its magnitude is higher in comparison with the other computed works. This fact has a great impact in the COP and COPP distributions (see Eq. 26) since a combined effect occurs determined by three variables: the cooling effect curve behavior is practically constant, the ram work has a low magnitude and the W_{pc} curve becomes predominant in the COP and COPP time-evolution shown in Fig. 12.

Note that, as the aircraft altitude increases (and the external pressure decays during the climb mode), both COP and COPP values increases affected mainly by the W_{pc} magnitude decay. The opposite effect occurs during the descent mode. Furthermore, COP and COPP maximum levels correspond to the primary compressor work minimum level during the cruise mode.

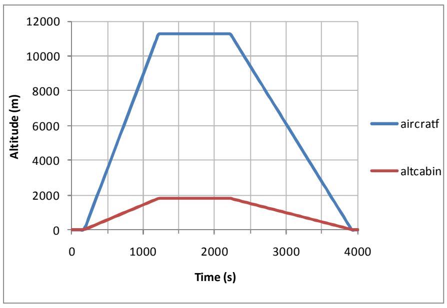


Figure 12. Typical flight mission.

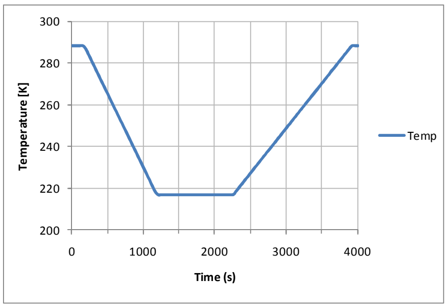


Figure 13. Ambient external temperature as a function of the altitude.

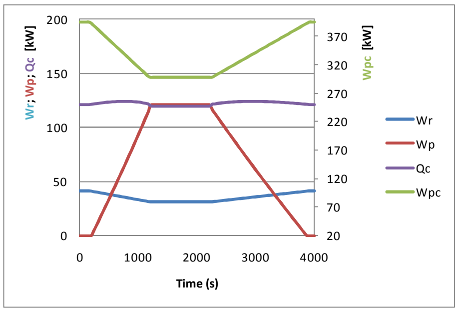


Figure 14. Wp, Wpc, Wr and Qc variation during the flight mission.

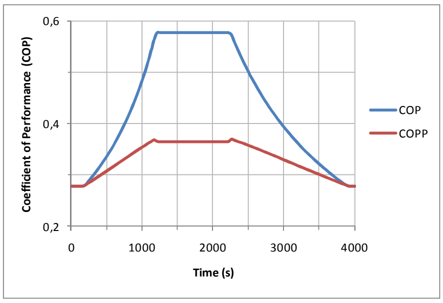


Figure 15 . COP and COPP variation during the flight mission.

5. FINAL DISCUSSION

At the present work, a thermodynamic analysis of the bootstrap air-cycle machine is performed to verify the ACM components efficiency and/or effectiveness on its COP. Results showed that a 30% variation on these parameters can represent an little effect of 3% on COP value when the ram efficiency is studied and almost 31% as occurred for the turbine efficiency. The turbine, primary compressor and primary heat exchanger are the components that present major impact on the ACM performance. It was verified, that the primary compressor work is the predominant variable in the ACM performance during a typical flight mission. This work represents a preliminary effort to develop a computational tool that will be used in future work intending to perform an coupled analysis of the ACM impact on the gas turbine performance.

6. 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.

Conceição, S. T., 2006, “Estudo Termodinâmico de Máquinas de Ar Condicionado Ciclo a Ar de Aplicação Aeronáutica”. Dissertação de Mestrado – Instituto Tecnológico de Aeronáutica, São José dos Campos.

EES, 2004, “Engineering Equation Solver Manual for Microsoft Operating Systems”, F-Chart Software, http://fchart.com/.

Garrett, A. D.,1991, “Aircraft Systems & Components”, Jeppesen Sanderson Inc., Englewwod, Colorado, USA.

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

Lombardo, D., 1993, “Advanced Aircraft Systems”, McGraw-Hill Publishing Company Limited, New York, USA.

7. RESPONSIBILITY NOTICE

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