A preliminary study for selecting and optimizing the environmental control system

María Aranda Rosales

Technical University of Madrid

Empresarios Agrupados, Simulation Department

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Abstract

The aim of this work lies in providing an insight into the two main types of environmental control system (ECS) installed in current civil aircrafts, and establishing a solid methodology that allows its study and analysis. Through this study, an optimization of these two systems is carried out following two criteria: mass minimization and bleed pressure minimization (or electric power minimization when required). Naturally, an ECS mass estimation and a simulation of the involved thermodynamic cycle are needed at this point: all the models are developed through PROOSIS, simulation software enabling the address of the whole methodology. Finally, after the optimization and the subsequent off-design study, an assembly between an engine and its bleed system is simulated. Pressure and temperature conditions demanded by the ECS are imposed in this model, being the final objective making a quick estimation of each optimal design's impact on the total fuel consumption.

Introduction

Aside from developing other new improvements, the introduction of electric equipment in any aircraft's system has become a subject of utmost importance. Diminishing the non-propulsive power demanded by the aircraft's auxiliary systems can lead to significant improvements with regard to fuel consumption. One of the most representative examples reflecting this new philosophy is the environmental control system: a recently developed electric solution proves to be more efficient and environmentally friendly than the configuration used conventionally among civil aviation.

Throughout any civil aircraft's flight, the ambient conditions surrounding the vehicle can be unfavorable and even incompatible with human life. Such is the example of cruise stages, whose conditions are, approximately, -60ºC and 26000 Pa. At this point, as necessary as having a power plant providing the thrust required for pushing the aircraft forward, is counting on a system able to air-condition the cabin and ensure the passengers' comfort during the whole flight. The environmental control system (ECS) works, essentially, transforming an air stream, which enters at certain temperature, pressure and humidity conditions, until it reaches the desired conditions for accessing the cabin, ensuring acceptable temperature and pressure, as well as adequate air contents in carbon dioxide and ozone. Two main types of ECS exist: the conventional one, which functions with an air stream bled from the aircraft's engine; and the recently developed electric system. Instead of coming from the bleed system, the air stream enters this cycle thanks to an intake directly installed at the aircraft's outside. So that the stream's conditions are similar to what they would be after being bled, an electric compressor rises its pressure and temperature. In both cases, aside from the aforementioned difference, the following thermodynamic cycle has the same characteristics.

The propulsive power provided by the aircraft's engines is responsible for the necessary thrust generation. Nonetheless, aside from this propulsive force, secondary non-propulsive power for feeding auxiliary systems is required. Among this auxiliary equipment, the environmental control system stands out, since it represents the highest non-propulsive power consumption. Due to its significant supply demand — which can reach 1% of the total power provided by the power plant (Martínez, 2014) — it is crucial to carry out an optimal design of its components.

This work focuses on the study, separately, of two common ECS configurations: conventional and electric. The main similarities and differences between both systems are checked, and a process of optimization is carried out. To address the study of both systems, the following methodology is considered: first, based on certain ambient design conditions, cabin requirements are established. Then, the optimization of each system is developed after making the proper design decisions — optimization criteria, degrees of freedom, parameters and variables involved, etc. Once the design procedure is completed, an off-design verification of both configurations must be done to ensure an appropriate performance through different flight and ambient conditions. Finally, a quick estimation of savings associated to the systems' fuel consumption is made.

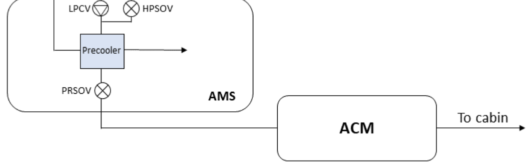
ECS: main concepts

The environmental control system is responsible for the cabin pressurization, as well as providing fresh air into the cabin at the required temperature and composition levels. At the same time, the conventional system is divided into three subsystems: the Engine Bleed Air System (EBAS), whose mission is to extract the air stream from the engines; the Air Management System (AMS) and the Air Cycle Machine (ACM), where the thermodynamic cycle takes place.

- *Engine Bleed Air System and Air Management System*

Before entering the Air Cycle Machine, the air stream is bled from the engine at high pressure and temperature conditions. The pneumatic bleed system can extract air from two ports: one at advanced compressor stages and one at intermediate stages. Once bled, the air stream's resulting pressure is controlled by the Air Management System through three valves: a High Pressure Shut-Off Valve (HPSOV); a Low Pressure Check Valve (LPCV) and a Pressure Regulating and Shut-Off Valve (PRSOV) right at the final stage. Thus, if the pressure demanded by the ECS is higher than that corresponding to the bleed pressure at earlier stages, the HPSOV opens for providing air stream at high pressure. In the meanwhile, the LPCV ensures that there is no reverted flow through the high and low pressure conducts. The pressure-regulating valve adjusts eventually the bleed pressure to the pressure demanded by the ECS.

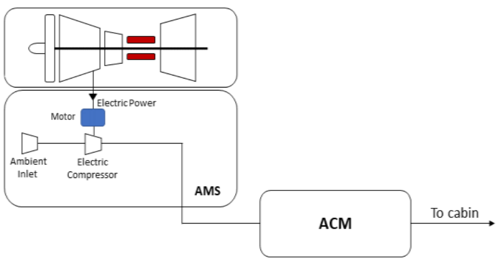
Figure 1. Environmental Control System: conventional layout.



Note that the air temperature cannot exceed a safety level when it accesses the Air Cycle Machine. The reason is, mainly, that the air transportation takes place through conducts close to fuel lines, which may result in serious flammability problems. Due to the aforementioned fact, a precooler must appropriately refrigerate the air stream before accessing the Air Cycle Machine thanks to a stream derived from the engine's fan (see Figure 1).

The electric configuration does not count on a bleed system (EBAS), though. In its place, the engine's shaft must provide an extra auxiliary power to feed an electric compressor (see Figure 2). The mission of this compressor consists of rising the air's upstream pressure and temperature values so that its conditions are similar to those if being bled.

Figure 2. Environmental Control System: electric layout.

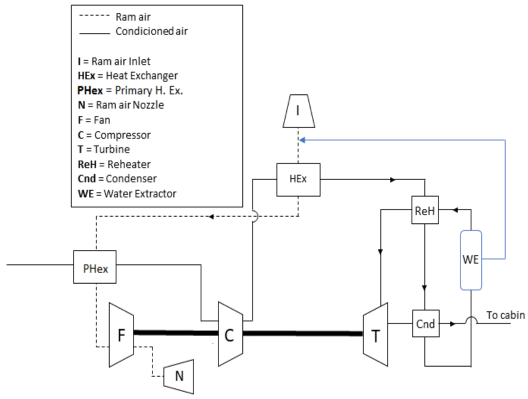


- *Air Cycle Machine*

After being refrigerated, the air enters the Air Cycle Machine, where the remaining thermodynamic processes occur before its access to cabin. Part of the air in the cabin is expelled to the ambient, while the other part goes through filters and is then recirculated into the cabin. This air recirculation is done to meet the minimum air composition's requirements (adequate levels of carbon dioxide and ozone), and to minimize the mass flow being bled in the meanwhile. Note that, usually, there are two independent air cycle machines, each one belonging to one aircraft's engine, whose air streams converge at a chamber along with the recirculated air, being the mixture ready to enter the cabin.

The widely employed ACM configurations for civil aircrafts are, fundamentally: simple cycle; two-wheel bootstrap; three-wheel bootstrap and four-wheel bootstrap cycles. The selected case of study is a three-wheel bootstrap configuration, whose aspect is depicted in Figure 3.

Figure 3. 3-Wheel bootstrap cycle layout.



At certain stages of the thermodynamic cycle the air stream can reach, in numerous occasions (especially with high levels of humidity in the ambient), conditions that provoke vapor water condensation. The conditions that the air usually has when entering the Air Cycle Machine (450 K and 300000 Pa) are such that the water's state contained in the stream is vapor. Nonetheless, up as it goes along the cycle, the temperature decreases progressively until it condenses or even reaches the state of ice. This problem favors, primarily, the effect of water condensation at cabin walls and avionics and, secondly, it is likely that the stream through the turbine contains water drops and worsen its performance. To avoid these inconveniences, a water extractor eliminating the rests of water drops in the air stream is installed. The liquid water wed out is injected in the ram stream so that it increases its cooling power. Depending on the stages where the water is extracted, there may be two different configurations: if the extraction takes places upstream of the turbine, it is called a high-pressure water extraction. On the contrary, if the water is extracted after the expansion, it is a low-pressure layout.

Cabin requirements' establishment

The starting point of an ECS preliminary design is establishing the cabin requirements. Because there is a heat transfer process between the cabin and the ambient, the temperature at which the air stream accesses the cabin is different from the desired cabin temperature. The results obtained after the following calculation may depend on the heat transfer model selected for the cabin and the design ambient conditions. These selected conditions correspond to the most critical ones for the thermodynamic cycle: take-off flight stage; hot day on ground (50ºC) and high humidity levels. Through this heat transfer model, whose desired cabin temperature is 27ºC, the main outputs are the necessary temperature at each ACM pack exit; the necessary mass flow; and the access temperature of the air stream into the cabin. Essentially, the heat transfer model selected takes into consideration the following contributions (ASHRAE, 2011):

- Metabolic heat.

$$\dot{Q}_{met} = n_{Pax}\,\dot{Q}_{Pax} + n_{Crew}\,\dot{Q}_{Crew}\ ,$$

where $\dot{Q}_{Pax}$ and $\dot{Q}_{Crew}$ are, respectively, the metabolic heats generated by the passengers and the crew, in W; and n_{Pax} and n_{Crew} depict the number of passengers and crew members.

- Sun heat transfer through the transparent surfaces of the cabin.

$$\dot{Q}_{sun} = \left(\frac{1}{2} A_{transp}\,\dot{q}_{sun}\right) SF,$$

where A_{transp} is the transparent area of the fuselage, in m^2; $\dot{q}_{sun}$ is the average solar heat transfer, in W/m^2, and SF is a solar factor that ranges from 0 to 1 and indicates the grade of solar incidence.

- Avionics heat.
- Wall heat transfer due to the own wall conductivity.

$$\dot{Q}_{wall} = \frac{k}{t_w}(A_{fus} - A_{transp})(T_{we} - T_{wi}),$$

where k is the fuselage's wall conductivity, in W/mK; t_w is the wall thickness, in m; A_{fus} refers to the total fuselage area, in $m2$; T_{we} is the exterior wall temperature, in K; and T_{wi} stands for the interior wall temperature, assumed equivalent to the cabin temperature, in K.

To estimate the aforementioned exterior wall temperature, it is necessary to resort to the heat balance between the ambient and this surface. Essentially, there is a heat exchange due to convection processes, as well as radiation absorbed and emitted by the wall. Let the final expression for this exchange be:

$$h_e(T_{wr} - T_{we}) + \alpha\,\dot{q}_{sun}\,SF = \sigma\epsilon\,(\,T_{we}^4 - T_\infty^4\,),$$

where h_e is the heat transfer coefficient, in W/m^2K; T_{wr} is the wall adiabatic temperature, in K; α refers to the fuselage's wall absorptance factor; σ stands for the Stephan-Boltzmann constant, in W/m^2K^4; ϵ is an emissivity factor of the fuselage surface; and T_∞ is the ambient temperature, in K.

The energy equation established to close the heat exchange model is:

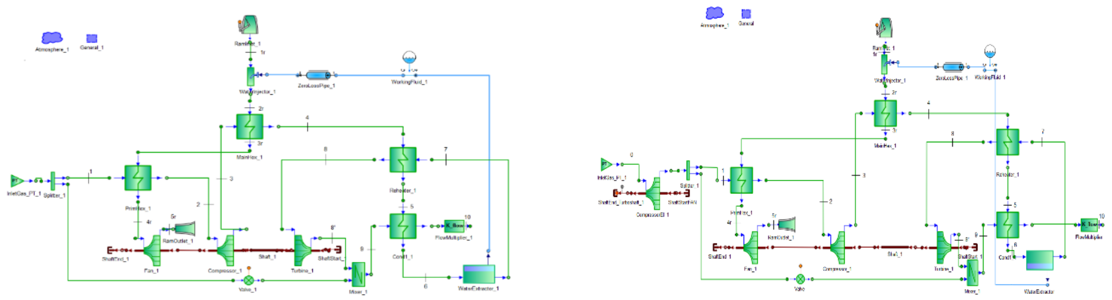
$$\dot{Q}_{tot} + \dot{m}_{tot}\left(h_{t,out} - h_{t,in}\right) = 0\ ,$$

being $\dot{m}_{tot}$ the sum of the recirculated air and the fresh air coming from the air cycle machine, in kg/s; and $h_{t,out}$ and $h_{t,in}$ the total enthalpies at the outside and inside of the cabin, respectively, in J/kg.

Table 1. Employed data for cabin requirements calculation.

Useful data for cabin requirements calculation			
		A_{transp}	6.8276 m^2
$\dot{q}_{sun}$	1367 W/m^2	A_{fus}	341.3796 m^2
$\dot{Q}_{Pax}$	70 W	k	0.185 W/mK
$\dot{Q}_{Crew}$	200 W	t_w	0.086 m
n_{Pax}	200	α	0.26
n_{Crew}	4	ϵ	0.95
SF	1	σ	5.67E-8 W/m^{2}K^4

Figure 4. ACM models for the conventional (left) and electric (right) layouts used in PROOSIS.



Environmental control system modeling and description

Essentially, the airflow passing through the Air Cycle Machine is thermodynamically transformed thanks to an auxiliary stream called ram, taken directly from the ambient. The selected conventional configuration for the ECS (3-Wheel bootstrap cycle with water extraction at high pressure) mainly consists of two heat exchangers, where the air-conditioned and the ram air enter; a compressor, a turbine and a fan linked together by a shaft; and the elements responsible for the airflow condensation, water extraction and injection (see Figure 4).

After having cooled in the primary heat exchanger (PHex), the air is then compressed and ready to be refrigerated through the main heat exchanger (MHex). Note that, along this main heat exchanger, the ram air is at a lower temperature than in the primary one, since it comes directly from the ambient and has not taken part yet in any other heat absorption process. The air-conditioned stream temperature progressively decreases through the hot side of the reheater (ReH) and condenser (Cnd), and a water extractor after the latter component is installed to eliminate any water drop present in the stream. Being dry the air, it heats up in the cold side of the reheater, allowing a better performance through the turbine. Eventually, the cold side of the condenser allows a last heating of the airflow, ready to be mixed with the recirculated air and enter the cabin.

The selected electric case has the same thermodynamic cycle, excepting a unique difference upstream the system (see Figure 4). Since the air stream is directly taken from an outside intake, an additional compressor is installed in the electric case to rise its inlet conditions until they are similar to what they would have been in case of being bled.

Optimization procedure and design point selection

The principal aim of carrying out this environmental control system's optimization is to minimize its non-propulsive power demand. First, it is necessary to identify which factors are to have an impact on this: the ECS mass, as well as the bleed pressure (or the electric power when considering the electric configuration). The lower mass the system has, the better will be for the aircraft performances during the flight, since less fuel will be necessary to provide equal levels of thrust. At the same time, reducing the bleed pressure reduces as well the extra power supply provided by the engine's turbine, making it beneficial for the fuel consumption.

- Conventional layout

For carrying out the optimization, a linearized objective function is to be defined as follows:

$$\phi = w_1 Bleed\ Pressure + w_2\ Mass,$$

where w_1 and w_2 are two factors indicating the importance that the designer gives to each objective. With $w_1 = 1$, the optimization would only consist of a mass minimization, while $w_2 = 1$ would point to a bleed pressure minimization. Note that $w_1 + w_2$ must be equal to one.

Design parameters definition

The conventional configuration has 6 degrees of freedom. Nonetheless, when carrying out the optimization, not all of them take part in it. Assuming that the compressor and fan pressure ratios will cause the major impact on the objectives, the optimization will be developed varying only these two parameters. In the parametric study, the variables will range between typical values:

$$1.2 \leq \pi_c \leq 3$$

$$1.05 \leq \pi_f \leq 1.2$$

Design limitations

Naturally, not every point calculated in the previous parametric study represent a valid design. Even if the calculations converged and reached a numeric solution, some ratios of the turbomachinery could be violated. Besides, there is a limitation for the access pressure at the air cycle machine, which cannot exceed 350000 Pa. For these reasons, design restrictions are applied to the parametric case so that only the acceptable design points are depicted. The final Pareto distribution is shown in Figure 5.

To make an easier analysis of the design optimization's results, only two cases of study regarding the conventional configuration are considered in the future:

- **A Case**: $\pi_c = 1.57$; $\pi_f = 1.05$, in which the bleed pressure is minimized.
- **B Case**: $\pi_c = 1.36$; $\pi_f = 1.07$, in which the system's estimated mass is minimized.

- Electric layout

The electric case has three design parameters: the formerly considered compressor and fan pressure ratios, as well as the electric compressor pressure ratio. The same design limitations regarding the turbomachinery geometry are applied. Nonetheless, instead of limiting the downstream's pressure, which now derives directly from the ambient conditions, the upstream's pressure is forced to be higher than 1 atm.

Figure 5. Optimization results for the conventional ECS.

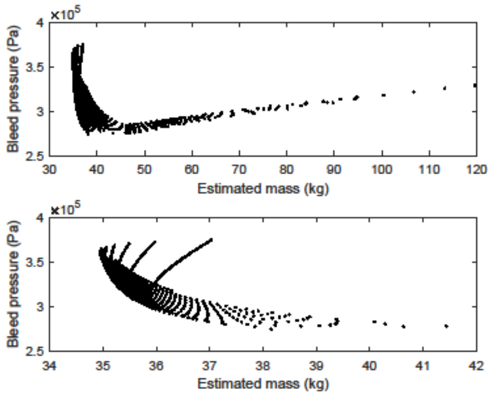
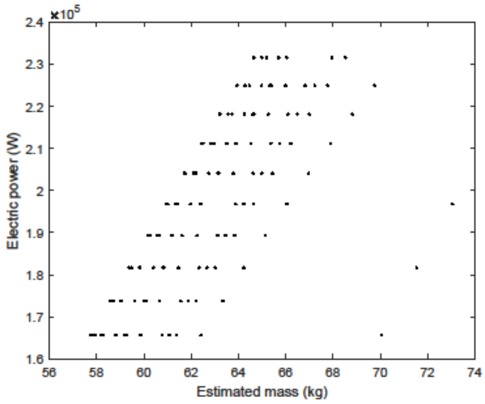


Figure 6. Optimization results for the EECS.



The resulting parametric study shows that there is not a whole curve formed by optimal design points, but the point minimizing the mass minimizes as well the demanded electric power. Taking into account that the electric generator is much heavier than the other elements' estimated mass, one can reasonably conclude that the more energy the electric compressor needs, the more powerful the generator must be, and the higher the estimated mass will be.

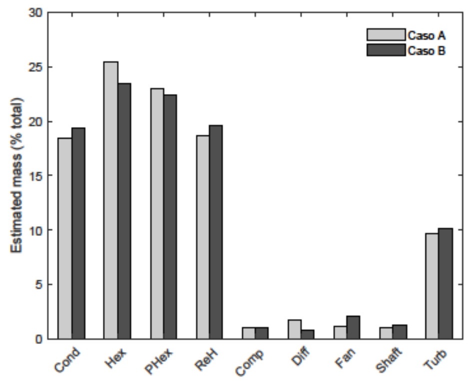
The values of the parameters in the resulting design point are as follow:

- EECS Case: $\pi_c = 1.4$; $\pi_f = 1.08$; $\pi_{c,el} = 3.2$ in which the electric power and system's estimated mass are simultaneously minimized.

Results analysis

The resulting A conventional case has a minimum bleed pressure of 283196 Pa, while in the B case it is of 326552 Pa. In the electric design case, the electric power demand is of 218136 W.

Figure 7. Mass distribution for the conventional cases.



So that the minimum mass points can be located, the following assumption is taken:

$$M_{tot} = \sum_{i=1}^{N} M_i = \sum_{i=1}^{k} M_{dep,i} + \sum_{k+1}^{N} M_{indep,i} ,$$

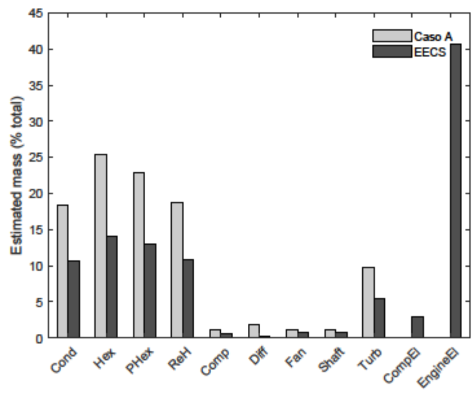
where N is the number of elements belonging to the system. It is considered that there are k elements whose mass is dependent on the design parameters and $N-k$ elements whose mass does not depend on them. Since the objective at this stage is not to obtain an accurate, absolute mass but locating the minimum point, only the dependent elements are considered, assuming that the remaining mass contributions do not have an impact on the minimum point location process. Hence, the mass of the turbomachinery (compressor, turbine and fan); the shaft; the heat exchangers and the ram air outlet are estimated. The contributions of the water extractor and injector; the pipes; the ram air inlet and the valves are assumed independent on the design parameters and consequently neglected.

The mass contribution of each system's element with respect to the total sum is depicted in Figure 7. The total mass estimations are 36.97 kg and 35.23 kg for the A and B cases, respectively. As expected, the heaviest elements belonging to the system are the heat exchangers: the sum of these four elements is some 85% of the total system's mass estimation, without being many other differences between both cases. Another significant element is the turbine, which, steel-made and being its dimensions larger than the compressor's, corresponds to a 10% of the present estimation. The principal consequence deriving from these results is that the remaining elements' mass could have been neglected without making a high error.

Naturally, elements whose material is less dense than steel (aluminum or titanium) and whose thickness is tenths of millimeter will have a considerably lower mass than the rest. Taking the approximate datum of the ACM weighting 150 kg (Martínez, 2014), the estimated mass is some 24% of the whole system. Thus, those elements whose mass has not been taken into account – pipes and conducts; outlet plenum; water extractor and injector - are an important part of it, which has been considered invariable no matter the selected design point.

The absolute saving coming from the B case has been of 1.41 kg per each ACM pack (approximately 1% of the total), whose impact on the fuel consumption will be estimated in further sections.

Figure 8. Mass distributions for B and electric cases.



Even though all the elements in the electric case have a geometry similar to the conventional layout, the electric compressor is heavier than that linked to the turbine and the fan. The reason is, fundamentally, that it has larger dimensions deriving from a higher pressure ratio. Figure 8 depicts a comparison between the electric layout's mass estimation and one of the conventional case (A). The most outstanding result is the fall of the heat exchanger's contribution to the total weight, since the mass of the electric generator has been added. The electric generator mass has been estimated by means of a power to weight ratio of 8.4 kW/kg (e-motors, 2017) used in the aeronautic field. The heat exchangers' contribution to the mass estimation is now some 50%, while it was practically the whole sum before. The remaining half sum of the estimation is, mainly, due to the electric generator. More justified, if possible, is neglecting the mass of elements such as the fan, the outlet diffuser, the shaft and the compressor. Even though as a starting point it was assumed that these elements might have an impact on the mass estimation, it has been finally checked that its variations with the design parameters, as well as its contribution to the total mass, are negligible.

In absolute terms, each ACM mass in the electric case is of 63.29 kg, which involves a rise of 26.32 kg with respect to the conventional case. This time, the difference in mass is appreciable due to the introduction of the electric generator.

Off-design study

Once the design points have been chosen, a further step would consist of ensuring an adequate performance of the system throughout different flight conditions. It must be taken into account that, among the aspects which could affect the system's performances, they stand out:

- Invalid ACM outlet temperature.

After going through the condenser in the thermodynamic cycle, the air stream temperature must be higher than a limit to avoid icing problems.

- Air stream accessing the cabin at an inappropriate pressure or temperature.

The temperature that the stream has when accessing the cabin must as well be between two values. Nonetheless, this limitation has to do with the passengers' comfort this time: a too hot/too cold temperature could be uncomfortable during the flight. An appropriate access pressure is necessary to ensure the cabin pressurization and to avoid problems related to the fuselage's structural overload.

- Fan overload.

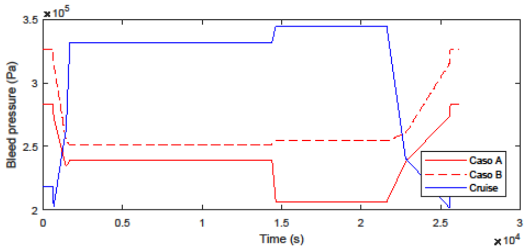
The principal aim that leads to the fan installation in the system is causing the ram stream suction, hence forcing it to pass through the following heat exchangers. On ground conditions, there is no element in the ram line increasing the stream pressure so that it can naturally access the thermodynamic cycle. When Mach number and altitude increase, the stream enters the system through the ram inlet, making it dispensable the presence of the fan. For this reason, when working outside the design point, the fan performance is not relevant. However, being the compressor, the turbine and the fan connected through the same shaft, it is unavoidable that this fan will keep on rotating at certain speed, resulting in overload problems. The solution to this problem consists of redistributing the stream (Aeroespace, 2004) so that part of it goes through the fan, avoiding excessive mass flows causing irreversible damages for the blades. The redistributed mass flow exits the last heat exchanger and goes directly through the exit diffuser.

- Bypass valves design.

Since the systems' design points do not involve trim air mass flows, the bypass valve design was of no particular importance at that stage. However, when addressing an off-design study, where some trim air would exist to adjust the outlet temperature, it is significant that a design area is defined, for it will condition the mass flow going through it. Knowing the design area of these valves, the passing mass flow is calculated in terms of the opening signal.

Knowing what temperature and pressure conditions must be imposed downstream the cycle at each flight stage, a particularly interesting output deriving from this study is the demanded bleed pressure of each conventional case, as well as the electric power demand with regard to the EECS case (see Figure 9).

Figure 9. Demanded bleed pressure/electric power.



Fuel consumption estimation

The objective of this section is to study the impact on the fuel consumption caused by each ECS design point throughout a typical mission profile. The considered turbofan model in PROOSIS depicts the layout of a CFM-56 turbofan. Its design point has not been particularly adjusted to the study cases, and being the ECS separately designed, the possible synergy between both systems' design points has been neglected. In other words, the design point for the turbofan does not depend on the ECS case being treated. Once the turbofan design point is implemented, its geometry and configuration are ready for the mission profile imposition. Note that the selected model for the turbofan has just one degree of freedom.

Initial turbofan simulation without ECS

First, a preliminary simulation of the isolated turbofan is needed. The reason is that, through the study, the impact on the fuel consumption caused by each ECS case is checked, assuming that the thrust generated by the engine is always the same. To calculate the thrust during the flight, a law for the engine's combustion temperature is required. Besides, altitude and Mach conditions are to be indicated throughout the whole flight (see Table 2).

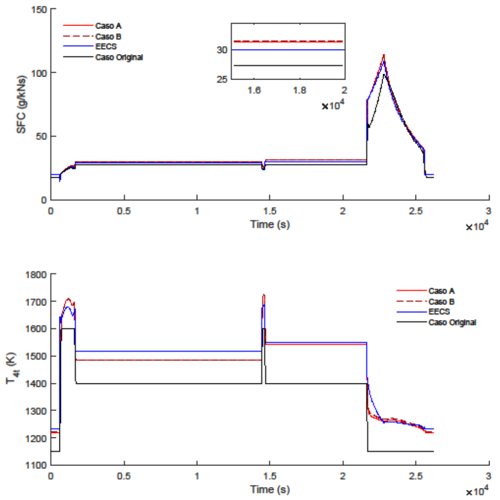
Table 2. Employed mission profile.

Time (s)	Altitude (m)	Mach	T_{comb} (K)
0	0	0	1150
603	0	0	1620
660	0	0.25	1620
661	0	0.25	1600
1440	9000	0.8	1600
1680	10886	0.8	1600
1682	10886	0.8	1400
14400	10886	0.8	1600
14402	11887	0.8	1600
14642	11887	0.8	1400
22800	7000	0.65	1150
25560	0	0.2	1150
26160	0	0	1150

ECS impact on fuel consumption: results

In all the simulations where the ECS demanded pressure/electric power is already imposed to the engine, the boundary closing the model in PROOSIS corresponds to the required thrust obtained in the former calculation. Adding two new bleed ports or, in the electric case, demanding some extra power supply, involves a subsequent increase in the combustion temperature and specific fuel consumption during the flight. These results can be seen in Figure 10.

Figure 10. Results of the turbofan simulation.



Fundamentally, based on the design procedures, two possible factors having a direct impact on the total fuel consumption exist: the ECS mass, as well as the bleed pressure/electric power demanded in the flight. Due to that, the optimization takes into account these two aspects, being of significance checking the final effect derived from both of them.

First, from the simulation where bleed pressure or power demand are imposed, an integration of the instantaneous fuel consumption is carried out throughout the whole flight, being the results depicted in Table 3. From now on, the reference case is the A conventional case.

Table 3. First fuel consumption estimation.

	Initial system	A Case	B Case	EECS
Fuel saving (%)	11.43	-	-0.242	1.78

Installing the environmental control system implies an approximate increase of 11% of the total fuel consumption after completing the mission. However, it has been proved that the electric system saves some 2% in comparison with its conventional competitor. The conventional B case, which demands a higher bleed pressure, needs a slightly higher amount of fuel.

Heretofore, an estimation of the fuel consumption associated to the ECS has been carried out without taking into consideration the changes in mass among the designs. At this point, taking the specific fuel consumptions formerly obtained in each case at cruise stages, as well as cruise speed and mission range, the Breguet Range equation allows a quick estimation of this effect:

$$\Delta S = \frac{u_\infty L/D}{SFC\ g} \ln \frac{W_i}{W_f}$$

Table 4. Employed data for the Breguet equation (services, 2018).

	A Case	B Case	EECS
Lift-drag ratio	16.3	16.3	16.3
Cruise speed (m/s)	236.464	236.464	236.464
Initial mass (kg)	73500	73496.5	73552.6
Range (km)	5542.82	5542.82	5542.82

The principal hypothesis taken in this section is that the initial mass of fuel is the same no matter what case is being considered. This assumption involves a significant error, since fuel savings will strongly depend on the total amount of fuel consumption through the mission. Nonetheless, the main objective at this stage is knowing what the tendencies in the two systems are like when both optimization objectives (bleed pressure and mass) are simultaneously taken into account.

Table 5. Final fuel consumption estimation.

	A Case	B Case	EECS
Fuel saving (%)	-	0.0047	0.8

Naturally, in the final estimation, due to the changes in mass of the electric system, the resulting fuel savings are lower than in the previous calculation, falling from a value of 2% to a new approximation of less than 1%. However, the Breguet's equation assumes cruise conditions during the whole flight and the change in mass due to the fuel savings has not been considered, but only due to the different ECS configurations. A more rigorous approach would have consisted of keeping a constant level in the variable T/W obtained in the A reference case, instead of maintaining just the isolated thrust. Proceeding this way, the feedback between the two optimization objectives would have been registered. The starting point of this prospective, deeper approach would be the take-off weight corresponding to the A case. From this first calculation, the reference T/W law would be obtained and imposed in the remaining cases. For the other study cases, the same take-off weight is imposed, added the difference in mass due to the ECS presence. An iterative process is to be carried out, until the fuel consumption calculated through PROOSIS would have been equal to that at the starting point (calculated as the take-off weight less the empty weight, the payload and the fuel savings). Calculating the necessary fuel savings fixed by regulations, and after doing some iterations with the take-off weight, the final consumption calculation would be more efficiently adjusted to a real case.

Concluding remarks and future work

The preliminary design stage of any aircraft's system is an arduous task, so much so when many factors are included. Particularly, the carried-out study of the environmental control system involves, among other aspects, heat transfer; turbomachinery design; mass estimations, etc. The principal aim of this work was to understand the performance of this system; to analyze the main differences between the conventional and the electric configurations; and to establish a solid design methodology to be applied in further studies. After optimizing the design point in the conventional case, in the first place, two cases of study have been considered: an A case, whose bleed pressure is minimum, and a B case, whose estimated mass was minimum. The results seen through the off-design and the turbofan studies show that there are certain disparities between both layouts.

To complete a mission of, approximately, 7 hours, choosing a design point that minimizes the bleed pressure is favorable for the total amount of consumed fuel, and so it is, at the same time, selecting a design point with minimum mass. Even though this multi-objective optimization has been justified, it has not been deduced with high accuracy the aspect of more importance.

With regard to the electric case, it has been proved that there is no Pareto distribution, but being predominant the mass of the electric generator, those points with a reduced power are also the lightest designs. Although this system is heavier, based on the last fuel consumption calculations, the electric environmental control system proves to require less fuel quantities and be more efficient.

Some points for further improvements and subject to a deeper study are:

- There are elements in the model whose mass has not been estimated due to a lack of information and under the assumption that its variation with the design parameters is negligible. Assuming that the estimated mass corresponds only to elements dependent on the design parameters, it has been possible to locate the point where the mass minimum is, but not its absolute value. Neither has been calculated the mass of the Engine Bleed Air System nor Air Management System.

- The turbofan model, in which the bleed system has been integrated, has been designed aside from the ECS, consequently neglecting the possible synergy between both systems. Since the proper turbofan's design point established for the electric system may differ from that selected in the conventional case, a subsequent error has been made.

- Through the last turbofan study, the impact on the fuel consumption caused by the aircraft mass has been done under the hypothesis that the initial fuel weight was equal in all the cases. Nonetheless, fuel savings may depend on the amount consumed during the trip, making an error in the calculation. An iterative process with the take-off weight leading to a more rigorous approach would have allowed obtaining results that are more accurate.

Apparently, the electric environmental control solution proves more favorable in terms of fuel consumption. Nonetheless, its use among current civil aircrafts is still limited. A study on economic and reliability aspects related to both systems would have been interesting to check why the recently developed electric system is not yet widely employed.

Neglecting the possible effect of some aspects is definitely unavoidable when handling a system of high complexity. A more rigorous study carried out, the conclusion regarding the benefits or drawbacks associated to both systems would have been categorical. Being irremediable the airlines' struggle to be the most profitable ones, their future lies undoubtedly in developing new, environmentally friendly solutions.

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