# AIRCRAFT AIR MANAGEMENT SYSTEMS TRADE-OFF STUDY USING EXERGY ANALYSIS AS A DESIGN COMPARISON TOOL

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***Abstract.*** *Airplanes are designed to attend the client needs by minimizing fuel consumption and inefficiencies – this approach is named "traditional optimization". The aeronautical industry has evolved to design extremely complex aircrafts, with highly integrated systems. The traditional methods to design and optimize are based on trade-off studies. Some authors criticize this type of analysis of evaluating new systems as they present lack of information. Besides, due to the high level of integration between aircraft systems, the optimization of a single system would drive to sub optimized solutions for other systems or aircraft as a whole. Therefore, the search for an optimized aircraft becomes a search for commitment solutions of different systems. These authors indicate a necessity to develop a general methodology that allows a complete vehicle design as a system that contains sub-systems in the same basis. It is possible to weight, fuel consumption and drag as energy functions. In this case, the initial optimization problem can be categorized as an optimization problem that aims the energy quantity that is required by mission , minimizing additional weight and Thermodynamic losses. In this way, the project becomes committed to maximum efficiency and minimum waste of useful energy (exergy destruction), considering the adequate constraints. The aircraft design can specify the mission requirements as an energy problem. Farther on, exergy allows to analyze qualitatively and quantitatively the involved losses in different systems, presenting the contribution of each sub-system to the total losses. This work presents a exergy analysis of two architectures for the AMS system of a commercial aircraft: conventional archietecture and 'more electric'architecture. The analysis evaluates the exergy efficiency, exergy destroyed rate and exergy destroyed cost for each architecture. Also, it shows the economic impact (related to fuel consumption savings) of the change from the conventional architecture to the 'more eletric'one.*

***Keywords****: exergy analysis; aircraft; systems design; environmental control system; ice protection*

## 1. INTRODUCTION

Energy systems have become increasingly more complex, leading to higher levels of interaction between a sub-system. Consequently, there is a need to develop tools that would allow the design/synthesis of the system in complete integrated way, allowing all demands of each sub-system to be reached in the best possible way (Muñoz, 2000). The aeronautical industry has also evolved to design extremely complex aircrafts, with highly integrated systems, requiring more information in order to evaluate the whole system (Moorhouse, 2003).

Modern aircrafts are designed to attend the client needs, minimizing fuel consumption and inefficiencies - this approach is named 'traditional optimization'. Most of these studies rely on rules-of-thumb, individual experience and non-integrated, non-interdisciplinary approaches of basic calculations, i.e. simple trade-off analysis (Muñoz, 2000). Such analysis relies on cost-benefit studies among different options, but not in the same basis. Thus, it may lead to sub-optimal solutions.

Many authors have criticized such analysis (Paulus and Gaggioli, 2000; Vargas and Bejan, 2001; Bejan and Siems, 2001; Muñoz and von Spakovsky, 2003; Figliola *et al.*, 2003; Roth, 2003; Rancruel and von Spakovsky, 2003; Moorhouse, 2003; Periannan, 2005). These authors agree that there must be a common basis to compare different alternatives in aircraft design, especially when developing new systems.

According to Tsatsaronis (1993), Classical Thermodynamics provides the concepts of energy, energy transfer by heat and work, energy balance, entropy, entropy balance, among others. The Second Law of Thermodynamics complements and enhances an energy balance by enabling calculation of the true Thermodynamic value of an energy carrier, and the real thermodynamic inefficiencies and losses from processes and systems. Therefore, the concept of exergy is extremely useful for this purpose.

Exergy analysis and minimization of exergy destruction can be used by themselves mainly in areas where the total cost of the installation is dominated by the cost due to thermodynamic irreversibility (Bejan and Siems, 2001). Paulus and Gaggioli (2000) state that the design of vehicles do not have the same goal of energy systems designed to provide mass flow, heat or work transfer. Instead, they are designed to attend performance goals, and these are related to Thermodynamic inefficiencies.

The use of exergy indicates directly the location of the main sources of irreversibilities; hence, it provides new information to the designer regarding the operation of the system. Also, exergy allows a more rational way to attribute costs in energy systems; therefore it is possible to associate irreversibilities and costs. Unfortunately, exergy analysis does not indicate directly the system alteration required to minimize these irreversibilities (Bejan and Siems, 2001).

The exergy approach has been used for some years in aerospace industry involving isolated systems and integrated aircraft-systems analysis, due to the reason that several systems and processes on an aircraft contribute to the destruction of all the exergy furnished by the fuel. A comprehensive review of different works related to the use of exergy in the aeronautical industry can be found in Pellegrini *et al.* (2007).

The present paper uses exergy analysis in order to compare different architectures, conventional and 'more electric', of the air management system (AMS). The methodology used in a previous work, by Pellegrini *et al.*( 2007), for a comparative analysis of different environmental control system (ECS) architectures, defining adequate strategies for system optimization, is applied in the present paper but with hypothesis not assumed previously.

## 2. POWER PLANT AND AIRFRAME

The powerplant is the aircraft power source. It provides thrust to the airframe as well as electrical, pneumatic and hydraulic power to drive all the aircraft equipment and sub-systems. Depending on configuration, it is composed by piston or turbine engines, propellers or fan as well as all engine sub-systems and utilities. Usually in aeronautics, airframe is the structure of an aircraft exclusive of its powerplant. In the present paper, the airframe is represented by an aircraft flight mechanics, i.e., a mathematical model that applies the force balance to a steady state and leveled flight. The force balance considers altitute, outside air temperature, phase of flight, flaps configuration, weight, aerodynamic forces (lift and drag) and engine thrust in order to find, for instance, the equilibrium true air speed and the angle of attack. Depending on ambient temperature and altitude, the engine can provide a range of thrust within a range of speed. Therefore, the pilot is allowed to equilibrate the flight by adjusting the thrust lever angle.

Figure 1 presents an example of exergy analysis that considers the exergy demand and penalties imposed by air management systems to aircraft. Basically, it is necessary to evaluate the flight mechanics coupled with engine numerical simulation tool to find the thrust, aircraft speed and associated fuel consumption.

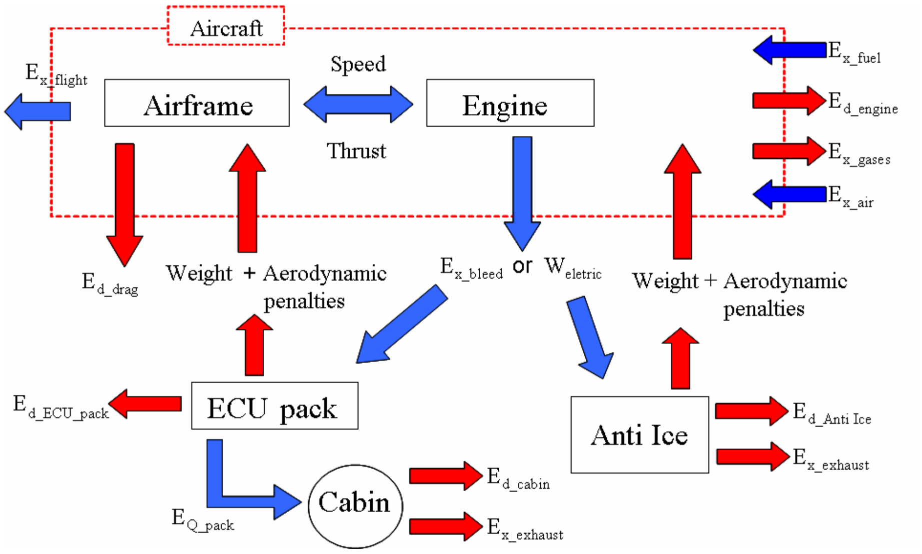

Figure 1. Demand and Penalties Imposed by Air Management Systems to Engine and Airframe.

## 3. SYSTEMS DESCRIPTION

### 3.1. Engine Bleed Air Architecture

The air management systems (AMS) for commercial aircraft are mainly composed of: a) pneumatic system; b) air conditioning system; c) ice protection system; d) engine starting system; e) pressurization system. In conventional architectures, the pneumatic system distributes and controls bleed air to the pneumatic users (air conditioning, engine start, ice protection, pressurization) – Fig. 2.

Bleed pressures from low stages of the engine compressor may be insufficient at lower engine power settings. Bleed pressures from high stages of the engine compressor may be too elevated at higher engine power settings. One function of the engine bleed system is to alternately select between low pressure (LP) and high pressure (HP) bleed supply sources. This is necessary to maintain adequate and safe bleed supply pressures at all engine operating conditions.

The aircraft air conditioning system may be composed by one or more machines, which usually are vapor or air cycles (reverse Brayton cycle). The machines provide cooling and heating for flight deck and cabin, filtered cabin air recirculation, conditioned air supply for gaspers, cooling air for avionics and emergency ram air ventilation for flight deck smoke clearance. In case of air cyle, the air supplied is compressed to keep cabin pressurized at safe and comfort levels. On the other hand, the vapor cycle requires an external compressor to pressurize the cabin. Pellegrini et al. (2007) provide an exergy analysis of an air cycle environmental control unit (ECU) pack.

The ice accretion on aircraft wings and stabilizers causes aerodynamic performance degradation, weight increase, sensors and probes readings errors, control and maneuverability difficulties, which may decrease the operational safety margin. When an aircraft flies through a cloud formed by supercooled water droplets, the ice will accrete on the non-protected surfaces subjected to impingement. As the water droplets are in a meta-stable equilibrium, any perturbation of thermal, mechanic or chemical nature can trigger the freezing process.

The specification of the protected regions of the wing is essential in ice protection system design. For example, it will affect fuel consumption and engine thrust, if engine bleed air is used to supply a hot air anti-ice system. An appropriate design should be a compromise between the ice protection system performance maximization and the impact minimization in aircraft overall operational performance. In order to protect the airfoils and allow safe flight in icing conditions, commercial and some military aircraft have ice protection systems, which can be classified in de-ice and anti-ice types. The de-ice system operates cyclically to remove the ice layer accreted after some exposition time. When the system is not actuated, the ice is allowed to grow on the airfoil; when it is actuated, the system removes the ice from the airfoil. On the other hand, the anti-ice system prevents the ice accretion on airfoils and continuously works while the aircraft flies in icing condition. Most commercial aircraft has a hot air anti-ice system for airfoil leading edges (wings and stabilizers) and engine nacelle lips protection. It transfers heat to protected surfaces using engine hot and pressurized bleed air as a thermal source.

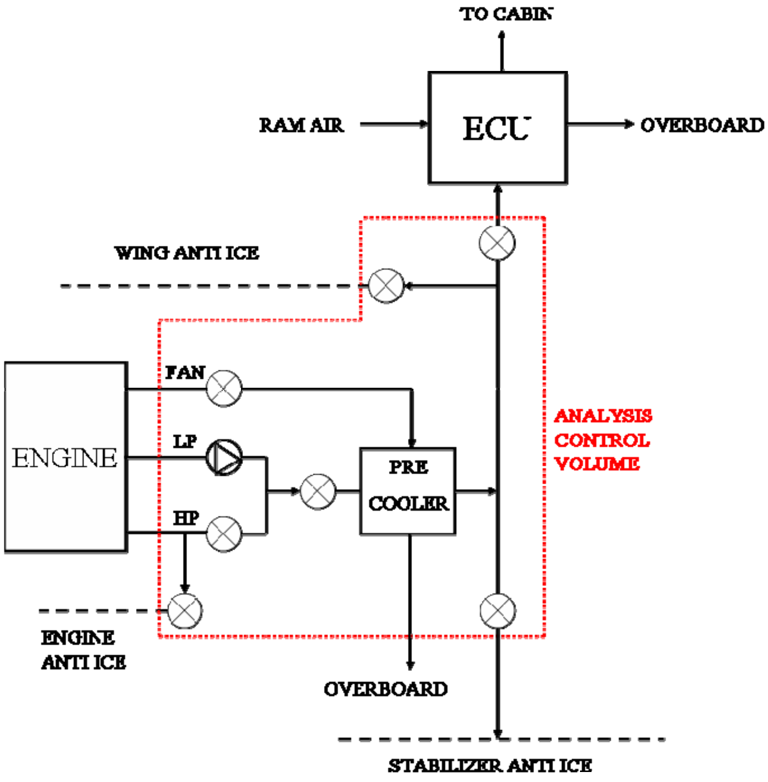

Figure 2. Integrated Pneumatic System – Conventional Architecture.

To estimate the electrical power or the engine bleed air exergy rate demand, it is necessary to use a mathematical model to simulate the operation airfoil of a thermal anti-ice system. This model was firstly implemented by Silva(2002), summarized by Silva and Silvares (2002) , published by Silva, Silvares and Zerbini (2003, 2005) and recently extended by Silva, Silvares and Zerbini (2006, 2007a,b). An adequate thermal anti-ice numerical code shall be used for conception, integrated optimization of aircraft systems, architecture definition, ice protection system sizing and system development. In addition, during the certification phase, the code shall support critical cases matrix definition and test campaign planning.

### 3.2. More Electric Architecture

Currently, one of the most researched solutions for systems energy optimization is the 'more or all electric' aircraft, whose architecture does not involve bleed air as a source of anti-ice power and cabin/cockpit air source (Fig. 3). In this type of architecture, the engine drives an electric generator that supplies electric power to all or most systems, including air management systems. Due to minimization of losses and optimum control of equipment (allowed by electronics), the electric power system can deliver, approximately, what is demanded by the users in that particular operational condition. However, the main gain in the electric architecture, with no engine air extraction, is the extension of engine life and economy, as tapping off the air may increase the turbine inlet temperature and disturb the flow field in the engine core. In addition, a more electric engine can be designed for an optimum condition with no bleed air, i.e., compressor pressure and mass flow can be what is required for the best combustion, turbine performance, shaft power and maximum thrust, not requiring the usual excess of air and pressure for ECS operation and pneumatic system losses.

One of the more electric solutions to air management systems is an electric engine driven cabin compressor, which pumps outside air to the ECU using a high efficient air intake (ram air). In this solution, the cabin compressor uses less energy because the compression rate is lower and more adequated to the ECU air requirements. There is a waste of energy in the conventional architecture and a decrease in engine performance while bleeding air (Pellegrini et al., 2007).

Regarding the 'more electric' concept for ice protection, a system based on electrical heating was developed to remove ice from aircraft surfaces, using a graphite heating element. Such element can be heated and cooled very rapidly. In this system, small areas of the graphite are strongly and suddenly heated, so the ice over that section debonds and leaves with airflow, without melting. The heating panels are strategically located on the leading edges and can be heated on a time basis, alternating locations on the wing and stabilizers, in order to minimize power consumption. A complete deicing cycle does not take long, and very thin accretions of ice can be shed without damaging the aircraft.

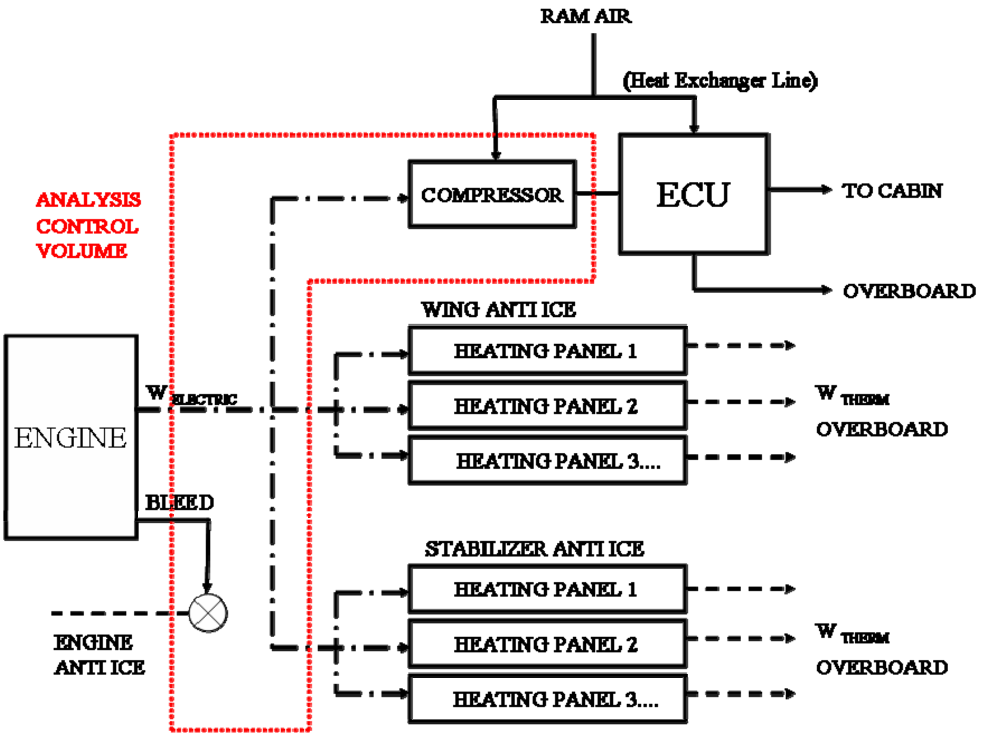

Figure 3. Air Management System – More Electric Architecture.

Yet, there are other more recent technologies for a more electric ice protection system, such as electro-mechanical expulsion deicing system, sonic pulse electro-expulsive deicer, shape memory alloy, piezoeletric among others (Goraj, 2004; Lawson, 2006; Venna, Lin and Botura, 2007).

The engine anti-ice solution for the 'more electric' alternative presents no changes comparing to the conventional architecture. Hot bleed air can be chosen to protect the engine lip because of the low power requirement (less protected area), the convenient location and for installation simplicity.

## 4. MODELING AND SIMULATION

The objective of the case study is to demonstrate the advantages of exergy analysis as a tool to compare different architectures, and to define adequate strategies for system optimization. Two architectures were chosen for the present study: 1) conventional design (engine bleed air driven and anti-ice); 2) more electric design (electric compressor, electric heating anti-ice and engine bleed for engine anti-ice). The ECU is identical in the two cases (same ducting, valves, heat exchangers, turbine, compressor and fan).

It was considered different systems weights (conventional and more electric architectures) and flight mechanics coupled with an engine numerical simulation tool (evaluation of the thrust, aircraft speed and associated fuel consumption). The engine anti-ice system was not considered in the analysis, since there is no change between engine anti-ice architectures of both aircrafts. This analysis also considers an increase in electric generators and wiring weights due to the higher electric power requirements of the more electric airplane. On the other hand, the more electric architecture presents a larger air intake (ram air scoop), whose drag penalty increase was not evaluated.

The case study considers one operational point during cruise and climb at maximum thrust, which are relevant flight phases in terms of fuel consumption. The operational parameters used in present analysis are shown in Tab. 1.

Table 1. Input data.

| Flight Phase | Altitude (kft) | Outside Air Temperature (°C) | Mach | ECU | Anti Ice |
|---|---|---|---|---|---|
| Climbing | 20 | -24.6 | 0.57 | ON | ON |
| Cruise | 37 | -56.5 | 0.77 | ON | OFF |

In the conventional architecture, the AMS exergy efficiency can be defined as the ratio between the sum of the exergy delivered to the consumers (ECU, wing anti-ice, stabilizer and engine anti-ice) to the exergy available at the high pressure air source (bleed air) plus the exergy of the mass flow rate extracted from engine fan:

$$\eta_{Ex,AMS(convetional)} = \left( \frac{\dot{E}x_{ECU\_Air(inlet)} + \dot{E}x_{WAI\_Air(inlet)} + \dot{E}x_{SAI\_Air(inlet)} + \dot{E}x_{EAI\_Air(inlet)}}{\dot{E}x_{Bleed} + \dot{E}x_{Fan\_Air}} \right) \tag{1}$$

In the more electric architecture, the AMS exergy efficiency can be defined as the ratio between the sum of exergy delivered to the consumers (compressed air exergy increase to ECU, electric power to wing and stabilizer anti-ice, exergy to the engine anti-ice) to the power required from the engine electric generator plus the exergy available at the high pressure air source (bleed air) and air from the engine fan:

$$\eta_{Ex,AMS(electric)} = \left( \frac{\left(\dot{E}x_{ECU\_Air(inlet)} - \dot{E}x_{RAM\_Air}\right) + \dot{W}_{WAI} + \dot{W}_{SAI} + \dot{E}x_{EAI\_Air(inlet)}}{\dot{W}_{Generator} + \dot{E}x_{Bleed} + \dot{E}x_{Fan\_Air}} \right) \tag{2}$$

In addition, it is also interesting to know how much exergy from the aircraft fuel (burnt in the engine) is consumed in the AMS system, since it will give a measure of the impact in overall aircraft performance. If this number is small, even a significant increase in exergy efficiency (Eqs. 1 and 2) will lead to a not so important decrease in aircraft fuel consumption. This index, named specific exergy consumption, is given by:

$$SEC_{AMS(convetional)} = \left(\dot{E}x_{Bleed} + \dot{E}x_{Fan\_Air}\right) / \dot{E}x_{Fuel} \tag{3}$$

$$SEC_{AMS(electric)} = \left(\dot{W}_{Generator} + \dot{E}x_{Bleed} + \dot{E}x_{Fan\_Air}\right) / \dot{E}x_{Fuel} \tag{4}$$

Equations (3) and (4) require the knowledge of fuel mass flowrate consumption that is obtained from the engine performance numerical tool.

A common performance index used in the aeronautical industry is the specific fuel consumption (SFC). This index is a measure of fuel consumption to provide a given power for a given period (fuel burnt per thrust), usually used for gas turbines with a mechanical shaft output (i.e. turboprops and turboshafts). The term is used to describe turbine efficiency; therefore, a lower number indicates better efficiency.

The normalization of fuel consumption rate, exergy efficiency, specific exergy consumption and specific fuel consumption are performed as:

$$\Delta F_{fuel,norm} = \left(F_{fuel,electric} - F_{fuel,conventional}\right) / F_{fuel,conventional} \tag{5}$$

where F is the generic function to be analyzed, i.e., it can be fuel consumption rate, $\eta_{Ex,AMS}$ , SEC or SFC.

In order to compare both architectures in a thermoeconomic basis, it is important to evaluate the exergy destroyed, defined as:

$$\begin{aligned}&\dot{E}x_{Dest,AMS(convetional)} = \\ &\quad \dot{E}x_{Bleed} + \dot{E}x_{Fan\_Air} - \left(\dot{E}x_{WAI\_Air(inlet)} + \dot{E}x_{SAI\_Air(inlet)} + \dot{E}x_{EAI\_Air(inlet)} + \dot{E}x_{ECU\_Air(inlet)}\right)\end{aligned} \tag{6}$$

$$\begin{aligned}&\dot{E}x_{Dest,AMS(electric)} = \\ &\quad \dot{E}x_{Bleed} + \dot{E}x_{Fan\_Air} + \dot{W}_{Generator} + \dot{E}x_{RAM\_Air} - \left(\dot{W}_{WAI} + \dot{W}_{SAI} + \dot{E}x_{ECU\_Air(inlet)} + \dot{E}x_{EAI\_Air(inlet)}\right)\end{aligned} \tag{7}$$

The exergy destruction is related to the ineficiencies that are inherent to each architecture. The cost associated with the exergy destruction in a process is a 'hidden' cost, but a very important one, that can be revealed only through a thermoeconomic analysis. The cost flow rate associated with the exergy destruction in a given component can be represented either by the cost of the additional fuel that needs to be supplied to this component to cover the exergy destruction and generate the same exergy flow rate of the product, or by the monetary flow rate lost at the product side because of the exergy destruction. In practical applications, the use of the fuel cost is more common (Tsatsaronis, 1993).

In this way, the cost evaluation of thermodynamic losses (exergy destroyed cost) is given by the exergy-based cost of aircraft fuel times the exergy destroyed in each flight phase:

$$\dot{C}_{Ex(Dest)} = c_{Ex(fuel)} \cdot \dot{E}x_{Dest} \tag{8}$$

Besides thermodynamic losses (which will have an influence on fuel consumption), a complete thermoeconomic analysis should consider other operational costs like maintenance, equipment, flight crew, etc. The analysis presented here aims at the evaluation of the exergy destruction cost only.

## 5. RESULTS

Tables 2 and 3 present the input and output exergy flow rates for both architectures, based on the control volumes shown in Figs. 1 and 2. It was considered that during the climbing phase the anti-ice system is always on. Such hypothesis is conservative and a simplification of the real operation of the system.

For the conventional architecture, the bleed exergy requirements were calculated at the engine bleed ports (high pressure port when anti-ice is ON and low pressure port when anti-ice is OFF) – Fig. 1. Furthermore, the inlet air requirements for ECU, wing anti-ice and stabilizer anti-ice were also evaluated. In this case, it is important to evaluate the engine fan air exergy, which cools the bleed air in order to meet the requirements of the consumers.

Table 2. Engine bleed port exergy and inlet exergy requirements for conventional architecture (results shown in kW for one pack, half wing, half stabilizer, one engine).

| | AMS INPUT | | AMS OUTPUT | | | |
|---|---|---|---|---|---|---|
| **Flight Phase** | **Bleed** | **Fan Air** | **ECU (inlet)** | **Engine AI (inlet)** | **Wing AI (inlet)** | **Stab AI (inlet)** |
| Climbing | 459.70 | 272.30 | 97.97 | 34.06 | 128.40 | 71.56 |
| Cruise | 76.47 | 155.20 | 62.96 | 0 | 0.00 | 0.00 |

For the 'more electric' architecture, it was considered the bleed air requirements for the engine anti-ice system calculated at the engine bleed ports, the electricity generated to attend the ECU compressor, and electric anti-ice systems (wing and stabilizer). Also, in this case it is necessary to evaluate the RAM air exergy, which is the exergy of external air flow that is compressed in the electric compressor and sent to the ECU. The electrical demand for the anti-ice systems were calculated based on available data from a supplier of anti-ice systems, the protected area was calculated according to the best practice recommended by the aeronautical industry.

Table 3. Exergy requirements for MEA architecture (results show in kW for one pack, half wing, half stabilizer, one engine).

| **Flight Phase** | **AMS INPUT** | | | | **AMS OUTPUT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Bleed** | **Fan Air** | $\mathbf{W_{Generator}}$ | **RAM Air** | **ECU (inlet)** | **Engine AI (inlet)** | $\mathbf{W_{Wing\ AI}}$ | $\mathbf{W_{Stab\ AI}}$ |
| Climb | 48.75 | 0 | 65.80 | 52.61 | 83.82 | 34.06 | 21.80 | 7.10 |
| Cruise | 0 | 0 | 33.30 | 38.19 | 60.88 | 0 | 0.00 | 0.00 |

It is interesting to notice a considerable decrease in exergy consumption of the electric anti-ice systems. The reason is that the conventional architecture uses excess of hot bleed air, by forcing the air to the internal leading edge area. In such systems, the air mass flow rate is usually controlled either by altitude or by airfoil skin temperature. This may cause the system to provide more enthalpy than required to prevent significative ice accretion in critical areas. On the other hand, the 'more electric' anti-ice system optimizes the power requirement because it does not heat all panels at the same time and applies the electrical power to remove cyclically the ice. There is also an exergy decrease in the requirements of the more electric architecture ECU, since in this case the cabin compressor can operate more efficiently and attend the ECU requirements more effectively.

Table 4 presents the values of the exergy efficiencies and specific exergy consumption, calculated according to Eqs. (1)-(4).

Table 4. Bleed exergy efficiency and specific exergy consumption (%).

| | **Conventional** | | **MEA** | |
|---|---|---|---|---|
| **Flight Phase** | $\boldsymbol{\eta_{AMS}}$ | **SEC** | $\boldsymbol{\eta_{AMS}}$ | **SEC** |
| climbing | 45.36 | 5.99 | 88.45 | 0.95 |
| cruise | 27.18 | 3.61 | 68.14 | 0.52 |

It is interesting to note that for both architectures, the climbing phase is more efficient than cruise, although the impact on the consumption of fuel is higher during climbing.

During cruise, when only the ECU is ON, the MEA architecture is more efficient and has a lower impact on the exergy consumption, in accordance to Pellegrini et al (2007).

More energy efficient systems reflect in lower fuel consumption, as shown in Tab. 5. Climbing is the flight phase that improvements are more evident, also because it was considered anti-ice ON in this phase. This can be significant during winter in regions that icing conditions are frequently forecasted, for example North America and Europe which represent about 59% of the new airplane deliveries in the next 20 years (Boeing, 2006).

Table 5. Electric architecture improvement results (%).

| | **Consumption Relative Difference** | | | |
|---|---|---|---|---|
| **Flight Phase** | **ΔFuel** | **ΔSFC** | $\boldsymbol{\Delta\eta_{AMS}}$ | **ΔSEC** |
| climbing | -8.16 | -7.73 | 95.00 | -84.16 |
| cruise | -0.82 | -4.22 | 150.70 | -85.51 |

The ΔSEC parameter indicates a better use of exergy, as it shows great improvements for the MEA (Tab. 5). To complement this statement, the exergy destroyed (shown in Tab. 6) also evidences the MEA more efficient systems. In this case the exergy destroyed is significantly lower, basically because the bleed waste is much smaller in this configuration.

In addition, it is interesting to note that exergy destroyed rate during climbing phase, for the conventional architecture, is almost 140% higher than during cruise phase. Such difference is much lower for the MEA architecture.

The values presented in Tab. 6 show the great impact on exergy destroyed rate of the conventional anti-ice system. Regarding the MEA architecture, the compressor is the main source of exergy destruction in the AMS system.

Table 6. Comparison between conventional and MEA exergy destroyed rates (kW).

| | Exergy Destroyed Rate | |
|---|---|---|
| Flight Phase | Conventional | MEA |
| climb | 400.01 | 12.30 |
| cruise | 168.71 | 10.61 |

The calculated exergy of the kerosene type jet fuel is 45,673 kJ/kg (Szargut et al, 1988). By supposing that the Jet-A fuel price is US$5.00/gallon (US$ 1.32/L or, with average density, US$ 1.65/kg) and the exergy-based cost of Jet-A fuel is US$ 3.62e-5/kJ, Tab. 7 indicates the costs of exergy destruction by operation hour.

Table 7. Costs associated to exergy losses (US$/h).

| | Exergy Destroyed Costs | |
|---|---|---|
| Flight Phase | Conventional | MEA |
| climbing | 52.13 | 1.60 |
| cruise | 21.99 | 1.38 |

It is considered a mission with 15 minutes climbing and 40 minutes cruise, without descent and holding, and considering anti-ice on during climbing. The cost of exergy destroyed, calculated based on time values shown before, is US$ 27.69 for the conventional airplane, and US$ 1.32 for the MEA. This indicates that the MEA saves US$ 26.37 per mission due to fewer thermodynamic losses. This number should be higher if one considers the complete mission profile. This may represent US$ 21,096.00 in savings in a year per aircraft, while operating eight flight legs a day, twenty five days a month and four months a year with anti-ice on (winter time).

The total economic savings per aircraft, related to fuel consumption decrease, represent US$ 29,576.00, calculated with the same considerations made above.

## 6. CONCLUSIONS

Exergy analysis may bring different aspects of aircraft design into a common basis. However, some of these must be further studied in order to understand how they could be addressed in the analysis. Still, the indexes based on exergy do show the location of the main sources of irreversibilities, allowing a comparison of the increase/decrease of them because of a change in the architecture of the system. The combined use of aeronautical traditional indexes (such as fuel burnt, SFC and take off weight) and exergy-based ones proved to be more interesting since it provides more information regarding the whole system. Such integrated analysis allows the comparison of different architectures, helps the engineer to find the equipment to be optimized in the plant, and provides understanding on how much the system is important for the aircraft and compared to other systems. Again, future works must study ways to address non-exergy related aspects into the exergy analysis framework.

The case study presented allowed a validation of the conclusions above. The results showed a better use of the exergy supplied to the ECU, wing and stabilizer anti-ice systems in the 'more-electric' architecture. Even with the simplification assumed in this present case study (same drag for both architectures), the fuel burnt rate and SFC index presented reduction. In addition, there is a significant reduction in exergy consumption of the wing and stabilizer anti-ice systems, which led to almost 8% fuel reduction impact in engine performance.

In spite of adding a source of irreversibility (electric motor and air compressor), the electric architecture reduces the exergy destroyed since there is no precooler and bleed valves, which causes exergy destruction and are located upstream the environmental control unit. The electric anti-ice systems present significant lower exergy destruction; however, the anti-ice systems remain OFF the majority of the flights. These results may indicate that the new generation of engine, which is adopted in more or all-electric aircrafts, must have additional net gain on fuel consumption by providing only shaft power and not bleeding air, this one is proved by the results obtained to be more penalizing the engine. Moreover, due to high exergy destruction rate inherent to current jet propulsion systems, the engine performance gains may not be sufficient to reach significant fuel consumption reduction values. Therefore, an integrated exergy analysis for all or more electric aircraft must consider the effects of the new generation of engines and its new user systems plus weight decrease due to new materials, structure optimization and breakthrough electric system architecture as well as less drag due to improved aerodynamics.

Regarding the exergy destroyed cost, results indicate that the 'more electric' architecture has a better performance compared to the conventional one. Furthermore, considering the impact of the change of the AMS architecture, it represents 71% of the total economic savings from the reduction of the fuel consumption.

A complete thermoeconomic analysis must be performed, in order to validate the results presented. Also, such analysis will indicate if the optimization procedure should be made in order to reduce the exergy destroyed rate (cost related to fuel consumption) or on the use of different equipment (related to capital cost).

## 7. ACKNOWLEDGEMENTS

L. F. Pellegrini and S. Oliveira Jr wish to acknowledge Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional de Pesquisa (CNPq) for the financial support received (grants 03/12094-8 and 301115/2006-0, respectively). R. Gandolfi and G. A. L. da Silva would like to thank the Environmental Systems Manager, Roberto Petrucci for the opportunity.

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