

Exergy Analysis Applied to a Complete Flight Mission of a Commercial Aircraft

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The aeronautical industry has evolved to design extremely complex aircraft, with highly integrated systems. Commonly used methods to design and later optimize are based on trade-off studies, which are faulty in evaluating new systems, as they present lack of information. Previous works have shown the applicability of exergy analysis as a decision making tool to aircraft systems design and optimization. Besides locating and quantifying the sources of entropy generation, exergy analysis can relate these irreversibilities with fuel consumption, and thus with operational cost of a mission. Following the methodology developed in recent works, this paper presents an exergy analysis of a complete flight mission of a conventional commercial aircraft. Such analysis allows the evaluation of exergy efficiency and exergy destroyed rate for the whole flight, as well as for each one of the flight phases (climbing, cruise, descent, holding and landing).

Nomenclature

EX_{Fuel}	= total fuel exergy consumed, kJ
$EX_{inlet, air}$	= total inlet air exergy, kJ
$EX_{dest, mission}$	= total destroyed exergy during the mission, kJ
$\dot{EX}_{Fuel}$	= fuel exergy flow rate, kW
$\dot{EX}_{Air}$	= exergy flow rate of the air at the inlet of the engine, kW
$\dot{EX}_{Gases}$	= exergy flow rate of the gases leaving the engine, kW
$\dot{EX}_{Thrust}$	= exergy rate associated to engine thrust, kW
$\dot{EX}_{Bleed}$	= exergy flow rate of extracted bleed air from the engine, kW
$\dot{EX}_{Fan, Air}$	= exergy flow rate of extracted fan air from the engine, kW
$\dot{EX}_{Fan, Air, out}$	= outlet exergy flow rate of extracted fan air from the engine, kW
$\dot{EX}_{Anti-Ice, inlet}$	= exergy flow rate of anti-ice air at the inlet of the system, kW
$\dot{EX}_{Anti-Ice, outlet}$	= outlet exergy flow rate of anti-ice air at the inlet of the system, kW
$\dot{EX}_{Q, Leading_Edge}$	= exergy rate related to leading edge heat transfer of anti-ice system, kW
$\dot{EX}_{ECU, Inlet}$	= exergy flow rate of the high pressure air at the inlet of the ECU, kW

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$\dot{E}x_{ECU,Outlet}$	= exergy flow rate of the outlet ECU air, kW
$\dot{E}x_{HX,Air,in}$	= exergy flow rate of the inlet ram air of the ECU heat exchanger, kW
$\dot{E}x_{HX,Air,out}$	= exergy flow rate of the outlet ram air of the ECU heat exchanger, kW
$\dot{E}x_{Q,Heat_Transfer}$	= exergy rate related to cabin heat transfer, kW
$\dot{E}x_{Cabin,Air,out}$	= exergy flow rate of the outlet cabin air, kW
$\dot{E}x_{Dest,Engine}$	= destroyed exergy rate in the engine, kW
$\dot{E}x_{Dest,Bleed}$	= destroyed exergy rate in the bleed system, kW
$\dot{E}x_{Dest,Anti-Ice}$	= destroyed exergy rate in the anti-ice system, kW
$\dot{E}x_{Dest,ECU}$	= destroyed exergy rate in the environmental control unit, kW
$\dot{E}x_{Dest,Cabin}$	= destroyed exergy rate in the cabin, kW
$\dot{E}x_{Dest,ElectricSystem}$	= destroyed exergy rate in the electric system, kW
$\dot{W}_{Electric}$	= mechanical power extracted from engine to electric system, kW
$\dot{W}_{Mec_Hydraulic}$	= mechanical power extracted from engine to hydraulic system, kW
$\dot{W}_{Hydraulic}$	= electric power consumed by hydraulic system, kW
$\dot{W}_{Bleed}$	= electric power consumed by bleed system, kW
$\dot{W}_{ECU}$	= electric power consumed by ECU, kW
$\dot{W}_{cabin}$	= electric power consumed by cabin, kW
$\dot{W}_{Anti-Ice}$	= electric power consumed by anti-ice system, kW
$\eta_{Ex,Engine}$	= exergy efficiency of the engine
$\eta_{Ex,Bleed}$	= exergy efficiency of the bleed system
$\eta_{Ex,ECU}$	= exergy efficiency of the ECU
$\eta_{Ex,Anti-Ice}$	= exergy efficiency of anti-ice system
$\eta_{Ex,Cabin}$	= exergy efficiency of cabin
$\eta_{Ex,Mission}$	= mission exergy efficiency
SEC_{Bleed}	= specific exergy consumption by the bleed system
SEC_{ECU}	= specific exergy consumption by the environmental control unit
$SEC_{Anti-Ice}$	= specific exergy consumption by the anti-ice system
$SEC_{Electric}$	= specific exergy consumption by the electric system
$SEC_{Hydraulic}$	= specific exergy consumption by the hydraulic system
SEC_{Cabin}	= specific exergy consumption by the cabin

I. Introduction

It has been long discussed that, in order to design and optimize aircraft in a complete integrated way, commonly used trade-off studies should be used together with other methods to enhance the analysis. Also, it is agreed that there must be a common basis to compare different alternatives in aircraft design, especially when developing new systems. Thus, the use of exergy analysis might provide new information in which a comparative study could rely on, since trade-off studies are faulty in evaluating new systems, as they present lack of information¹⁻⁴.

Besides locating and quantifying the sources of entropy generation, exergy analysis can relate these irreversibilities with fuel consumption, and thus with operational cost of a mission. Exergy analysis does not indicate directly the system alteration required to minimize these irreversibilities³. However, it does provide a methodology to rank the systems or equipment that contribute to operational thermodynamic inefficiencies. This evaluation may define optimization-priorities among systems and direct investment to where solutions will be more cost-effective or exergy-efficient.

The authors have proposed the exergy analysis as a decision making tool to aircraft air management systems design^{5,6}.

A first approach to the use of exergy analysis was developed to compare two different architectures for the environmental control system (ECS) of a commercial aircraft. The goal was to evaluate the impact of using a 'more-electric' architecture in the destroyed exergy rate of the ECS⁵.

Following that work, the same methodology was applied to the Air Management System (AMS), considering the anti-ice and ECS systems. Different system weights (conventional and more electric architectures) were considered. Flight mechanics coupled with an engine numerical simulation tool (thrust, aircraft speed and associated fuel consumption) was used. Thus, it was possible to quantify the economic gain (as fuel consumption decrease) for a 'more-electric' architecture, and also show that a great part of that gain is a result of the decrease in the destroyed exergy rate of the AMS⁶.

II. Objective

The objective of the present paper is to evaluate a complete flight mission of a conventional commercial aircraft, using same methodologies used in previous works. Such analysis allows the evaluation of exergy efficiency, destroyed exergy rates and the distribution of irreversibilities among the systems, as well as performance indexes that will be defined. Hence, the aircraft system is divided into 8 sub-systems: Airframe, Engine, Bleed System, Electric System, Hydraulic & FC Systems, Anti-ice, Environmental Control Unity (ECU) and Cabin. Figure 1 shows the exergy flows in and out of each of the sub-systems listed. Exergy flows in blue represent useful exergy flows, while those in red stand for exergy destruction or losses.

The methodology proposed in this paper allows one to evaluate how the fuel exergy is

consumed by each of the sub-systems, and also to quantify their thermodynamic losses. The definition of a mission exergy efficiency that accounts the ratio of useful exergy to the input of exergy (inlet air and fuel) may provide an adequate comparison between different architectures or designs for the same flight mission. The distribution of irreversibilities among systems and/or flight phases makes it possible to assess the major sources of thermodynamic losses. Such information is valuable when considering a future optimization methodology application to aircraft design process.

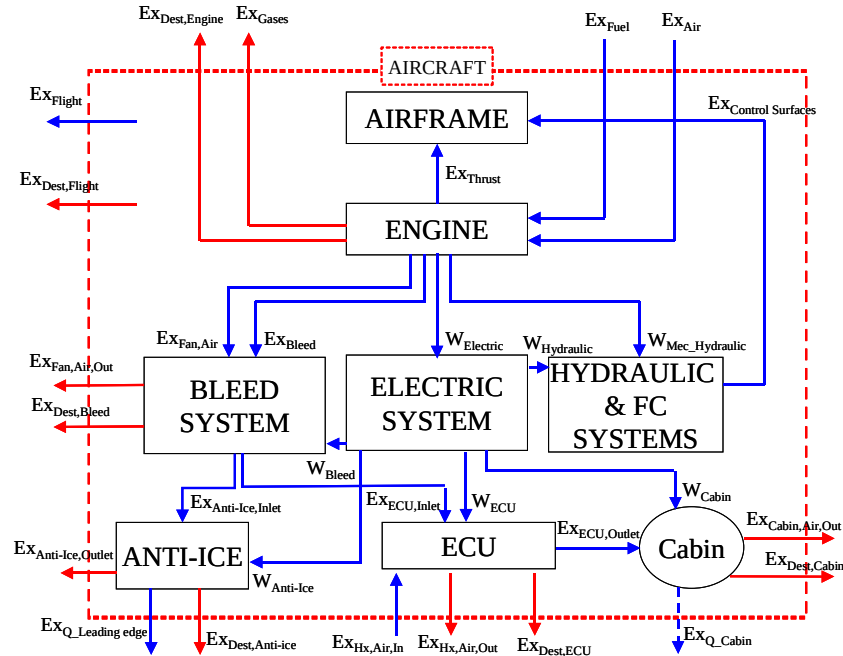


Figure 1. Demand and Penalties Imposed by Aircraft Systems to Engine and Airframe.

III. 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 the configuration, it consists of a 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 altitude, 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 systems to aircraft. Basically, it is necessary to evaluate the flight mechanics coupled with an engine numerical simulation tool to find the thrust, aircraft speed and associated fuel consumption.

Hence, the GSP software (*Gas Turbine Simulation Program*)⁷, developed by the National Aerospace Laboratory in the Netherlands^{**}, was used to evaluate fuel consumption, thrust and inlet air, bleed, fan air and outlet gases thermodynamic characteristics. Also, the power that is required to run the hydraulic pumps and a generator responsible for the electricity necessary in the electronic systems was evaluated and used as input of the engine simulation tool. Figure 2 shows the schematic of the turbofan engine modeled in the GSP.

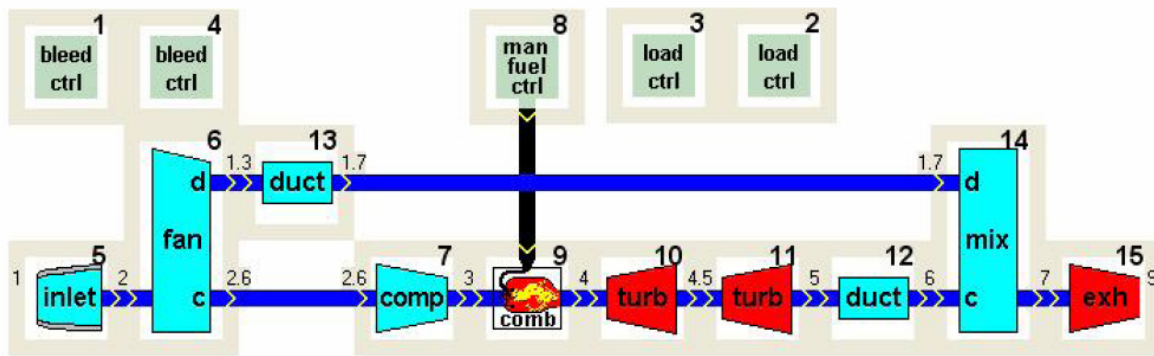


Figure 2. GSP model of the turbofan engine.

IV. Air Management System

The air management system (AMS) for a commercial aircraft is 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).

The pneumatic system must control temperature and pressure provided to its users as well as maintain safe operational conditions. In some aircrafts and engines, pneumatic system is also required to select engine bleed air port.

The aircraft air conditioning system may be composed of one or more machines, which usually are vapor or air cycles (reverse Brayton cycle). In the case of air cycle, 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.

The anti-ice system prevents the ice accretion on airfoils and continuously works while the aircraft flies in icing condition. Most commercial aircraft have 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. In order to estimate the engine bleed air exergy rate demand, it is required to use experimental data or a mathematical model to predict ice protection operational parameters. This type of thermal anti-ice model has been developed by Silva, Silveiras and Zerbini^{8,9}. 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.

In this paper the air management system is decomposed into 4 sub-systems (Fig. 1):

^{**} <http://www.gspteam.com>.

- i. Bleed system – responsible for extracting hot air and fan air from the engine, and adjusting pressure and temperature before delivering to the consumers (anti-ice and ECU).
- ii. ECU – provides cooling and heating for flight deck and cabin
- iii. Anti-ice - prevents the ice accretion on airfoils
- iv. Cabin – provides filtered air recirculation, conditioned air supply for gaspers, cooling air for avionics and emergency ram air ventilation for flight deck smoke clearance

V. Other Systems

The hydraulic power of an aircraft is supplied by two independent systems which provide constant pressure and variable flow according to services demand. Hydraulic power system provides rudder, aileron, elevator, spoilers, landing gear, brakes, nose wheel steering, thrust reverser actuators with power extracted from the engine. Also, auxiliary systems are powered by this system. Usually, the hydraulic power is generated by engine driven hydraulic pumps, which are connected to independent hydraulic system. The system is also composed of reservoir, level indicators, thermal and pressure switches, filters, valves and lines.

In case of engine driven pump failure, electric motor driven pumps provide supply to hydraulic system. Usually, main engine pumps have electric pumps as a backup. In this work, only normal operation hydraulic loads were considered.

The electrical system is able to furnish the required power to each load circuit in the aircraft. The aircraft electric energy is generated by generators connected to the aircraft engines and also to the APU (Auxiliary Power Unit). Usually, the generators are brushless and controlled by dedicated control units. The engine generators are connected to segregated bus. The APU generator, when operative, is normally connected in parallel to the engine generators. Electrical buses distribute the electric load to the several systems.

The electrical system is designed to operate under normal and under failure conditions in order to provide the electrical load necessary for each flight situation. An electrical load analysis is performed to evaluate the amount of load of all electrical equipment required to operate under normal and failure conditions. Therefore, the electrical system is responsible for managing electric loads according to flight phases and aircraft failure conditions. Also, in this work, only normal operation electrical loads were considered.

VI. Modeling and Simulation

Figure 3 presents the flight mission profile considered in the present paper. The case study considers operational points during climbing, cruise, descent, holding and landing. The operational parameters used in the analysis are shown in Table 1. As a complement, the study also considers anti-ice on, however, only on specific phases that are susceptible of ice formation as shown in Table 2.

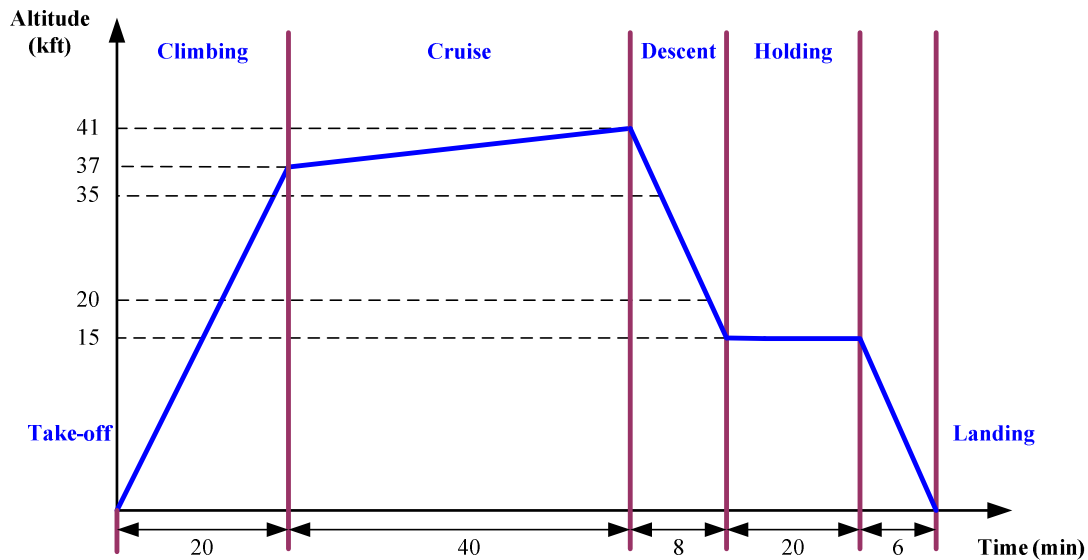


Figure 3. Flight Mission Profile

Table 1. Input data (anti-ice OFF).

Flight Phase	Altitude (kft)	Outside Air Temperature (°C)	Mach	Time Duration Between Phases (min.)
1- Run & Take-off	0	15.0	0.20	2.0
2- Climb	20	-24.6	0.57	10.0
3- Climb	35	-54.3	0.66	7.5
4- Cruise	37	-56.5	0.77	1.0
5- Cruise	41	-56.5	0.77	40.0
6- Descent	35	-54.3	0.77	2.4
7- Descent	20	-24.6	0.62	6.0
8- Holding	15	-14.7	0.40	20.0
9- Approach & Landing	0	15.0	0.20	6.0

Table 2. Input data (anti-ice ON).

Flight Phase	Altitude (kft)	Outside Air Temperature (°C)	Mach	Time Duration Between Phases (min.)
1- Run & Take-off	0	15.0	0.20	2.0
2- Climb	20	-24.6	0.57	10.0
3- Climb	35	-54.3	0.66	7.5
4- Cruise	37	-56.5	0.77	1.0
5- Cruise	41	-56.5	0.77	40.0
6- Descent	35	-54.3	0.77	2.4
7- Descent	20	-24.6	0.62	6.0
8- Holding	15	-14.7	0.40	20.0
9- Approach & Landing	0	15.0	0.20	6.0

In order to develop an exergy analysis of the complete mission, the destroyed exergy rate, the exergy efficiency of each system and the specific exergy consumption (SEC)^{5,6} were calculated, using the equations that are now presented.

The exergy destruction is related to the inefficiencies that are inherent to each system. The exergy losses are associated to exergy flows that leave the system without any further use (for instance, exhaust gases from a powerplant). In aircraft systems, the exergy losses might be related to the thermal exergy of the gases leaving the engine, RAM air leaving the heat exchanger of the ECU and Fan air after the pre-cooler. Since these flows are no longer used they will be considered in this paper as a source of destruction of exergy. Thus, with the products of each system known, as well as its exergy inputs, the destroyed exergy rate may be calculated by:

$$\dot{E}x_{Dest,Engine} = \dot{E}x_{Fuel} + \dot{E}x_{Air} - (\dot{E}x_{Thrust} + \dot{E}x_{Bleed} + \dot{E}x_{Fan,Air} + \dot{W}_{Electric} + \dot{W}_{Mec_Hydraulic}) \quad (1)$$

$$\dot{E}x_{Dest,Bleed} = \dot{E}x_{Bleed} + \dot{E}x_{Fan,Air} + \dot{W}_{Bleed} - (\dot{E}x_{Anti-Ice,Inlet} + \dot{E}x_{ECU,Inlet}) \quad (2)$$

$$\dot{E}x_{Dest,ECU} = \dot{E}x_{ECU,inlet} + \dot{E}x_{HX,Air,in} + \dot{W}_{ECU} - (\dot{E}x_{ECU,outlet}) \quad (3)$$

$$\dot{E}x_{Dest,Anti-Ice} = \dot{E}x_{Anti-Ice,Inlet} + \dot{W}_{anti-ice} - (\dot{E}x_{Q,Leading_Edge}) \quad (4)$$

$$\dot{E}x_{Dest,Cabin} = \dot{E}x_{ECU,Outlet} + \dot{W}_{Cabin} - (\dot{E}x_{Q,Heat_Transfer}) \quad (5)$$

$$\dot{E}x_{Dest,Electric\,System} = \dot{W}_{Electric} - (\dot{W}_{Bleed} + \dot{W}_{ECU} + \dot{W}_{Cabin} + \dot{W}_{Hydraulic} + \dot{W}_{Anti-Ice}) \quad (6)$$

The exergy efficiency of a system can be defined as the ratio between the exergy of the net effect in the system to the exergy consumed in it¹⁰. The relations used for the calculation of the exergy efficiency of a system

must agree with the assumptions made for the evaluation of the destroyed exergy rate. The exergy efficiencies of the systems considered in the analysis are:

$$\eta_{Ex,Engine} = \left(\frac{\dot{Ex}_{Bleed} + \dot{Ex}_{Fan,Air} + \dot{W}_{Electric} + \dot{W}_{Mec_Hydraulic} + \dot{Ex}_{Thrust}}{\dot{Ex}_{Fuel} + \dot{Ex}_{Air}} \right) \quad (7)$$

$$\eta_{Ex,Bleed} = \left(\frac{\dot{Ex}_{ECU,Inlet} + \dot{Ex}_{Anti-Ice,Inlet}}{\dot{Ex}_{Bleed} + \dot{Ex}_{Fan,Air,in} + \dot{W}_{Bleed}} \right) \quad (8)$$

$$\eta_{Ex,ECU} = \left(\frac{\dot{Ex}_{ECU,Outlet}}{\dot{Ex}_{ECU,Inlet} + \dot{Ex}_{HX,Air,in} + \dot{W}_{ECU}} \right) \quad (9)$$

$$\eta_{Ex,Anti-Ice} = \left(\frac{\dot{Ex}_{Q,Leading_Edge}}{\dot{Ex}_{Anti-Ice,inlet} + \dot{W}_{Anti-Ice}} \right) \quad (10)$$

$$\eta_{Ex,Cabin} = \left(\frac{\dot{Ex}_{Q,Heat_Transfer}}{\dot{Ex}_{ECU,Outlet} + \dot{W}_{Cabin}} \right) \quad (11)$$

The exergy efficiency of electric and hydraulic systems were not considered in the analysis, since these are responsible mainly for supplying power to other systems, with no energy conversion process involved. However, electric and hydraulic powers extracted from the engine were evaluated. It was also considered in the analysis the exergy flows related to electric energy that each system requires for functioning and control (not shown in Fig. 1).

In addition, it is interesting to know how much exergy from the aircraft fuel (burnt in the engine) is consumed by the systems, 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 will lead to a not so important decrease in aircraft fuel consumption^{5,6}. This index, named specific exergy consumption (SEC), is given by:

$$SEC_{Bleed} = (\dot{Ex}_{Bleed} + \dot{Ex}_{Fan_Air} + \dot{W}_{Bleed}) / \dot{Ex}_{Fuel} \quad (12)$$

$$SEC_{ECU} = (\dot{Ex}_{ECU,Inlet} + \dot{W}_{ECU}) / \dot{Ex}_{Fuel} \quad (13)$$

$$SEC_{Anti-Ice} = (\dot{Ex}_{Anti-Ice,Inlet} + \dot{W}_{Anti-Ice}) / \dot{Ex}_{Fuel} \quad (14)$$

$$SEC_{Electric} = (\dot{W}_{Electric}) / \dot{Ex}_{Fuel} \quad (15)$$

$$SEC_{Hydraulic} = (\dot{W}_{Mec_Hydraulic} + \dot{W}_{Hydraulic}) / \dot{Ex}_{Fuel} \quad (16)$$

$$SEC_{Cabin} = (\dot{Ex}_{ECU,Outlet}) / \dot{Ex}_{Fuel} \quad (17)$$

With the destroyed exergy rates determined for each system in each flight phase, it is possible to estimate the total destroyed exergy of the mission, using the time duration of the phases specified in Tables 1 and 2.

$$Ex_{dest,mission} = \sum_{\substack{flight \\ phase}} \left(\sum_{system} \dot{Ex}_{dest,system} \right) \cdot \Delta t_{phase} \quad (18)$$

Since the exergy efficiency might be calculated using the destroyed exergy¹⁰, the exergy efficiency of the complete mission is defined as:

$$\eta_{mission} = 1 - \frac{Ex_{dest,mission}}{Ex_{fuel} + Ex_{inlet_{air}}} \quad (19)$$

The total exergy of the fuel and inlet air are calculated in the same way as the total destroyed exergy.

Based on the equations shown above, an exergy analysis of each flight phase was performed using the EES[®] software (*Engineering Equation Solver*)¹¹, with the following hypotheses:

- For each flight phase, the systems were simulated in a steady-state condition;
- All gas flows were considered as an ideal mixture of ideal gases;
- For the gas turbine, a turbofan model was developed in the GSP software based on operational data of a commercial aircraft, and the results were implemented in the EES[®] for the exergy analysis;
- The ECU was simulated using a model developed by the authors⁵;
- All heat transferred by the enthalpy difference between the inlet and out let anti-ice air is considered as the useful effect of the anti-ice system.
- The electric and hydraulic power needs were set according to operational data of a commercial aircraft;
- The reference state for the exergy calculations was set by the static outside air temperature and pressure for each flight phase.

V. Results

The results can be seen in Figs. 4 to 10. Figures 4 and 5 show the distribution of the irreversibilities among the systems for two flight phases (cruise and holding with anti-ice on). The engine is by far the higher source of irreversibilities, representing around 95% of the total aircraft exergy destruction during all phases. However, it is responsible for supplying the other systems with exergy from the fuel (bleed air and electric power). The main source of exergy destruction inside the engine is the combustion chamber, followed by the mixer and the lost exergy related to the exhaust gases. The bleed system accounts for 5 to 6% of the destroyed exergy. This system is responsible for the temperature and pressure regulations of the bleed air before going to the consumers. Hence, the bleed system is composed by pressure regulating valves and a pre-cooler, which are the main of the exergy destruction inside the system. The other systems represent less than 1% of the total irreversibilities.

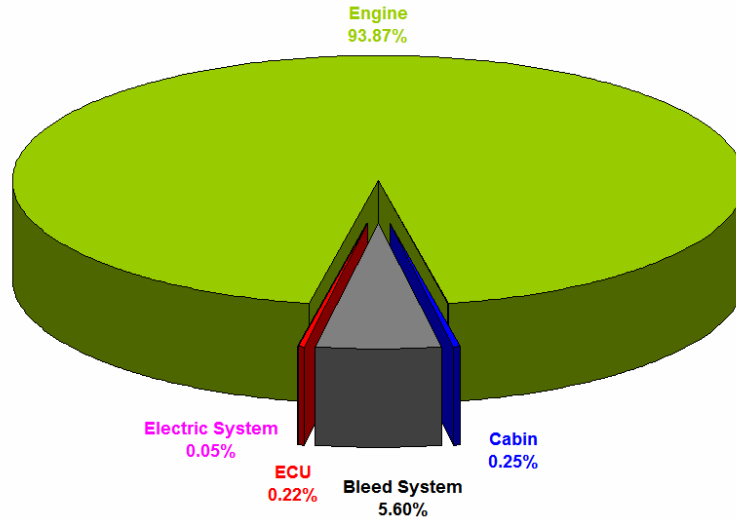


Figure 4. Distribution of Irreversibilities during Cruise@41 kft.

Figures 6 and 7 show the exergy efficiency during the mission with and without anti-ice, respectively. The exergy efficiency of the engine is higher during the cruise, meaning it is operating in a condition closer to its design point. Also, the ECU efficiency has its greatest values during cruise. Furthermore, this system is very

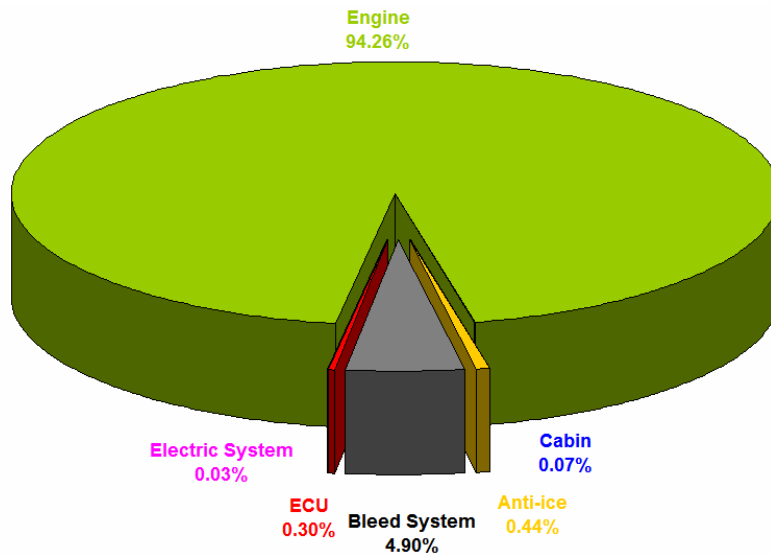


Figure 5. Distribution of Irreversibilities during Holding@15 kft (Anti Ice ON).

increases because of the higher temperature gradient between cabin and outside environments, despite the fact that at higher altitudes, skin heating is higher. Also, the mechanical and thermal exergy associated to the outlet cabin air are no longer used, hence are considered as destroyed exergy. These values are higher for higher altitudes.

Figures 6 and 7 indicate that the exergy efficiencies of the bleed system are higher for descent and approach phases, since in these phases the aircraft is slowing down (in idle, minimum PS3 or approach), hence the temperature and pressure of the air extracted by the bleed system are closer to those needed by the consumers. Thus, the destroyed exergy are lower.

The exergy efficiency of the anti-ice system is almost the same for the phases in which this system is turned on. This is a consequence that such system is not optimized for different icing conditions and flight altitudes. It is dimensioned for the most severe icing condition.

The SEC index is a value that indicates how much of the fuel exergy is consumed by the different systems. According to Fig. 8, the bleed system is the higher consumer of exergy, followed by the anti-ice system and ECU. Hence, measures to optimize the operation of the bleed system will have a greater impact on fuel consumption than an optimization of the other systems.

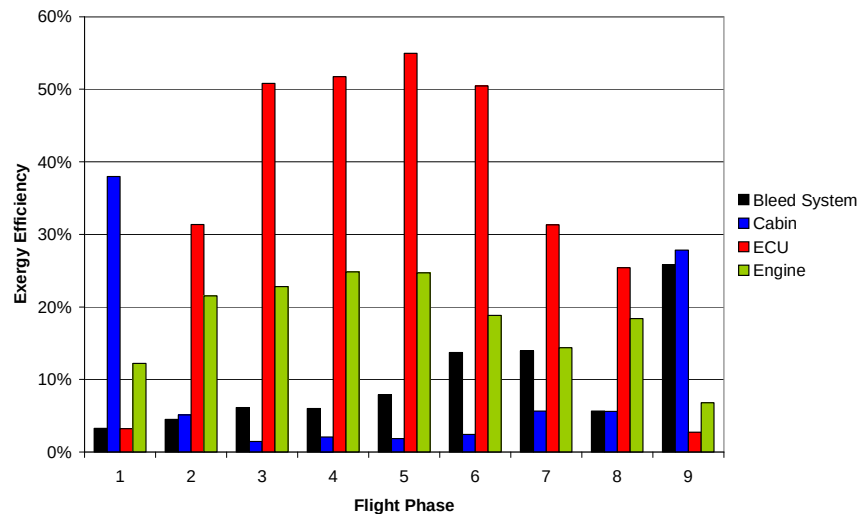


Figure 6. Exergy Efficiency (Anti Ice OFF).

efficient, reaching values greater than 50%. This high efficiency is a consequence of the lower temperature of the RAM air used in the heat exchanger in high altitudes. This analysis is in accordance to the results obtained by Conceição, Zaparoli and Turcio¹².

On the other hand, the exergy efficiency of the cabin has an opposite behavior to the ECU. The exergy destruction associated with the cabin increases during flight, which decreases the exergy efficiency. This is explained by the increase of the exergy associated to the heat transfer. At higher altitudes the heat transfer through the fuselage

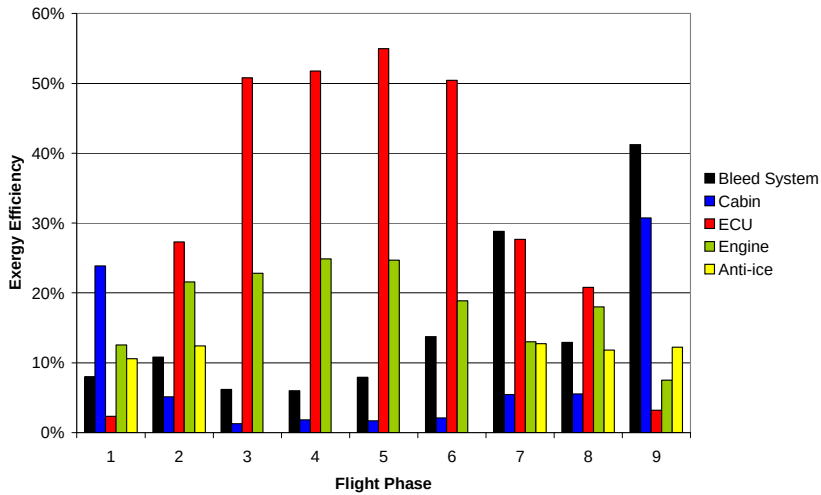


Figure 7. Exergy Efficiency (Anti Ice ON).

destroyed exergy rate basis. It is important to notice that the holding phase varies from mission to mission according to air traffic. Whenever it occurs, it imposes high rates of destroyed exergy to the flight mission.

Finally, the exergy efficiency of the mission was calculated for both situation, anti-ice off and on. For the first case, the value found was 12%, while for second one, 14%. The higher value for the second case results from the better efficiency of the bleed system whenever the anti-ice is on. However, such result should not lead to the wrong conclusion that the use of anti-ice improves the efficiency of the aircraft, since it increases the fuel consumption (see the SEC index for the anti-ice – Fig. 8) and has no useful effects during phases above 31 kft, representing only exergy losses.

VI. Conclusions

An exergy analysis of a commercial aircraft during a complete mission has been proposed. The results show that the engine is responsible for almost all exergy destruction and losses inside the aircraft. However, the engine is also responsible for providing the other sub-systems with exergy from the fuel, as specified by the SEC index.

The SEC index indicates that the bleed system is the greatest consumer of exergy after the engine, supplying exergy for the ECU and anti-ice systems. The exergy destruction inside this sub-system is mainly related to the cooling of the air extracted from the engine.

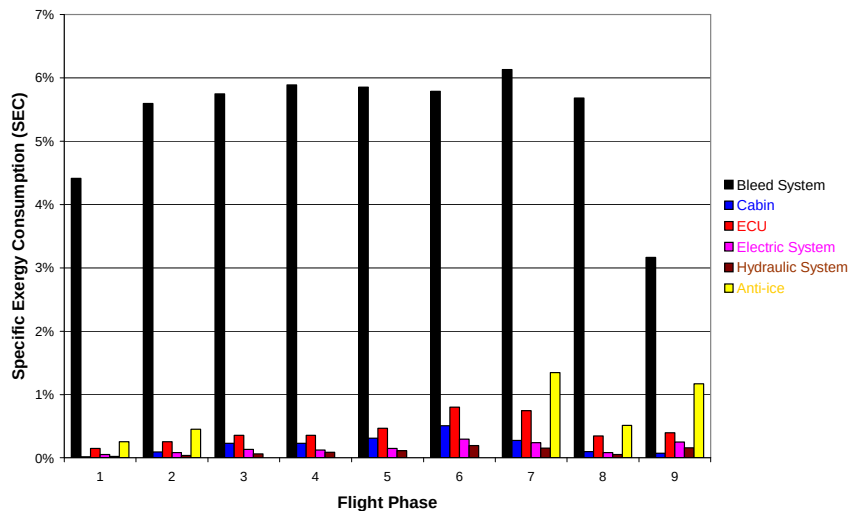


Figure 8. SEC (Anti Ice ON).

Figure 9 shows the distribution of irreversibilities among each flight phase, considering the use of anti-ice turned on. The cruise is responsible for the highest total irreversibility (33%). However, it is the longest phase (40 minutes), while climbing and holding are responsible for 24% and 29%, respectively, of the total irreversibilities with time duration of 20 minutes. Thus, this flight phase might be considered the most irreversible one, in a

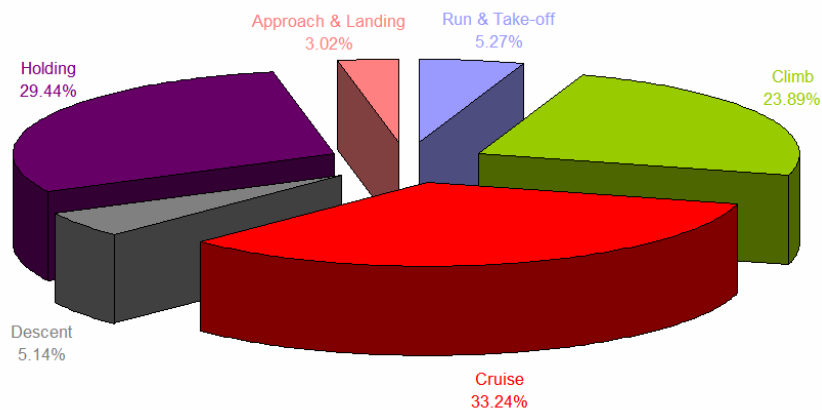


Figure 9. Distribution of Irreversibilities among flight phases (Anti Ice ON).

Furthermore, as discussed previously by the authors⁵, the main source of irreversibilities inside the ECU is the control valve and pre-cooler needed to adjust the bleed air before going into the ECU machine. The use of an electric compressor reduces by more than 90% the irreversibilities in the valve and pre-cooler, optimizing the performance of the ECU.

The anti-ice system represents 0.44% of the total irreversibilities, the third greatest source of them inside the aircraft. The use of electric anti-ice system also reduces the exergy destruction and losses, since the operation of the anti-ice system is optimized through the use of electric panels. 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. In contrast, when bleed air is used, it is sent continuously to the anti-ice system.

Considering the complete mission, the cruise, climbing and holding phases represent 76% of the total losses for the mission. Since the holding phase varies according to air traffic, it should be minimized as much as possible, since it imposes high destroyed exergy rates.

An integral analysis was performed, and the exergy efficiency of the mission was defined. For a complete mission without the use of the anti-ice system, the exergy efficiency was 12%. With the anti-ice on, the value decreases to 14%. However, the simple use of one exergy index might lead to wrong conclusions, since there is no sense in using anti-ice system for altitudes higher than 31 kft, what would lead to an increase in fuel consumption without adding a useful effect.

The exergy efficiency of a complete mission might provide a fair comparison among competitive designs for aircrafts, and also the exergy destruction and losses distribution allows one to identify correctly the impact of each sub-system on the performance of the aircraft during the mission.

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