



**Politecnico
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Master of Science in Aerospace Engineering

Master of Science Thesis

Impact of Fuel Cell Integration on the Architecture and Weight of a Bleedless Environmental Control System, with Analysis of Fuel Cell Hydrogen and Air Consumption

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*Aviation is now entering its fourth major revolution.
The first revolution made planes fly,
the second focused on safety and
the third democratized air travel, making it accessible globally.
Today, the fourth revolution centres on sustainability,
representing a fundamental change in how the aerospace industry operates.*

— Greg Ombach,
Head of Disruptive Research & Technology, Senior Vice President at Airbus.
Forbes Tech Council, September 2024

”Sustainable Aviation: Navigating The Fourth Revolution In Aerospace”

Abstract

The growing attention to the reduction of climate-altering emissions in the aeronautical sector is driving research towards hydrogen fuel cells for the generation of electrical power on board aircraft. The incorporation of Fuel Cell systems requires a dedicated thermal management system to dissipate the heat generated during operation, and the possibility of integrating the Thermal Management System (TMS) with the Environmental Control System (ECS) of the aircraft represents a promising design opportunity. At the same time, the transition towards More-Electric Aircraft (MEA) architectures and electric propulsion is driving the adoption of bleedless ECS configurations, which eliminate the extraction of air from multiple stages of the engine compressor (bleed air), replacing it with external air compressed by a dedicated electric compressor for cabin conditioning. Although the ECS and the Proton Exchange Membrane Fuel Cell (PEMFC) have been extensively studied and characterised separately in the literature, a system-level model capable of evaluating their integration in terms of mass, aerodynamic drag, and hydrogen consumption along a realistic mission profile is still lacking. In this work, a modular framework of a bleedless ECS (featuring a Three-Wheel Air Cycle Machine configuration) and a black box model of a PEMFC are developed, implemented within the OpenMDAO framework. The ECS model is validated against literature data from an Airbus A320, achieving a mean error of less than 1% for temperatures and 3.11% for pressures. The two models are integrated according to three distinct architectural configurations: air bypass after the electric compressor, a dedicated compressor for the Fuel Cell, and a dedicated compressor featuring hydrogen-based ECS air cooling. The three configurations are applied to a reference aircraft comparable to a Bombardier Challenger 300. The total mass of the system, which includes the ECS and the additional components for the integration of the Fuel Cell, increases between +131% and +211% with respect to the bleedless ECS baseline, depending on the configuration. Considering the ECS alone, the mass variation ranges from -29% to $+208\%$: the hydrogen-cooled configuration is the only one that reduces the mass of the ECS. The aerodynamic drag increases between $+268\%$ and $+337\%$ across all configurations. Furthermore, the architectures with an independent air channel for the Fuel Cell require lower electrical power, resulting in lower hydrogen consumption during the climb and cruise phases. The proposed framework constitutes, for the preliminary design of an aircraft, a useful tool for comparing different ECS-Fuel Cell architectures, evaluating the main design trade-offs in terms of mass, aerodynamic drag, and hydrogen consumption.

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List of Acronyms

ACM	Air Cycle Machine
ACS	Air Conditioning System
AMC	Acceptable Means of Compliance
APU	Auxiliary Power Unit
ATM	Air Traffic Management
BoP	Balance of Plant
CARs	Canadian Aviation Regulations
CBV	Cross-Bleed Valve
CDC	Cold Day Cruise
CDG	Cold Day Ground
CMP	Compressor
CS	Certification Specifications
EASA	European Aviation Safety Agency
EBV	Engine Bleed Valve
ECS	Environmental Control System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FC	Fuel Cell
FCHX	Fuel Cell Heat Exchanger
GEF	Galleys, Entertainment, Furnishing
HDG	Hot Day Ground
HHV	Higher Heating Value
HX	Heat Exchanger
ICAO	International Civil Aviation Organization
IPS	Ice Protection System
ISA	International Standard Atmosphere
MDAO	Multidisciplinary Design, Analysis and Optimisation
MEA	More Electric Aircraft
MLW	Maximum Landing Weight
MTOW	Maximum Take-Off Weight
NTU	Number of Transfer Units
OEI	One Engine Inoperative
PEMFC	Proton Exchange Membrane Fuel Cell
PHX	Primary Heat Exchanger
SAE	SAE International
SHX	Secondary Heat Exchanger
SOFC	Solid Oxide Fuel Cell
TC	Transport Canada
TMS	Thermal Management System
UF	Usage Factor

List of Symbols

A	Area / cross-section [m^2]
C	Thermal capacity rate [J/K]
D	Diameter [m]
F	Faraday constant [$\text{A}\cdot\text{s/mol}$]
F_D	Drag Force [N]
HL	Heat load [W]
I	Current [A]
L	Length [m]
M	Mach number / molar mass [$-$ / g/mol]
N	Number (of cells, crew, components, etc.) [$-$]
P	Power [W]
Q_v	Volumetric flow rate [m^3/s]
R	Specific gas constant [$\text{J}/(\text{kg}\cdot\text{K})$]
S	Surface area [m^2]
T	Temperature [K]
U	Global heat transfer coefficient [$\text{W}/(\text{m}^2\cdot\text{K})$]
V	Velocity / voltage [m/s / V]
W	Fuselage width/diameter [m]
Δh	Enthalpy of reaction [MJ/kg]
$\dot{Q}$	Heat flow rate [W]
$\dot{m}$	Mass flow rate [kg/s]
a	Speed of sound [m/s]
c_p	Specific heat at constant pressure [$\text{J}/(\text{kg}\cdot\text{K})$]
f	Friction factor / mass flow function [$-$]
h	Heat transfer coefficient [$\text{Btu}/(\text{h}\cdot\text{ft}^2\cdot^\circ\text{F})$]
k	Thermal conductivity / correction factor [$\text{W}/(\text{m}\cdot\text{K})$]
k_m	Mass correction factor [$-$]
m	Mass [kg]
p	Pressure [Pa]
r	Radius [m]
t	Thickness [m]
v	Specific volume [m^3/kg]
w	Specific work [J/kg]
x	Bypass fraction / layer thickness [$-$ / m]

Greek Letters

Δp	Pressure drop [%]
δ	Specific diameter [$-$]

η	Efficiency $[-]$
γ	Specific heat ratio $[-]$
λ	Air excess ratio $[-]$
ϕ	Power-to-mass ratio $[\text{kW}/\text{kg}]$
π	Pressure / compression ratio $[-]$
ρ	Density $[\text{kg}/\text{m}^3]$
σ	Specific speed $[-]$
τ	Shear stress $[\text{Pa}]$
ε	Heat exchanger effectiveness $[-]$
φ	Solar flux / recirculation fraction $[\text{W}/\text{m}^2 / -]$

Superscripts

* Critical (sonic) condition, $M = 1$

Subscripts

0	Total (stagnation) condition
<i>ACM</i>	Related to the Air Cycle Machine
<i>Al</i>	Related to the aluminium alloy material
<i>CMP</i>	Related to a compressor
<i>ECS</i>	Related to the Environmental Control System (power context)
<i>FAN</i>	Related to the fan
<i>FC</i>	Related to the Fuel Cell
<i>GEF</i>	Related to Galleys, Entertainment, Furnishing
<i>HHV</i>	Related to the Higher Heating Value of hydrogen
<i>TRB</i>	Related to the turbine
<i>ai</i>	Related to the air intake (reference value)
<i>air</i>	Related to air
<i>avi</i>	Related to avionics
<i>body</i>	Related to the main body of a component
<i>c</i>	Related to the cold stream (heat exchanger)
<i>cab</i>	Related to the cabin
<i>duct</i>	Related to a duct
<i>e – CMP</i>	Related to the Electric Compressor
<i>em</i>	Related to the electric motor
<i>eng</i>	Related to the propulsion engine
<i>fit</i>	Related to fitting/joint elements
<i>fresh</i>	Related to fresh (outside) air
<i>fus</i>	Related to the fuselage
<i>h</i>	Related to the hot stream (heat exchanger)
<i>hx</i>	Related to the heat exchanger
<i>in</i>	Inlet condition

<i>mass</i>	Mass-specific quantity (vs. molar)
<i>max</i>	Maximum value
<i>min</i>	Minimum value
<i>mix</i>	Related to the mixed flow
<i>molar</i>	Molar-specific quantity (vs. mass)
<i>mu</i>	Related to the mixing unit
<i>net</i>	Net value
<i>out</i>	Outlet condition
<i>pax</i>	Related to passengers
<i>prop</i>	Related to propulsion
<i>ram</i>	Related to ram air
<i>rec</i>	Related to the cabin recirculation flow
<i>ref</i>	Reference value (scaling law)
<i>s</i>	Related to the supply flow
<i>skin</i>	Related to the aircraft skin
<i>t</i>	Related to the turbine
<i>tm</i>	Related to the turbomachine
<i>tot</i>	Total value

1 Introduction

This introductory chapter is structured as follows:

- Section 1.1 introduces the context and motivation in which this thesis work is situated;
- Section 1.2 presents the state of the art of the Environmental Control System (ECS);
- Section 1.3 presents the state of the art of Fuel Cells;
- Section 1.4 discusses the legislation relating to cabin conditioning;
- Section 1.5 identifies the research gap;
- Section 1.6 defines the thesis scope and the structure of the work.

1.1 Context and Motivation

The civil aviation sector reached, in 2019, a contribution equal to 2.5% of global CO₂ emissions, as defined by Ritchie in [1]. In absolute terms, global aviation CO₂ emissions have grown almost continuously from 1940 to 2019, albeit with distinct periods of stagnation, followed by phases of marked acceleration. It is interesting to note that since 1960, the tonnes of CO₂ emitted have, in fact, increased almost sevenfold by 2019 [1, 2].

The context in which this trend is embedded is made even more critical by the fact that 2023 and 2024 were the warmest years on record globally, with Europe warming at twice the global average rate, becoming the fastest-warming continent [3]. To this must be added air traffic, forecast to grow steadily until 2050 in all three scenarios (low, base, high) defined by EASA, reaching up to 13.8 million flights per year in the high-traffic scenario, compared to 9.19 million in 2019 [3]. Consequently, in the absence of further technological progress¹, CO₂ and NO_x emissions are forecast to increase proportionally to the growth of traffic itself [3]. Only in the most optimistic scenario, in which advanced technology, improvement of Air Traffic Management (ATM), and electrification of onboard systems act jointly, could net CO₂ emissions drop, by 2050, to levels comparable to those observed during the COVID-19 pandemic, despite an increase in air traffic [3].

The achievement of this scenario depends, however, largely on the ability of the aeronautical sector to develop and integrate innovative technologies for the electrification of the aircraft and its subsystems, an approach historically associated with the concept of the More-Electric Aircraft (MEA) [4]. The evaluation of different system architectures in the early design phases is fundamental, as the omission of an integrated system analysis can lead to errors of 40% in the assessment of onboard systems [5]. This need to evaluate the integration between subsystems is particularly relevant in the context of the use of hydrogen for the generation of electrical power on board the aircraft by means of Fuel Cells. Among the onboard systems most affected by this shift towards increased electrification is the Environmental Control System (ECS), which, as reported by Planès et al. [6], represents the second largest system in terms of fuel consumption after the propulsion system, and whose redesign toward an electric architecture (known as the bleedless architecture) reflects the broader shift toward electric propulsion and subsystem integration outlined above. In such configurations, cabin conditioning no longer depends on engine bleed air, but on external air that dedicated electric compressors initially pressurise. Furthermore, the introduction of the Fuel Cell into the system architecture of an aircraft offers significant potential in this context, as it directly converts the chemical energy of hydrogen into

¹The frozen technology scenario is defined as the one in which no advancement in aeronautical technology is foreseen.

electrical energy through an electrochemical reaction whose only product is water, completely eliminating CO₂ emissions during operation. However, it entails numerous thermal management challenges: indeed, the electrochemical reaction that takes place within the cell itself produces a significant amount of waste heat, and the reactants themselves must be conditioned within specific temperature ranges before being able to enter the cell, requiring a dedicated Thermal Management System (TMS). Physical and thermal integration between the TMS of the fuel cell and the ECS of the aircraft itself can meet this need for cooling and conditioning, exploiting the conditioning and cooling capacity of the latter to address this requirement, rather than treating the two systems in a completely independent manner. This convergence, between the electrification of the ECS and the emergence of Fuel Cells as a source of electrical power on board, motivates the objective of this thesis, defined in Section 1.6, concerning the development of a framework that allows the system-level analysis of the integration between these two systems.

1.2 Environmental Control System

As defined by the SAE ARP85G standard [7], the Environmental Control System, abbreviated as ECS, is the air conditioning system on board the aircraft that allows fresh, pressurised air to be distributed into the compartment occupied by the passengers.

The functions performed by the system are the following:

- Heating or cooling the cabin;
- Removing excess humidity;
- Providing ventilation, i.e., the process that allows the cabin air to be replaced with fresh air coming from the outside;
- Allowing temperature control;
- Allowing pressure control.

Several architectures of Environmental Control Systems exist, each of which can adopt different types of air conditioning cycles, as defined in the following sections.

1.2.1 Different Architectures of the ECS

The ECS subsystem comprises two different architectures: the conventional one and the bleed-less one. The fundamental difference lies in the way air compression is achieved: in the first case, air is bled from the engine, whereas in the second, it is compressed by a dedicated compressor.

1.2.1.1 Conventional Architecture

In the conventional architecture, the ECS is supplied with high-pressure air from the Bleed System, which extracts air from one or more stages of the engine compressor, from the Auxiliary Power Unit (APU), or from a ground power supply system. In addition to the ECS, the Bleed System also supplies other onboard systems of the aircraft, such as the Ice Protection System (IPS) and engine start-up [4].

The Bleed System is typically divided into two independent parts, in order to protect the other systems and the structure from possible leakage or malfunction events, ensuring that the remaining functioning system is able to supply bleed air. This is ensured through the use of a valve called the cross-bleed valve (CBV), which is typically closed. Other important components are the Engine Bleed Valve (EBV), which allows the pressure to be modulated and can be controlled by the crew (or is automatically closed in the event of anomalies), the High

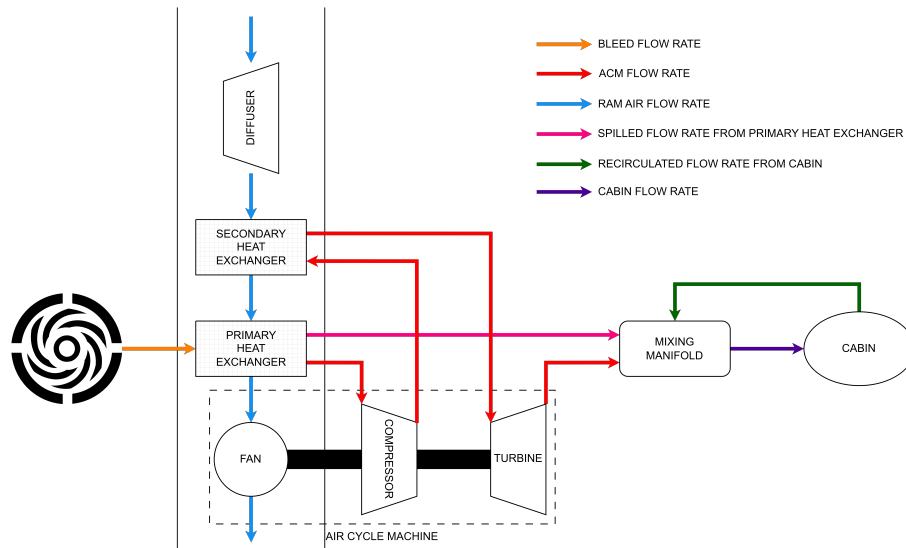


Figure 1.1: Conventional ECS Architecture

Stage Valve, which is opened when ice formation occurs and during low engine regimes, and the Pre-cooler, which is a cross-flow air-to-air heat exchanger that allows the air extracted from the engine fan to be used to control the bleed air within a certain temperature range.

Within the ECS itself, the Air Conditioning System (ACS) is the system that manages the received bleed air and distributes it within the cockpit and the passenger cabin, ensuring sufficient ventilation, pressurisation, temperature control, and humidity management. Typically, the ACS comprises an Air Cycle Machine, which further expands and cools the bleed air, in combination with heat exchangers and a mixing unit that mixes the conditioned air with an air flow coming from the cabin.

1.2.1.2 Bleedless Architecture

The bleedless architecture reflects this same trend towards electric propulsion and subsystem integration introduced in Section 1.1, according to which the preferential use of electrical power is proposed as the form of actuation for onboard systems, with the aim of minimising the number of energy conversions and maximising the efficiency of power transmission and use.

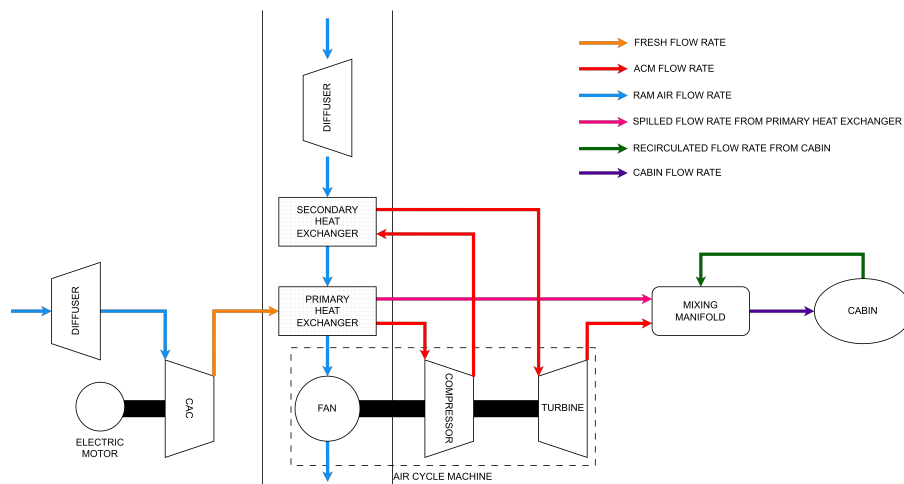


Figure 1.2: Bleedless ECS Architecture

Compared to what was defined in the previous section, in the bleedless architecture the source

of compressed air is no longer constituted by the extraction of air from the engine compressor, but by a dedicated compressor, which is connected to an electric motor powered by the aircraft's electrical generation system. Therefore, the primary air source is provided by a high-efficiency dynamic air intake, and the air coming from it is conditioned in terms of pressure and temperature by the electric compressor.

From an architectural point of view, the bleedless ECS system is composed of the following parts [4]:

- **Electric Power Supply System:** provides the electrical energy required to drive the dedicated compressor;
- **Air Conditioning System:** this is analogous to what was described for the conventional architecture, with the only difference being that the air entering the system comes from the dedicated compressor and not from the engine.

This configuration can present a critical issue related to the management of electrical emergency conditions: in fact, in the event of generator loss, the electric compressors are no longer able to supply pressurised air to the cabin, leading to a progressive increase in the altitude perceived by the passengers due to the decrease in pressure. Under these conditions, it is essential that the aircraft be brought to lower altitudes, so that cabin conditioning can occur through the air intake alone, thus ensuring the survival of the entire crew and the passengers.

Within the scope of this thesis project, and in line with this trend towards electric propulsion and subsystem integration, the bleedless architecture has been selected.

1.2.2 Air Conditioning System Types

Air conditioning systems for aircraft can be classified into vapour cycle systems, conventional air cycle systems, and integral recirculation air cycle systems, as defined in the SAE ARP85G standard [7].

1.2.2.1 Vapour Cycle Systems

The operating principle of this type of air conditioning system is based on cooling the cabin using fresh air and/or recirculated cabin air, which is cooled to approximately 10 °C in the refrigerant evaporator.

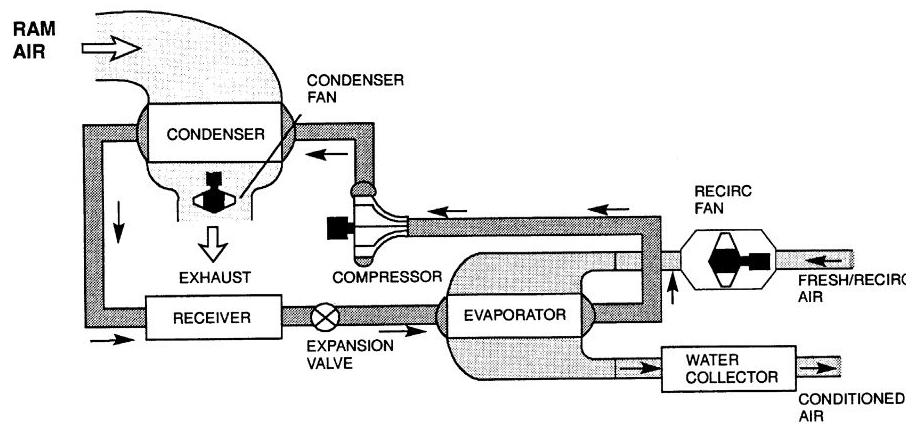


Figure 1.3: Basic Vapour Cycle [7]

The main components, visible in Figure 1.3, are:

- Compressor;

- Condenser;
- Evaporator;
- Expansion valve;
- Fans for supplying ambient air to the condenser heat sink;
- Fans for supplying fresh and/or recirculated air to the evaporator.

For this type of system, it may be necessary to consider two or more compression stages, useful for providing the temperature gradient required for the phase change in the evaporator and the condenser. Furthermore, the refrigerant compressor and the air supply fans are typically driven by an electric motor, but the use of hydraulic or pneumatic motors can also be considered.

The humidity of the supply air for the compartment occupied by the passengers is typically discharged to the outside, after being condensed in the evaporator.

To ensure the heating of the aforementioned compartment, a separate means must be provided, such as engine bleed air, electric heaters, exhaust gas heaters, or internal combustion heaters.

1.2.2.2 Air Cycle Systems

This system involves cooling the compressed supply fresh air through the use of heat exchangers, using ambient air as a heat sink, and then further refrigerating that same supply air through a turbine expansion process. This process makes it possible to generate power, which will be absorbed by a ram air fan and by a supply air compressor.

Several Air Cycle Machine (ACM) configurations exist, listed below:

- Simple Cycle, which involves the implementation of a turbine for the supply air and a fan for the ambient air, visible in Figure 1.4;
- Bootstrap Cycle, which involves the implementation of a turbine and a compressor for the supply air, visible in Figure 1.5;
- Three-Wheel Cycle, which involves the implementation of a turbine and a compressor for the supply air, and a fan for the ambient air, visible in Figure 1.6.

The main characteristics of the different configurations are presented below.

Simple Cycle This is the first type of Air Cycle Machine (ACM) that was implemented on early turbojet fighter aircraft and on helicopters, where it was possible to extract low flow rates of high-pressure air directly from the last compression stage of the engine.

The main advantage of this architecture is that it ensures the supply of ambient air to the heat exchanger during ground operations, hover flight, or low-speed flight, where the dynamic contribution of the air flow (ram air) is insufficient.

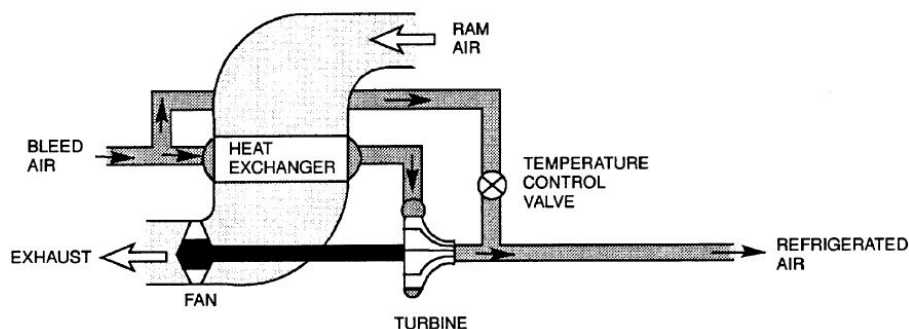


Figure 1.4: Simple Cycle [7]

Bootstrap Cycle This type of Air Cycle Machine (ACM) allows for a significant increase in cycle efficiency compared to the Simple Cycle, although the complexity of the system is greater. In particular, the Bootstrap Cycle makes it possible to provide an additional compression stage for the air bled from the engine, thus replacing the fan with a compressor, mounted on the same shaft as the turbine. This aspect ensures that the air flow entering the turbine has a higher pressure, resulting in an increase in the power supplied by the turbine.

A disadvantage related to the integration of the compressor is that it introduces an additional heat exchanger to remove the heat added by the compression, as well as a fan to supply cooling air to the heat exchanger during ground operations and, possibly, low-speed flight conditions.

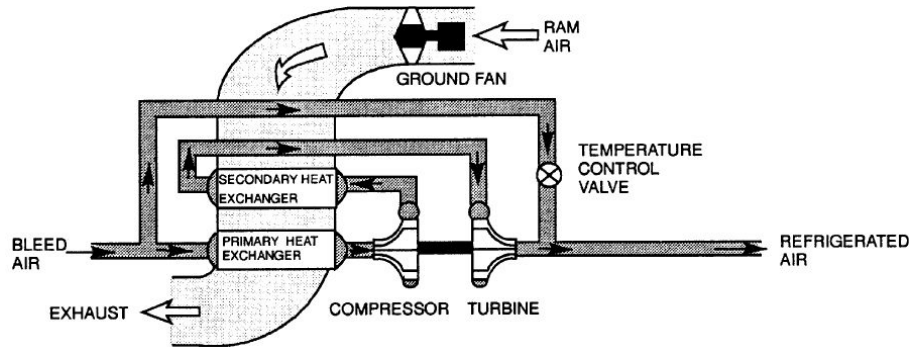


Figure 1.5: Bootstrap Cycle [7]

Three-Wheel Cycle This type of Air Cycle Machine (ACM) makes it possible to combine the advantages of the previously described configurations.

In particular, the simplicity of the Simple Cycle is combined with the performance advantage of the Bootstrap Cycle. Indeed, it allows the fan of the Simple Cycle and the compressor of the Bootstrap Cycle to be integrated on the same shaft as the expansion turbine.

The overall advantages of this system lie in the elimination of the need for a separate fan, and in the additional compressor, which increases the cycle efficiency.

Typically, approximately 85% of the power generated by the turbine is absorbed by the compressor [7], while the remaining part is absorbed by the fan, which ensures the correct cooling air flow required by the heat exchanger.

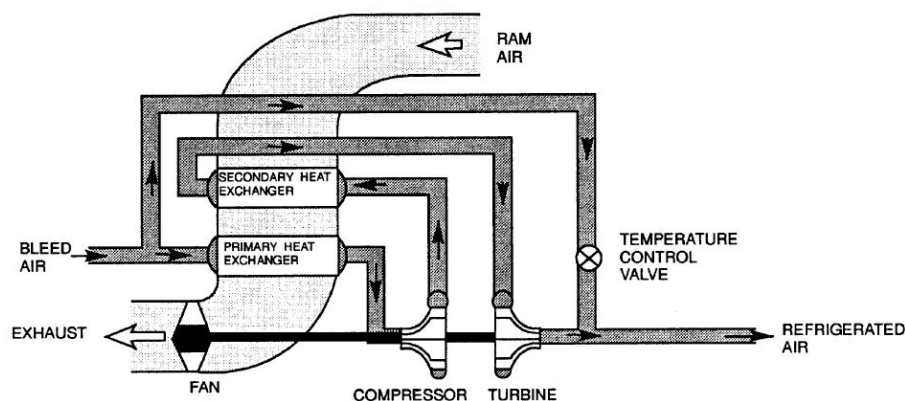


Figure 1.6: Three-Wheel Cycle [7]

The different types of Air Cycle Machines are summarised in Table 1.1.

As defined by Cavalcanti and de Andrade in [4], the choice of the air conditioning system is typically oriented toward the Air Cycle Machine (ACM), as it ensures a lower system weight,

Table 1.1: Comparison of Air Cycle System Configurations (ACM)

System Type	Added Component	Main Advantage	Complexity
Simple Cycle	Fan (turbine-fan)	Works well on ground or low speed without ram air	Lower Efficiency
Bootstrap Cycle	Compressor (turbine-compressor)	Higher efficiency	Higher complexity (extra HX and fan)
Three-Wheel	Fan and compressor on same shaft	Efficiency close to bootstrap and no separate fan needed	Higher mechanical complexity (three wheels on one shaft)

better maintainability, and benefits from the well-established know-how in the aeronautical field.

This type was chosen within the scope of this thesis, with a Three-Wheel Cycle configuration, since, although the mechanical complexity is greater, it ensures an efficiency comparable to the Bootstrap Cycle without the need for a separate fan, thus reducing the overall mass of the system. Although the system requirements imply the need to manage the humidity present in the air, within the scope of this analysis the presence of humidity has been neglected.

1.3 Fuel Cells

Having introduced the ECS and the growing electrification of its architecture, this section presents the electrical power generation technology integrated in this thesis work with the ECS: the hydrogen fuel cell.

The model, defined below, has been derived according to the methodology described by Cavini, Liscouët-Hanke, and Viola in [8] and by Cavini in [9].

1.3.1 Definition

As described by [9], the fuel cell is an electrochemical device that converts the chemical energy of hydrogen into electrical energy, ensuring high efficiency and low environmental impact. Fuel cells are typically composed of the following elements:

- The unit cells: where the chemical reaction takes place;
- The stacks: these represent the combination of several unit cells in order to ensure the desired capacity;
- The Balance of Plant (BoP): these are all the auxiliary components essential for the correct and effective use of the fuel cell. Within the scope of this thesis, the BoP is considered in a simplified manner: depending on the adopted configuration, defined in Chapter 4, a compressor is present for supplying air to the cathode, and a heat exchanger for cooling the air entering the cathode within the established limits. Other components, such as humidifiers or regulating valves, are not the subject of this analysis.

This analysis does not consider the modelling of the unit cell and of the stacks, as the fuel cell is treated as a black box.

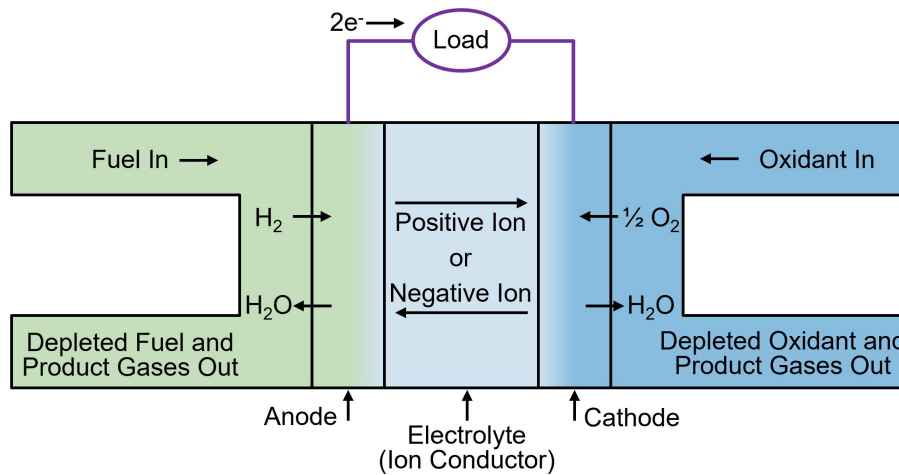


Figure 1.7: Basic Structure of a Fuel Cell Unit [9]

In particular, the unit cell is composed of different layers, each associated with a specific function. In Figure 1.7, the basic structure of a unit cell can be observed, where the fuel (i.e., hydrogen) and the oxidant (i.e., air) are supplied to the anode and the cathode of the component, through two separate channels. The anode and the cathode are defined as electrodes and are connected to each other through an electrolyte layer. Furthermore, the latter are the parts where the reaction takes place, with the consequent production of ions and electrons: the ions are transferred to the other electrode through the electrolyte, and the electrons create the current that flows through the applied electrical load.

Several types of fuel cells exist, classified according to the composition of the electrolyte and the fuel used. In the aeronautical sector, the most widely used are:

- Proton Exchange Membrane Fuel Cells (PEMFCs);
- Solid Oxide Fuel Cells (SOFCs).

1.3.1.1 Proton Exchange Membrane Fuel Cells (PEMFCs)

This type of Fuel Cell requires the use of hydrogen at a high level of purity, free of external contaminants.

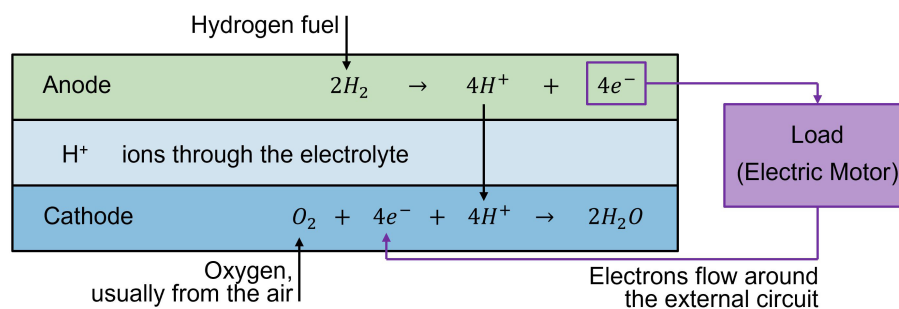
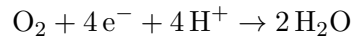


Figure 1.8: Semi-Reactions Within the PEMFC [9]

In particular, as can be observed in Figure 1.8, defined by Cavini in [9], the chemical process is made possible by the semi-reaction that occurs within the anode, where hydrogen splits into H^+ ions and e^- electrons:



The electrons move through the circuit and the electrical load, while the hydrogen ions pass through the membrane. The second semi-reaction occurs at the cathode, where water is produced:



The PEMFC is a technology that can be applied to different transportation sectors, although it presents several disadvantages in the aeronautical field. In particular:

- The variation of inertial forces due to the different flight phases can lead to a variation in the water distribution within the membrane, with a consequent decrease in performance;
- The Balance of Plant (BoP) is very complex;
- This type of Fuel Cell can only be fed using pure hydrogen.

The advantages, on the other hand, concern extremely low start-up times and good responsiveness to electrical load variations.

1.3.1.2 Solid Oxide Fuel Cell

The chemical process that takes place within the SOFC is represented in Figure 1.9.

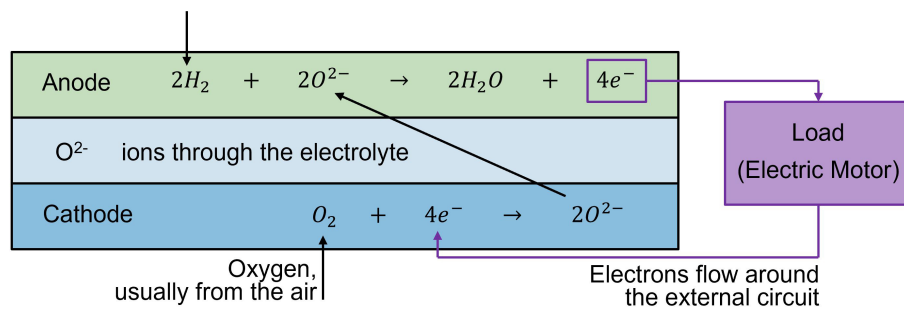
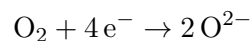
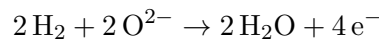


Figure 1.9: Semi-Reactions Within the SOFC [9]

It begins when the oxygen reaches the cathode of the Fuel Cell, where the following reaction takes place:



The oxygen ions then pass through the electrolyte and, at the anode, react with the hydrogen molecules, producing water:



This type of Fuel Cell offers several advantages for its use in the aeronautical field:

- It is not necessary to integrate a water management system within the membrane;
- The membrane is not sensitive to variations in inertial forces;
- The heat produced by the high temperatures can be used by other systems that require high-temperature flows;
- It can be implemented on aircraft, as it can also operate with aviation-grade fuel.

The choice of the PEMFC is consistent with the model available and validated in [8, 9], used here as the basis for the analysis of the integration of the Fuel Cell into the ECS system. As defined previously, although the SOFC presents some theoretical advantages in the aeronautical field, the use of an already well-established PEMFC model made it possible to focus the thesis work on the system-level analysis, the main subject of this research.

1.4 Regulation Requirements

In aviation legislation there is no specific section dedicated to the ECS system alone, but all the information necessary for a correct definition of the model can be derived from the sections related to ventilation, heating, and pressurisation.

The requirements derived from the main worldwide regulatory agencies, EASA², FAA³ and Transport Canada, were obtained, respectively, from CS-25 Amendment 28 [10], FAR Part 25 [11], and CARs Part V Subpart 25 [12], and concern the sections relating to ventilation, heating, and pressurisation. They are summarised and compared in Table 1.2. It should be noted that the mass flow rate values refer to the single occupant.

Table 1.2: Comparison of ECS-Related Regulatory Requirements (EASA, FAA, TC)

Category	Parameter	EASA	FAA	TC
Ventilation and heating	Minimum mass flow rate	0.25 kg/min (0.55 lb/min)	0.25 kg/min (0.55 lb/min)	0.25 kg/min (0.55 lb/min)
	Mass flow rate in failure conditions	0.18 kg/min (0.4 lb/min)	Not defined	Not defined
Pressurisation	Cabin pressure	2438 m (8000 ft)	2438 m (8000 ft)	2438 m (8000 ft)
	Cabin pressure under any type of failure	4572 m (15000 ft)	4572 m (15000 ft)	4572 m (15000 ft)

As can be seen from Table 1.2, the three regulatory bases are largely overlapping, because the aviation regulations of the different aviation authorities (EASA, FAA, TC⁴) are harmonised with each other, in order to facilitate the recognition of airworthiness certifications among the different authorities. Furthermore, they are based on the regulations and directives imposed by ICAO.⁵

It can also be noted that the EASA regulation defines an Acceptable Means of Compliance (AMC) relating to a cabin temperature value of 24 °C, as well as a requirement on the minimum flow rate under failure conditions, neither of which is reported in the corresponding FAA and TC sections.

1.5 Research Gap

The architecture of the Environmental Control System (ECS), in particular the bleedless one, and hydrogen fuel cells have been the subject of extensive study, but independently of one another.

Indeed, on the one hand the literature has thoroughly characterised the bleedless architecture as an alternative to engine bleed air extraction [4, 13], with the Boeing 787 Dreamliner as the

²EASA: European Aviation Safety Agency, Europe.

³FAA: Federal Aviation Administration, United States of America.

⁴TC: Transport Canada, Canada.

⁵ICAO (International Civil Aviation Organization) is an UN organisation that establishes global aviation rules, ensuring uniformity and safety worldwide.

only commercial airliner adopting this architecture [13, 14]; on the other hand, several fuel cell models have been developed, in particular Proton Exchange Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC), for the generation of electrical energy on board [8, 9].

However, the integration of a fuel cell on board entails non-negligible critical issues, related in particular to the multiple critical functions managed by the Balance of Plant (BoP), such as cooling, water management, reactant flow, and electrical conversion [8, 15], which have repercussions on the onboard systems with which the cell must interface, including the ECS.

To date, a system-level analysis for the Environmental Control System that concretely evaluates this impact is lacking, particularly in terms of mass variation, aerodynamic drag, and hydrogen consumption along a realistic mission profile.

This thesis aims to bridge this gap.

1.6 Thesis Scope and Structure

The objective of this thesis is to define a model of an Environmental Control System and of a Proton Exchange Membrane Fuel Cell, in order to determine the impact of the integration of the cell on the architecture of the system itself. This impact is measured in terms of the percentage variation in mass and aerodynamic drag, and the trends of hydrogen and air consumption, as well as water production, for a simple mission profile.

Chapter 2 presents the Literature Review, in which the chapter critically analyses the literature relating to the state of the art on the modelling of the bleedless Environmental Control System and of the Fuel Cell for aeronautical applications, in order to identify what is missing and/or what differs with respect to the approach adopted in this thesis.

Chapter 3 discusses the Methodology, i.e., the modelling methodology employed. In particular, the calculation of the cabin heat loads (metabolic, solar, electrical, and external) is presented, along with the detailed modelling of each component of the ECS system, according to a modular approach that allows their recombination into different architectures, with each component's validation, and the fuel cell model used for the estimation of consumption.

Chapter 4 on Case Studies covers the actual integration of the PEMFC on an aircraft sized like the Bombardier Challenger 300 (further details of which are provided in Appendix A). The chapter presents three different integration configurations with the corresponding results in terms of mass and aerodynamic drag, together with the time trends of consumption for a simple mission profile.

Chapter 5 presents a critical analysis of the work produced and the identification of the next steps for the improvement of the model itself.

2 Literature Review

The Environmental Control System (ECS) and Fuel Cells have been the subject of numerous research studies, but in a completely independent manner, and never integrated with one another.

A considerable part of the literature models the ECS from a thermodynamic and dynamic point of view, without considering the mass and dimensions of the system or its components. Ordonez and Bejan [16] derive realistic limits on the minimum power requirements of the ECS, as well as the design characteristics that facilitate its operation at minimum consumption, through thermodynamic optimisation of the system itself, whilst Conceição et al. [17] compare the thermodynamic performance of Three-Wheel and Four-Wheel Air Cycle Machine configurations. Fioriti and Di Fede [14] present a model for the calculation of ECS performance for conventional and electric architectures during conceptual design. Several approaches concerning the dynamic simulation of the system have also been proposed: Müller et al. [18] develop the FLECS library for dynamic simulations of the ECS, while Sielemann [19, 20] proposes a device-oriented framework for ECS design and for the dynamic simulation of a vapour cycle, developed within the DENECS project; Iqbal et al. [21] and the review by Chowdhury et al. [22] address the dynamic simulation and diagnostics of an ECS, whilst Jennions et al. [23] propose a framework, called SESAC, for the simulation of the ECS at component level, validated on a Boeing 737-800 pack. Other works focus on energy efficiency and system optimisation at component level, such as Duan et al. [24] and Yang et al. [25], or, as in the case of Zavaglio et al. [26], who propose a new architecture defined as adaptive ECS (aECS), within the Clean Sky 2 project. As highlighted at the beginning of the paragraph, none of these works estimates the mass of the modelled architecture nor the aerodynamic drag generated.

A smaller part of the literature, on the other hand, also addresses the estimation of the mass and dimensions of the ECS. Planès et al. [6] propose scaling laws for the calculation of the mass of the rotating components of the Air Cycle Machine, based on the Cordier Diagram, which have been implemented in this thesis. Lager [27] proposes a mass prediction methodology for the ECS of a military fighter aircraft, whilst Devadurgam et al. [28] develop a knowledge-based engineering tool for the analytical design and three-dimensional estimation of both conventional and electric ECS architectures. Perez-Grande and Leo [29] carry out the optimisation of the mass and entropy generated by the ECS heat exchangers, and Sagala and Liscouët-Hanke [30] propose a parametric sizing method for cryogenic heat exchangers adopted in this thesis, whilst Chakraborty [31] evaluates the mass of the ECS at system architecture level, within an overall framework for the sizing of onboard systems, in support of trade-off analysis between different subsystem configurations.

With regard to aerodynamic drag, Planès et al. [6] estimate the drag penalty generated by a bleedless ECS system, whilst Giuffrè et al. [13] compare the drag penalty between an ACM-based ECS and an electrically driven vapour compression cycle, demonstrating that minimising mass and drag can be two conflicting design objectives, as an architecture with a lower mass may generate a greater drag penalty. Crabé et al. [32] evaluate the drag penalty caused by an electric ECS along a complete mission profile.

With regard to Fuel Cells, several models have been implemented for aeronautical applications [8, 9, 15], as well as for their use as a replacement for the Auxiliary Power Unit (APU) [33, 34]; in these latter works, however, the ECS is mentioned simply as one of the systems supplied through the APU, either electrically or pneumatically, and through engine bleed air, without considering any physical or thermal interaction between the Fuel Cell and the ECS itself. A conceptually related work is that proposed by Dmitruk and Tishchenko [35], in which the residual cooling capacity of the liquid nitrogen used on a hybrid propulsion aircraft to condition the ECS air is analysed, demonstrating that thermal integration between the ECS and another onboard energy system is a plausible solution, although Fuel Cells are not considered in their analysis.

In summary, no work in the literature proposes a system-level analysis of the integration of a Fuel Cell into a bleedless ECS architecture in which the impact in terms of mass, aerodynamic drag, and hydrogen consumption along a realistic mission profile is evaluated. This effectively confirms the gap identified in Section [1.5](#), which this thesis proposes to bridge.

3 Methodology

The objective of this chapter is to provide an exhaustive explanation of the methodology employed in this work.

In particular, the chapter presents:

- The framework used for the implementation of the different models (Section 3.1);
- The model for the determination of the heat loads (Section 3.2);
- The definition and characterisation of the Environmental Control System components (Section 3.3), comprising the assumptions at system and component level, the thermodynamic relations between inlet and outlet, the calculation of the total and individual component masses, the related dimensions, the limitations of the component models, and the validation of the ECS model;
- The definition of the Proton Exchange Membrane Fuel Cell model (Section 3.4), comprising the calculation of the cell efficiency, the flow rates of the consumables (air, oxygen, and hydrogen) and of the product (water).

3.1 Modelling Framework

The models developed in this work, presented below, have been implemented within OpenMDAO [36]. It is an open-source framework developed in Python by NASA for Multidisciplinary Design, Analysis and Optimisation (MDAO).

The choice of OpenMDAO is justified by the fact that it presents a modular structure. Indeed, each physical component of the system has been implemented as an independent computational block, defined as a Component, and characterised by a common interface that allows interconnection with other components through the exchange of values and information between inputs and outputs. This intrinsic modularity allows the recombination of the different components into alternative system architectures, such as the integration configurations between an ECS and a Fuel Cell defined in Chapter 4, without having to rewrite the model of each component and each configuration from scratch.

The individual Components are organised into Groups, which represent the overall architecture of the system, such as the bleedless ECS. This philosophy allows a clear hierarchy to be defined between the subsystems, and the connections among the different components, which carry the physical quantities exchanged, such as temperatures, pressures, or flow rates, to be managed in an organised manner.

This framework proves to be very useful in solving implicit computational loops, such as the one required to calculate the bypass air flow rate percentage x_{hx} , as defined in Section 3.3.2.7, downstream of the Primary Heat Exchanger.

Within the scope of this project, the convergence of the ECS system, and therefore of the group associated with it, was achieved using a Newton solver combined with a Direct Solver, which is capable of solving the linear system associated with each iteration.

3.2 Heat Loads Modelling

The calculation of heat loads is of fundamental importance, since the ECS system is responsible for managing the thermal loads inside the cabin in order to ensure suitable conditions of temperature, pressure, and humidity.

The management of cabin thermal loads is carried out by supplying a mix of fresh and recirculated air at a given temperature and pressure. If the mixed air temperature is lower than the

one required to manage heat loads, then a percentage of hot air is spilled downstream of the Primary Heat Exchanger.

The calculation of heat loads is essential, as it allows the determination of the temperature of the air mass flow to be supplied to the cabin to manage them.

The calculation of thermal loads is divided into four main categories:

- Metabolic heat: heat released by the cabin occupants;
- Solar heat: heat transferred to the aircraft by solar radiation;
- Electrical heat: heat released by electronic equipment¹ in the cabin;
- External heat: heat transferred by conduction between the external atmosphere and the cabin interior.

In this thesis, the modelling of the heat loads was carried out following the methodology proposed by Tfaily and Kokkolaras in [37] for the metabolic contribution, by Planès et al. in [6] for the solar and external contributions, and by Mohan in [38] for the electrical contribution. It is important to note the following notation, also shown in Figure 3.1:

- Heat entering the cabin, i.e., heat that is added, is considered positive;
- Heat leaving the cabin, i.e., heat that is removed, is considered negative.

The sign convention as a function of the different heat load contributions is summarised in Table 3.1.

Table 3.1: Sign Convention for Heat Load Contributions

Category	Sign Convention	Condition
Metabolic heat load	Always positive: $HL_{\text{metabolic}} > 0$ Minimum if $N_{\text{pax}} = 0$ (only crew heat accounted)	Enters the cabin
Electrical heat load	Always positive: $HL_{\text{electric}} > 0$	Enters the cabin
Solar heat load	Zero: $HL_{\text{solar}} = 0$ Non-negative: $HL_{\text{solar}} > 0$	During night: no heat load During day: enters the cabin
External heat load	If $T_{\text{skin}} < T_{\text{cab}}$: $HL_{\text{external}} < 0$ If $T_{\text{skin}} > T_{\text{cab}}$: $HL_{\text{external}} > 0$	Leaves the cabin Enters the cabin

Figure 3.1 presents the schematic of the considered heat loads.

3.2.1 Assumptions

Before proceeding with the calculation of the individual contributions, the main assumptions adopted for the modelling of the heat loads are presented and summarised below:

- **Fuselage geometry:** the aircraft fuselage is assumed to be a perfect cylinder;
- **Number of engines:** the number of engines N_{eng} is assumed to be equal to two;
- **Number of windows:** the reference aircraft (Bombardier Challenger 300) has 12 windows; the number of windows exposed to solar radiation N_{windows} must be defined according to the position of the sun relative to the aircraft;

¹Electrical equipment: any devices that reject heat into the compartment, including lights, flight deck displays, in-flight entertainment, galley ovens, and chillers.



Figure 3.1: Heat Loads Schematic

- **Nighttime solar load:** during nighttime hours the solar heat load HL_{solar} is assumed to be equal to zero;
- **Crew:** the number of cabin crew members $N_{\text{cabin crew}}$ is estimated as a function of the number of passengers N_{pax} and is equal to 1 for every 50 passengers. The number of pilots, on the other hand, is assumed to be constant and equal to 2;
- **Outer surface temperature:** the outer surface temperature T_{skin} is assumed to be constant at every point of the fuselage and of the aircraft, neglecting points at higher temperature due to aerodynamic friction at high speed;
- **Fuselage structure:** for the calculation of the overall heat transfer coefficient U , the fuselage wall is modelled as a sequence of three layers (outer layer, insulation layer, inner layer), whose thicknesses have been assumed, while the chosen materials are defined in the SAE AIR1168/9A standard [39];
- **Steady-state condition:** all heat load contributions are calculated under steady-state conditions, for a given flight phase, without considering any transients between phases.

3.2.2 Metabolic

Human metabolism produces two different types of heat, as defined by Iaia in [40]:

- **Sensible heat:** this contribution propagates in the cabin through convection and directly increases the cabin temperature;
- **Latent heat:** it propagates through breathing and the evaporation of sweat, and also affects the cabin's relative humidity.

The metabolic heat load depends on three main contributions: the heat generated by the passengers, by the cabin crew, and by the pilots.

$$HL_{\text{metabolic, pax}} = N_{\text{pax}} \cdot (188 - 4.7 \cdot T_{\text{cab}}) \quad (3.1)$$

$$HL_{\text{metabolic, cabin crew}} = 2 \cdot N_{\text{cabin crew}} \cdot (188 - 4.7 \cdot T_{\text{cab}}) \quad (3.2)$$

$$HL_{\text{metabolic, flight crew}} = 2 \cdot N_{\text{flight crew}} \cdot (188 - 4.7 \cdot T_{\text{cab}}) \quad (3.3)$$

The three equations differ because the heat produced by the passengers is lower than that generated by the crew, which is physically more active due to their tasks.

The number of crew members was determined based on the number of passengers. According to Commission Regulation (EU) No 965/2012, section ORO.CC.100 [41], one crew member is required for every 50 passengers.

$$N_{\text{cabin crew}} = \frac{N_{\text{pax}}}{50} \quad (3.4)$$

The result obtained may not be an integer, therefore the number of crew members is rounded up in order to obtain an integer number.

The number of pilots $N_{\text{flight crew}}$ is assumed to be equal to two.

The total metabolic heat load is determined as follows:

$$HL_{\text{metabolic}} = HL_{\text{metabolic, pax}} + HL_{\text{metabolic, cabin crew}} + HL_{\text{metabolic, flight crew}} \quad (3.5)$$

Limitations The model presented by Tfaily and Kokkolaras [37], adopted in this thesis for the calculation of the metabolic heat load, simply distinguishes between seated passengers and crew members, to whom a double load is assigned to account for their greater physical activity. Furthermore, their model considers the cockpit temperature T_{cockpit} for the calculation of the metabolic heat load of the pilots, whilst the model presented in this thesis considers that temperature to be equal to the cabin temperature T_{cab} .

3.2.3 Solar

Solar thermal heat is transmitted into the cabin through the windows.

In particular, this thesis defines the surface area S_{window} of each window (which in this case is taken from the Bombardier Challenger 300, presented in Appendix A), the total number of windows N_{windows} , and the flight altitude.

In general, this aircraft has 12 windows. However, the sun may be located on only one side of the aircraft, in front of it, or behind it. Consequently, it is necessary to specify how many windows are exposed to solar radiation.

The altitude is required to calculate the solar flux φ [W/m²], determined from the data presented by Oumbe and Wald in [42].

The equation for the estimation of the Solar Heat Load, presented by Planès et al. in [6], is:

$$HL_{\text{solar}} = 0.7 \cdot 0.5 \cdot N_{\text{windows}} \cdot S_{\text{window}} \cdot \varphi \quad (3.6)$$

In Equation 3.6, the coefficient equal to 0.7 is the coefficient for glass transmissivity, while the coefficient equal to 0.5 is the coefficient for projecting the glass surface.

During nighttime conditions, this term is set to zero.

Limitations For the solar heat load model, Planès et al. [6] do not identify specific limitations. However, the use of fixed coefficients for glass transmissivity and the projected surface represents a simplification with respect to a more detailed radiative model, which is nonetheless consistent with the preliminary design objective of this thesis.

3.2.4 Electrical

Electrical thermal heat is the heat emitted by the electronic and electrical devices present inside the cabin. In the following analysis, these devices are:

- Galleys;

- Entertainment;
- Furnishing;
- Lights;
- Avionics.

The equations reported below were obtained from [38], which have been simplified from the methodology presented by Esdras and Liscouët-Hanke in [43].

3.2.4.1 Galleys, entertainment, furnishing

The equation for the calculation of the heat released in the cabin by the galleys, by the onboard entertainment system, and by the furnishings is defined below:

$$HL_{GEF} = 10.284 \cdot e^{0.0139 \frac{L_{fus} W_{fus}}{N_{eng}}} \cdot UF \quad (3.7)$$

The terms appearing in Equation 3.7 are:

- L_{fus} : represents the length of the fuselage;
- W_{fus} : represents the diameter of the fuselage (see fuselage geometry assumption, Section 3.2.1);
- UF : or Usage Factor, is a multiplicative factor that makes it possible to distinguish the contribution of this heat load as a function of the considered flight phase. The values of the UF, obtained from Mohan in [38], can be found in Table 3.2;
- N_{eng} : represents the number of engines of the aircraft, always assumed to be equal to two.

3.2.4.2 Lights

The equation for the calculation of the heat released in the cabin by the lighting is defined below:

$$HL_{lights} = 0.31 \cdot L_{fus} \cdot UF \quad (3.8)$$

The terms appearing in Equation 3.8 are:

- L_{fus} : represents the length of the fuselage;
- UF : or Usage Factor, is a multiplicative factor that makes it possible to distinguish the contribution of this heat load as a function of the considered flight phase.

3.2.4.3 Avionics

The equation for the calculation of the heat released in the cabin by the avionics is defined below:

$$HL_{avionics} = 0.612 \cdot e^{0.048 L_{fus}} \quad (3.9)$$

The term appearing in Equation 3.9 is L_{fus} , which represents the length of the fuselage.

Finally, it is possible to determine the total electrical heat load $HL_{electrical}$ as:

$$HL_{electrical} = HL_{GEF} + HL_{lights} + HL_{avionics} \quad (3.10)$$

Table 3.2: Usage Factors [38]

	Ground	Taxi	Takeoff	Climb	Cruise	Descent	Approach	Landing
Galley, Entertainment, Furnishing	0.46	1.03	1	1	1.09	0.72	0.72	0.72
Lights	0.945	0.75	1	1	0.943	1.19	1.19	1.07
Avionics, Instruments	0.25	1	1	1	1	1	1	1

Limitations The model proposed by Mohan [38] for the calculation of the electrical heat loads is empirical and not physics-based, as acknowledged by the author; this thesis inherits this limitation, gaining the advantage of being able to calculate these contributions without the need to possess detailed data at subsystem level, which is consistent with the preliminary design objective of this work.

3.2.5 External

The external heat loads have been evaluated using the methodology presented by Planès et al. [6].

The external heat load can be calculated using the following equation:

$$HL_{external} = U A (T_{skin} - T_{cab}) \quad (3.11)$$

The terms appearing in Equation 3.11 are:

- U [W/(m²K)]: heat transfer coefficient;
- A [m²]: exchange surface of the aircraft;
- T_{cab} [K]: represents the cabin temperature;
- T_{skin} [K]: represents the temperature of the aircraft's outer surface, assumed to be constant at every point.

The exchange surface of the aircraft is obtained from the cylindrical fuselage geometry (Section 3.2.1), considering only half of it as the exposed surface to the Sun.

$$A = \frac{1}{2} \pi L_{fus} W_{fus} \quad (3.12)$$

The heat transfer coefficient has been obtained by using the relations in the SAE Standard AIR1168/3B [44].

$$U = \frac{1}{\frac{1}{h_o} + \sum_j^{n_{layers}} \frac{x_j}{k_j} + \frac{1}{h_i}} \quad (3.13)$$

The term $h_i \left[\frac{\text{Btu}}{\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}} \right]$, which represents the internal coefficient for heat transfer, is defined by the following equation:

$$h_i = 2.0 + 0.314 V_i \quad (3.14)$$

The term $V_i \left[\frac{\text{ft}}{\text{sec}} \right]$ is defined as the velocity of the air inside the passenger compartment, and takes values in the range between 0 and 3.3 ft/s, while h_i takes values between 2.0 and 3.04 $\frac{\text{Btu}}{\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}}$.

A similar equation can be used for the calculation of $h_o \left[\frac{\text{Btu}}{\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}} \right]$, which represents the outside coefficient for heat transfer:

$$h_o = 2.0 + 0.314 V_o \quad (3.15)$$

The term V_o $\left[\frac{\text{ft}}{\text{sec}}\right]$ is defined as the velocity of the outside air, assumed to be equal to the flight velocity. The SAE AIR1168/3B [44] standard does not provide a range of values for the term h_o , as it is strongly dependent on the defined flight velocity.

The terms x_j and k_j in Equation 3.13 represent, respectively, the thickness of the considered layer and the thermal conductivity $\left[\frac{\text{W}}{\text{m}\cdot\text{K}}\right]$. In the following, the methodology used to define the fuselage structure is presented.

The typical fuselage structure has been defined by reviewing the paper by Chatterjee and Bhowmik [45]. In particular, as shown in table 3.3, the fuselage structure consists of three layers, and the materials used are as follows. The values and materials considered were defined by SAE Standard AIR1168/9A [39]. Thicknesses have been hypothesised.

Table 3.3: Fuselage Structure and Materials

	Material	Thickness [mm]	Thermal Conductivity [W/(m·K)]
Outer Layer	Aluminium alloy 2024-T4	2.0	185.2
Insulation Layer	Glass Fiber	35	0.0188
Inner Layer	Glass Fiber Reinforced Phenolic Laminate	5	0.12

Once these parameters have been defined, it is possible to calculate the total external heat load $HL_{external}$ as defined in Equation 3.11.

Limitations The external heat load model follows the formulation proposed by Planès et al. [6], although in the model presented in this thesis the heat transfer coefficient U is calculated from the fuselage layer model, rather than being assumed equal to a reference value from the literature. However, this model presents some simplifications:

- A single value of U applied to the entire fuselage is assumed, on the hypothesis that it is at the same temperature, whilst the SAE AIR1168/3B Standard [44] calculates distinct coefficients for different zones of the fuselage and for different flight conditions;
- The choice of the layer composition and the shape of the fuselage are simplified;
- The greater aerodynamic heating to which the nose of the aircraft and the leading edges of the control surfaces are subjected is not accounted for.

3.2.6 Total Heat Loads

Finally, the total heat loads were obtained by summing all individual terms:

$$HL_{tot} = HL_{metabolic} + HL_{solar} + HL_{electrical} + HL_{external} \quad (3.16)$$

The total heat load is used for the calculation of the supply temperature T_s , required to maintain the cabin temperature T_{cab} constant, as defined in Section 3.3.2.7.

3.3 ECS Modelling

This section provides the definition of the Environmental Control System (ECS) model with the characterisation of each component analysed in this work.

3.3.1 System-Level Assumptions

Before proceeding with the detailed description of the model of each component, it is appropriate to summarise the main assumptions that have been made at the system level and that characterise the entire model:

- **Architecture:** a bleedless architecture has been selected, with a Three-Wheel Cycle Air Cycle Machine configuration (Sections 1.2.1.2, 1.2.2.2);
- **Humidity management:** for simplicity, the presence of humidity in the air is not modelled in any component of the system;
- **Regulatory compliance:** the model complies with the requirements defined by EASA (CS-25, Amendment 28), chosen as the reference among the considered regulations (Section 1.4); in particular, the minimum cabin pressure corresponds to that at 8 000 ft (2 438 m, 75.3 kPa), and the minimum air flow rate is equal to $\dot{m}_{min} = 0.25 \text{ kg}/(\text{min} \cdot \text{person})$;
- **Mass not explicitly modelled:** the mass of auxiliary elements such as fasteners, brackets, gaskets, electrical wiring, and the Air Cycle Machine shaft was not calculated independently, but was estimated through a corrective factor $k_m = 1.5$ applied to the sum of the masses of the modelled components.

3.3.2 Components

In this section, all component equations will be discussed, along with their respective assumptions.

3.3.2.1 Air Intake

The correct modelling of the air intake is of crucial importance, since the geometry of the inlet section determines the captured mass flow rate and the thermodynamic conditions of the flow. In this context, it is represented by means of a simplified diffuser model, capable of reducing the flow velocity and increasing the static pressure, assuming a quasi-isentropic behaviour and accounting for losses through an appropriate efficiency coefficient [46]. The sizing of the component and the calculation of the aerodynamic drag follow [47], whilst the mass calculation follows the methodology proposed by Planès et al. [6].

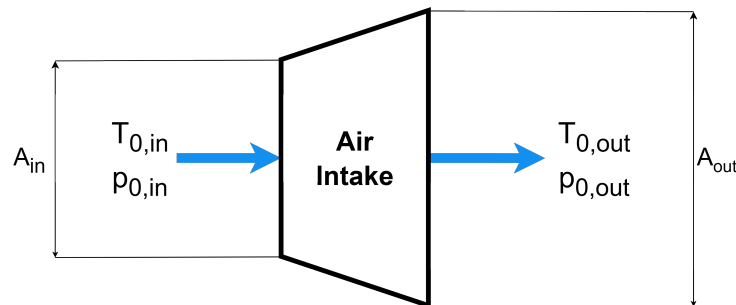


Figure 3.2: Air Intake Schematic

Assumptions The main assumptions adopted in the air intake model are listed below.

- **Geometric assumptions:**
 - The air intake is modelled as a truncated cone, with well-defined inlet and outlet circular cross-sections;

- The inlet section is defined as an effective capture area, assuming full flow ingestion without spillage losses;
- The inlet section causes drag formation.

- **Fluid dynamic assumptions:**

- The flow is one-dimensional, with uniform properties over each cross-section;
- The system operates under steady-state conditions;
- The flow is compressible, and compressibility effects are accounted for through Mach number variations.

- **Thermodynamic and modelling assumptions:**

- The working fluid is modelled as an ideal gas with constant properties:
 - * $\gamma = 1.4$;
 - * $R = 287 \text{ J}/(\text{kg}\cdot\text{K})$;
- The flow is assumed quasi-isentropic, with losses modelled globally through an efficiency factor;
- Deviations from isentropic behaviour are entirely accounted for through total pressure losses;
- The total temperature is assumed constant (adiabatic process).

Equations The equations used for the modelling of this component are reported below. Assuming an adiabatic process, the total temperature is conserved:

$$T_{0,in} = T_{0,out} \quad (3.17)$$

The outlet total pressure is computed using the intake efficiency factor as:

$$p_{0,out} = \eta_d p_{0,in} \quad (3.18)$$

Sizing The capture area is obtained from the continuity equation:

$$\dot{m} = \rho A V \quad (3.19)$$

$$V = M a \quad (3.20)$$

$$A_{in} = \frac{\dot{m}}{\rho V} \quad (3.21)$$

As the inlet cross-section is assumed to be circular, the inlet diameter D_{in} can be computed from equation 3.21 as:

$$D_{in} = 2\sqrt{\frac{A_{in}}{\pi}} \quad (3.22)$$

The outlet cross-sectional area A_{out} is obtained by rearranging the isentropic compressible flow mass flow rate relation:

$$\dot{m} = \frac{p_{0,out} A}{\sqrt{R T_{0,in}}} f(M) \quad (3.23)$$

$$A_{out} = \dot{m} \frac{\sqrt{R T_{0,in}}}{p_{0,out} f(M)} \quad (3.24)$$

where $f(M)$ is defined as the isentropic mass flow function:

$$f(M) = \frac{\sqrt{\gamma} M}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad (3.25)$$

The outlet diameter D_{out} is then defined as:

$$D_{out} = 2\sqrt{\frac{A_{out}}{\pi}} \quad (3.26)$$

Drag Calculation The dynamic air intake involves a deceleration and deviation of the free stream flow in order to enter the system. This generates a non-negligible contribution to the total drag, expressed by the following equation:

$$F_D = \dot{m} V_\infty \quad (3.27)$$

The terms appearing in Equation 3.27 are the drag force F_D [N], the flow rate entering the system $\dot{m}$ [kg/s], and the flight velocity V_∞ [m/s].

This relation consequently implies that:

$$\begin{aligned} \text{if } \dot{m}_{fresh} \uparrow &\Rightarrow F_D \uparrow \\ \text{if } V_\infty \uparrow &\Rightarrow F_D \uparrow \end{aligned}$$

Furthermore, the effect related to the increase in flow rate can be explained from the point of view of the section required to accommodate it, A_{in} [m²]: indeed, as can be seen from Equation 3.21, as the incoming air flow rate $\dot{m}$ [kg/s] increases, the section A_{in} [m²] increases proportionally, and a larger frontal section generates greater aerodynamic drag for the same flight velocity.

Mass Calculation The component mass is estimated as follows. In particular, the model relates the structural mass of the component to the required air mass flow rate $\dot{m}$, using a reference intake defined by a reference mass $m_{ai,ref}$ and a reference mass flow rate $\dot{m}_{ai,ref}$:

$$m_{ai} = m_{ai,ref} \frac{\dot{m}}{\dot{m}_{ai,ref}} \quad (3.28)$$

The reference values from [6] of $m_{ai,ref}$ and $\dot{m}_{ai,ref}$ are:

$$\begin{aligned} m_{ai,ref} &= 40 \text{ kg} \\ \dot{m}_{ai,ref} &= 0.5 \frac{\text{kg}}{\text{s}} \end{aligned}$$

Limitations This thesis does not identify a specific limitation discussed by Planès et al. [6] for this model; however, the mass calculation is carried out with respect to a reference value, without accounting for aspects related to the shape of the intake itself, thus simplifying its geometry.

3.3.2.2 Compressor

The compressor is the component of the system responsible for increasing the pressure and temperature of the air flow through mechanical work.

The calculation of the thermodynamic quantities follows the methodology proposed by Fioriti and Di Fede [14], the sizing follows [47], whilst the mass calculation follows the methodology proposed by Planès et al. [6].

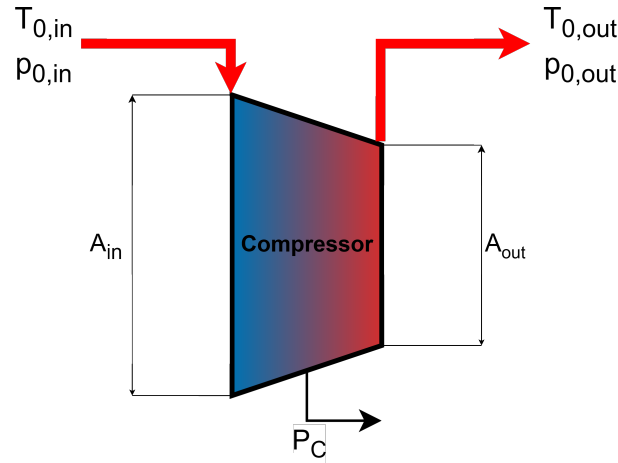


Figure 3.3: Compressor Schematic

As defined in section 1.2.1.2, two different compressor configurations can be considered within the system:

- Cabin Air or Electric Compressor: it ensures that the initial flow conditions within the system are suitable for proper air conditioning inside the cabin. The resulting pressure and temperature levels are lower than those obtained by extracting bleed air from intermediate stages of the engine compressor in a conventional ECS configuration. Moreover, it is driven by a dedicated electric motor;
- Main Compressor: a standard compressor, equivalent to that used in conventional bleed-based ECS configurations. It is driven by turbine expansion through a mechanical shaft and is located within the Air Cycle Machine (ACM).

In this work, a centrifugal compressor is considered.

The compressor performance is characterised by two main parameters:

- Compression ratio π_c : it is defined as the ratio between the outlet pressure and the inlet pressure;

$$\pi_c = \frac{p_{0,out}}{p_{0,in}} \quad (3.29)$$

$$\pi_c > 1 \quad (3.30)$$

- Efficiency η_c : it is defined as the ratio between the isentropic work required to achieve the same pressure rise and the actual mechanical work input to the compressor.

$$\eta_c = \frac{T_{0,s} - T_{0,in}}{T_{0,out} - T_{0,in}} \quad (3.31)$$

$$0 \leq \eta_c \leq 1 \quad (3.32)$$

Assumptions The main assumptions adopted in the compressor model are listed below.

- **Thermodynamic assumptions:**

- The working fluid is modelled as an ideal gas with constant properties:
 - * $\gamma = 1.4$;
 - * $R = 287 \text{ J}/(\text{kg} \cdot \text{K})$;
- The compression process is assumed to be quasi-isentropic, accounting for losses through a global efficiency parameter η_c ;

- **Fluid dynamic assumptions:**

- The flow is one-dimensional, with constant properties on each cross-section;
- The system operates under steady-state conditions, with no time-dependent effects;
- Compressibility effects are included through Mach number variations;

- **Geometry:**

- Only equivalent inlet and outlet areas are considered;
- The compressor mass is estimated using a scaling law based on a reference compressor;

- **Equations:**

- The equations defined in subsection 3.3.2.2 are applicable to both of the defined compressor types. In particular, it can be specified that:
 - * The power required by the electric compressor is electrical and is supplied by an electric motor connected to it;
 - * The power required by the compressor of the Air Cycle Machine is mechanical and is extracted from the expansion process that occurs in the turbine.

Equations From the inlet conditions, the outlet ones can be computed through the following relations.

The total pressure at the component outlet is defined using the compression ratio π_c :

$$p_{0,out} = \pi_c p_{0,in} \quad (3.33)$$

The total temperature is derived from the isentropic efficiency equation η_c , which relates inlet, outlet, and isentropic total temperatures.

$$\eta_c = \frac{T_{0,s} - T_{0,in}}{T_{0,out} - T_{0,in}} \quad (3.34)$$

The isentropic temperature is linked to the total pressure ratio, and therefore to the compression ratio π_c . Starting from Poisson's law for an isentropic process (equation 3.35) and combining it with the ideal gas law, the isentropic temperature $T_{0,s}$ is obtained (equation 3.36).

$$p v^\gamma = \text{const} \quad (3.35)$$

$$T_{0,s} = T_{0,in} \pi_c^{\frac{\gamma-1}{\gamma}} \quad (3.36)$$

Substituting equation 3.36 into equation 3.34, the outlet total temperature $T_{0,out}$ can be expressed as:

$$T_{0,out} = T_{0,in} \left[1 + \frac{1}{\eta_c} \left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \right] \quad (3.37)$$

The compressor power consumption is given by:

$$P_c = \frac{\dot{m} c_p T_{0,in}}{\eta_c} \left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \quad (3.38)$$

The specific heat at constant pressure c_p [J/(kg · K)] is evaluated using the Python library CoolProp [48]. In particular, c_p is computed as the average between $c_{p,in}$ and $c_{p,out}$, since inlet and outlet conditions differ. This package allows retrieving the property using the following command:

```
from CoolProp.CoolProp import PropsSI
c_p = PropsSI('C', 'T', T, 'P', p, 'Air')
```

Sizing The compressor is modelled as a truncated cone; therefore, the outlet cross-sectional area is computed as shown in section 3.3.2.1 for the Air Intake.

$$A_{out} = \dot{m} \frac{\sqrt{R T_{0,out}}}{p_{0,out} f(M_{out})} \quad (3.39)$$

Consequently, the outlet diameter is given by:

$$D_{out} = 2 \sqrt{\frac{A_{out}}{\pi}} \quad (3.40)$$

The outlet Mach number M_{out} is prescribed to ensure velocity control within the component, preventing the occurrence of surge and choke phenomena, since it is chosen as $M_{out} \ll 1$.

The inlet cross-section is equal to the upstream duct area.

By construction, these relations ensure that:

$$\begin{aligned} A_{out} &< A_{in} \\ D_{out} &< D_{in} \end{aligned}$$

Mass Calculation The component mass is estimated based on the Cordier Diagram, which relates two dimensionless parameters: the specific speed σ and the specific diameter δ , defined as:

$$\sigma = k \frac{N}{60} \frac{\sqrt{Q_v}}{w^{0.75}} \quad (3.41)$$

$$\delta = k r \frac{w^{0.25}}{\sqrt{Q_v}} \quad (3.42)$$

Where N [rpm] is the rotational speed of the compressor, w [J/kg] is the specific work, r is the turbomachine radius, Q_v [m³/s] is the volumetric flow rate, and $k = 2^{0.25} \sqrt{\pi}$ is a constant.

The diagram is shown in figure 3.4.

The corresponding interpolation curve for the compressor is:

$$\delta = 10^{0.24} \sigma^{-0.39+0.15 \log(\sigma)-0.17 \log(\sigma)^2+0.064 \log(\sigma)^3} \quad (3.43)$$

Given the compressor performance, the value of σ is first computed using equation 3.41. The corresponding value of δ is then obtained from equation 3.43, allowing the radius r to be finally derived from equation 3.42.

Finally, the mass m_c is estimated using a scaling law:

$$m_c = m_{c,ref} \frac{r_c}{r_{c,ref}} \quad (3.44)$$

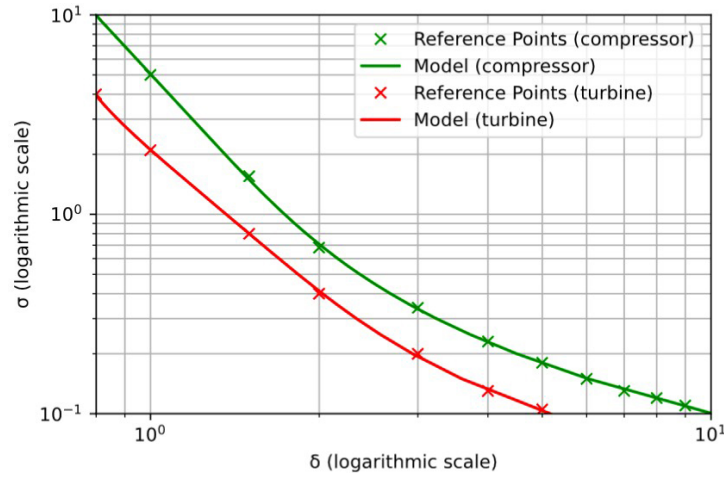


Figure 3.4: Cordier Diagram for Turbomachines [6]

Limitations Planès et al. [6] identify the turbomachine sizing model as an aspect to be improved in future works; this thesis inherits this limitation, as the Cordier diagram provides a mass estimation approach based on aerodynamic similarities, calculating only the radius of the turbomachine, without characterising its detailed geometry (axial length, number of stages, blade geometry). Furthermore, the reference mass $m_{c,ref}$ and reference radius $r_{c,ref}$ used in the scaling law are assumed values, as no reference component of this kind is available in Planès et al. [6] or elsewhere in the literature.

3.3.2.3 Electric Motor

This component has the function of supplying electrical power to the electric compressor, in order to ensure the correct pressurisation of the air entering the system. Furthermore, during the aircraft start-up procedure, the use of an electric motor makes it possible to create a pressure variation sufficient to allow the air to move through the system, thus ensuring cabin conditioning even when the aircraft is on the ground with the engine off.

Assumptions The assumptions defined for this component are reported below:

- **Efficiency assumptions:**

- The mechanical efficiency of the turbomachine (electric compressor) η_{tm} [–] to which it is connected is assumed to be equal to: $\eta_{tm} = 0.98$ [14];
- The efficiency of the electric motor η_{em} is assumed to be equal to: $\eta_{em} = 0.93$ [14].

- **Mass assumptions:**

- The mass is estimated through the power-to-mass ratio.

Equations The power of the electric motor is derived from the power required by the turbomachine, taking into account the efficiencies defined in the previous sub-section:

$$P_{em} = \frac{P_{tm}}{\eta_{tm} \eta_{em}} \quad (3.45)$$

Mass Calculation The mass m_{em} [kg] is estimated through the power-to-mass ratio ϕ [kW/kg], assumed to be equal to $\phi = 5$ kW/kg, a value representative of the current state of the art for electric motors in the aerospace field, in accordance with Leishman [49].

$$m_{em} = \frac{P_{em}}{\phi} \quad (3.46)$$

If the power P_{em} is calculated in [W], it is essential to convert its value into [kW].

Limitations The most significant limitation of this model relates to the power-to-mass ratio ϕ used for the mass calculation, as it represents a fixed coefficient and is not referred to a specific electric motor. The calculation of the dimensions of the component is not within the scope of this model.

3.3.2.4 Heat Exchangers

The heat exchanger is a component that allows heat transfer between two different fluids in contact with each other, which are at different temperatures, through thermodynamic mechanisms such as conduction or convection. The heat exchange takes place while keeping the flows separated, without additional external heat and without the use of work.

The thermodynamic model follows the methodology proposed by Sagala and Liscouët-Hanke [30] and by Liang [50], whilst the dimensional and mass model follows the methodology proposed by Sagala and Liscouët-Hanke in [30].

There are several classifications of heat exchangers, thus in this model, a cross-flow plate-fin type heat exchanger has been taken into account.

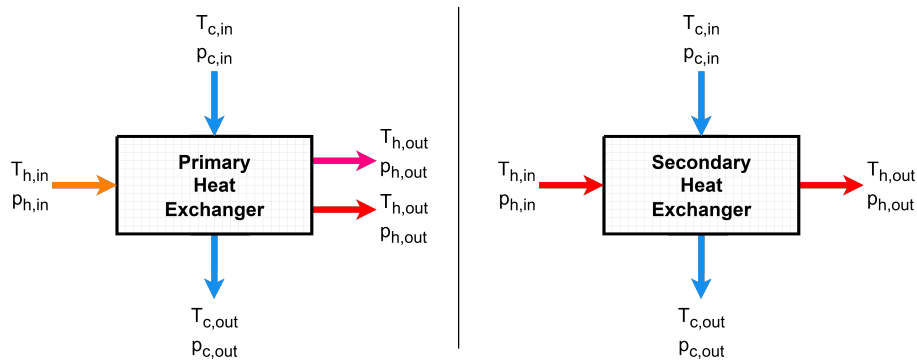


Figure 3.5: Heat Exchangers Schematic

In the ECS system there are two different types of heat exchanger:

- **Primary Heat Exchanger (PHX):** this is the heat exchanger that cools the air coming from the electric compressor, using the ram air coming from the Secondary Heat Exchanger;
- **Secondary Heat Exchanger (SHX):** this is the heat exchanger that cools the air coming from the compressor of the Air Cycle Machine, using the ram air coming from the outside.

Assumptions The assumptions considered for the heat exchanger model are defined below.

- **Thermodynamic assumptions:**

- The working fluid is modelled as an ideal gas with constant properties:
 - * $\gamma = 1.4$;
 - * $R = 287 \text{ J}/(\text{kg} \cdot \text{K})$;

- The heat exchange process is assumed adiabatic with respect to the external environment: heat is transferred only between the hot and cold streams, with no external heat addition or work interaction;
- Both the effectiveness ε and the total pressure drop Δp are treated as fixed design parameters;
- The specific heat at constant pressure c_p is evaluated independently for the hot and cold streams, at their respective inlet static conditions;

• **Fluid dynamic assumptions:**

- The flow is one-dimensional, with uniform properties across each cross-section;
- The system operates under steady-state conditions, with no transient effects;
- The Mach number of each stream is assumed constant between the inlet and the outlet of the heat exchanger;
- The hot and cold mass flow rates are treated as independent inputs, with no flow-rate balance constraint enforced between the two sides;
- The ε -NTU calculation is performed on static thermodynamic quantities;

• **Geometric and mass assumptions:**

- The heat exchanger is modelled as a cross-flow plate-fin exchanger;
- Sizing and mass estimation are not based on a scaling law, as for the other turbomachinery components, but are delegated to an external tool, developed by Sagala [30];

Equations The model of this component employs the ε -NTU methodology, presented by Sagala and Liscouët-Hanke in [30].

It is essential to define the following energy balance relating to the exchanged heat:

$$\dot{Q}_c = \dot{Q}_h \quad (3.47)$$

Equation 3.47 indicates that the heat released by the hotter fluid is equal to the heat absorbed by the cold fluid.

In particular, the equations for $\dot{Q}_c$ [W] and $\dot{Q}_h$ [W] are shown below:

$$\dot{Q}_c = \dot{m}_c c_{p,c} (T_{c,out} - T_{c,in}) \quad (3.48)$$

$$\dot{Q}_h = \dot{m}_h c_{p,h} (T_{h,in} - T_{h,out}) \quad (3.49)$$

$$(3.50)$$

For simplicity, the thermal capacity is denoted as C_c [J/K] and C_h [J/K]:

$$C_c = \dot{m}_c c_{p,c} \quad (3.51)$$

$$C_h = \dot{m}_h c_{p,h} \quad (3.52)$$

According to the ε -NTU methodology, it is necessary to define the minimum thermal capacity C_{min} [J/K], which is defined as the minimum between the thermal capacities of the cold and hot flows.

$$C_{min} = \min(C_h, C_c) \quad (3.53)$$

This is essential for defining the maximum heat flow $\dot{Q}_{max}$ [W], which is fundamental for defining the heat exchanger effectiveness ε . Considering the input temperatures for both flows $T_{h,in}$ [K] and $T_{c,in}$ [K], the maximum thermal power is defined as:

$$\dot{Q}_{max} = C_{min} (T_{h,in} - T_{c,in}) \quad (3.54)$$

Considering $\dot{Q}$ as the thermal power of the hot or cold flow, it is possible to define the effectiveness ε as follows:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{C_h (T_{h,in} - T_{h,out})}{C_{min} (T_{h,in} - T_{c,in})} = \frac{C_c (T_{c,out} - T_{c,in})}{C_{min} (T_{h,in} - T_{c,in})} \quad (3.55)$$

The proposed methodology has been modified to calculate the outlet thermodynamic quantities for a given value of the effectiveness ε . Indeed, it results that:

$$T_{h,out} = T_{h,in} - \varepsilon \frac{C_{min}}{C_h} (T_{h,in} - T_{c,in}) \quad (3.56)$$

$$T_{c,out} = T_{c,in} + \varepsilon \frac{C_{min}}{C_c} (T_{h,in} - T_{c,in}) \quad (3.57)$$

The thermodynamic process inside the heat exchanger also imposes a variation in the pressure of the fluids involved. Within the scope of this model, it is defined as a design parameter and is defined as a percentage variation Δp [%]:

$$\Delta p = \frac{p_{h,in} - p_{h,out}}{p_{h,in}} = \frac{p_{c,in} - p_{c,out}}{p_{c,in}} \quad (3.58)$$

Sizing and Mass Calculation Sizing and mass calculation were carried out using an external tool, developed by Sagala as described in [30], not connected to the hierarchy of the overall ECS model. A dedicated OpenMDAO Component instantiates and executes, at each call, a separate OpenMDAO model required for the estimation of the dimensions and mass of the heat exchanger. It is therefore treated as a black box, integrated into the model without compromising its modularity.

Limitations The methodology proposed by Sagala [30] assumes constant heat transfer coefficients on both sides of the heat exchanger, which may not be valid depending on the specific design; in any case, the author indicates that this simplification can be considered adequate for conceptual evaluation purposes, which is consistent with the fact that this thesis work falls within a preliminary design phase.

3.3.2.5 Turbine

The turbine is a component of the Air Cycle Machine (ACM). In particular, it is responsible for reducing the temperature and pressure of the airflow. The work extracted from the expansion is used to drive the shaft on which the compressor and fan are mounted.

The calculation of the thermodynamic quantities follows the methodology proposed by Fioriti and Di Fede [14], the sizing follows [47], whilst the mass calculation follows the methodology proposed by Planès et al. [6].

In this work, an axial turbine is considered.

The turbine performance is characterised by two main parameters:

- Expansion ratio π_t : it is defined as the ratio between the inlet and outlet total pressures;

$$\pi_t = \frac{p_{0,in}}{p_{0,out}} \quad (3.59)$$

$$\pi_t > 1 \quad (3.60)$$

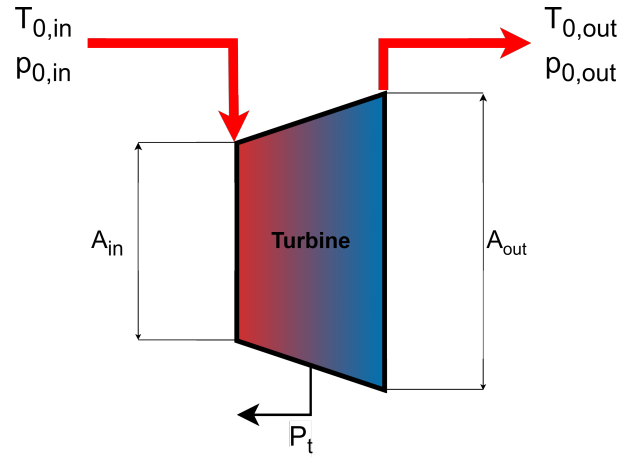


Figure 3.6: Turbine Schematic

- Efficiency η_t : it is defined as the ratio between the actual work extracted from the flow during expansion and the maximum work obtainable through an isentropic process between the same inlet and outlet conditions;

$$\eta_t = \frac{T_{0,in} - T_{0,out}}{T_{0,in} - T_{0,s}} \quad (3.61)$$

$$0 \leq \eta_t \leq 1 \quad (3.62)$$

Assumptions The main assumptions adopted in the turbine model are listed below.

- **Thermodynamic assumptions:**

- The working fluid is modelled as an ideal gas with constant properties:
 - * $\gamma = 1.4$;
 - * $R = 287 \text{ J}/(\text{kg} \cdot \text{K})$;
- The expansion process is assumed to be quasi-isentropic, with losses accounted for through a global efficiency parameter η_t ;
- The expansion may allow outlet temperatures to fall below zero; therefore, a sub-freezing type turbine is considered;

- **Fluid dynamic assumptions:**

- The flow is one-dimensional, with uniform properties across each cross-section;
- The system operates under steady-state conditions, with no transient effects;
- Compressibility effects are accounted for through variations in Mach number;

- **Geometric assumptions:**

- Only equivalent inlet and outlet areas are considered;
- The turbine mass is estimated using a scaling law based on a reference turbine.

Equations Starting from the inlet conditions, the outlet ones can be computed through the following relations.

The expansion ratio π_t is obtained as the ratio of the inlet and outlet total pressures:

$$\pi_t = \frac{p_{0,in}}{p_{0,out}} \quad (3.63)$$

The outlet total temperature is obtained from the isentropic efficiency equation η_t , which is expressed as:

$$\eta_t = \frac{T_{0,in} - T_{0,out}}{T_{0,in} - T_{0,s}} \quad (3.64)$$

As in the case of the compressor, the isentropic temperature $T_{0,s}$ can be expressed as a function of the inlet temperature $T_{0,in}$ and the expansion ratio π_t .

$$T_{0,s} = T_{0,in} \left(\frac{1}{\pi_t} \right)^{\frac{\gamma-1}{\gamma}} \quad (3.65)$$

Substituting equation 3.65 into equation 3.64, the following expression is obtained:

$$T_{0,out} = T_{0,in} \left[1 - \eta_t \left(1 - \frac{1}{\pi_t^{\frac{\gamma-1}{\gamma}}} \right) \right] \quad (3.66)$$

The power generated by the turbine expansion is given by:

$$P_t = \dot{m} c_p T_{0,in} \eta_t \left(1 - \frac{1}{\pi_t^{\frac{\gamma-1}{\gamma}}} \right) \quad (3.67)$$

The specific heat capacity at constant pressure c_p [J/(kg · K)] is obtained as presented in section 3.3.2.2, for the compressor.

Sizing The turbine is also represented as a truncated cone; therefore, the outlet area A_{out} is defined as follows, consistently with the previous models:

$$A_{out} = \dot{m} \frac{\sqrt{R T_{0,out}}}{p_{0,out} f(M_{out})} \quad (3.68)$$

The outlet diameter D_{out} is then given by:

$$D_{out} = 2 \sqrt{\frac{A_{out}}{\pi}} \quad (3.69)$$

The outlet Mach number M_{out} is prescribed to ensure velocity control within the component, preventing the occurrence of surge and choke phenomena, as it is chosen as $M_{out} \ll 1$.

The inlet cross-section is equal to the upstream duct area.

By construction, the previous relations ensure that:

$$\begin{aligned} A_{out} &> A_{in} \\ D_{out} &> D_{in} \end{aligned}$$

Mass Calculation The mass is computed as discussed in section 3.3.2.2. The same relations are maintained, with the exception of the interpolation curve for δ for a turbine:

$$\delta = 10^{0.14} \sigma^{-0.42+0.16 \log(\sigma)^3} \quad (3.70)$$

Consequently, the turbine mass m_t is obtained using a scaling law:

$$m_t = m_{t,ref} \frac{r_t}{r_{t,ref}} \quad (3.71)$$

Limitations This model is derived from that proposed by Planès et al. [6], and therefore the limitation of this model is the same as that defined for the compressor: only the radius of the turbomachine is calculated, without characterising its detailed geometry. Furthermore, the reference mass $m_{t,ref}$ and reference radius $r_{t,ref}$ used in the scaling law are assumed values, as no reference component of this kind is available in Planès et al. [6] or elsewhere in the literature.

3.3.2.6 Fans

The fan is a mechanical component used to generate an airflow in order to drive air through the system. It is employed at several locations in the system:

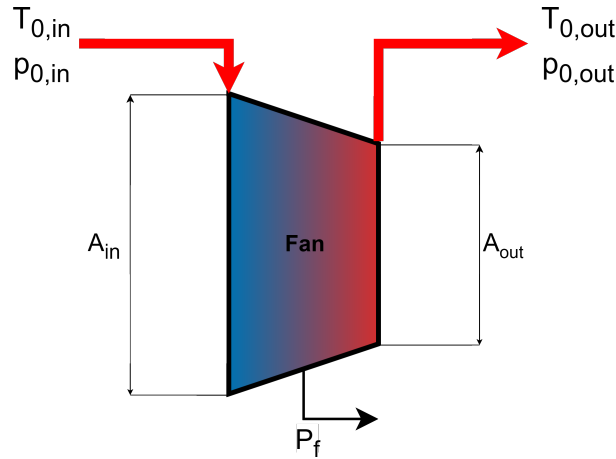


Figure 3.7: Fan Schematic

- Upstream of the air intake, in the context of the bleedless ECS, to move the incoming air toward the Electric Compressor;
- To expel the air leaving the Primary Heat Exchanger;
- To extract air from the cabin to ensure air recirculation;
- To guarantee the supply of air into the cabin.

In this work, only the ACM fan is considered.

The fan has been modelled as a compressor, since its effect on the airflow is to increase pressure and, consequently, temperature. It is therefore defined by two parameters:

- Pressure ratio π_f

$$\pi_f = \frac{p_{0,out}}{p_{0,in}} \quad (3.72)$$

$$\pi_f > 1 \quad (3.73)$$

- Efficiency η_f

$$0 \leq \eta_f \leq 1 \quad (3.74)$$

The values of π_f and η_f are significantly lower than those assumed for the compressor.

It should be noted that, in this modelling framework, the compressor assumptions (sub-section 3.3.2.2) and equations (sub-section 3.3.2.2) have been considered, replacing π_c with π_f and η_c with η_f .

Limitations As described, the fan model is derived from the compressor model, which is why it inherits the same limitations.

3.3.2.7 Mixing Unit

The mixing unit is the component of the system capable of mixing two or more flows. The basic mass and energy balance for the mixing of two flows follows the standard thermodynamic relation described by Moran and Shapiro [51]. However, for the three-flow mixing problem considered here, no dedicated methodology was found in the literature for the calculation of the bypass fraction x_{hx} , for the sizing, or for the mass estimation of the component. The model presented in this section, including the geometric approach used for the mass calculation, constitutes an original contribution of this thesis: the general thermodynamic relation of [51] is used only as a starting point.

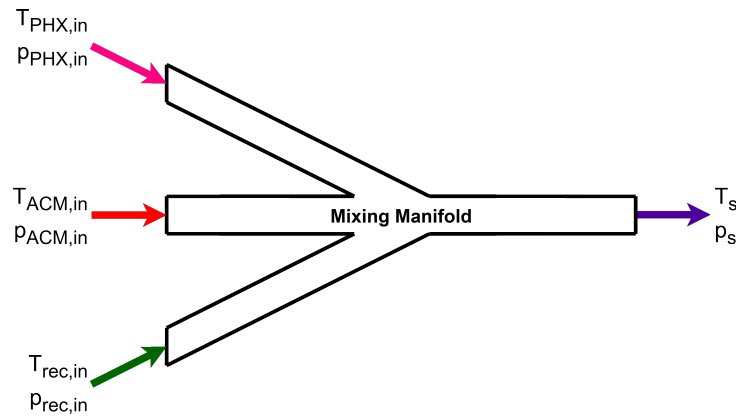


Figure 3.8: Mixing Unit Schematic

In the context of this system, the mixture is composed of three different air flows:

- Air flow coming from the turbine;
- Recirculated air flow coming from the passenger cabin;
- Bypass air flow coming from the Primary Heat Exchanger: this is used to correct the temperature of the mixture of the previous flows, so that the temperature of the resulting flow reaches the value required for the heat loads to be effectively managed. This procedure is described within the SAE Standard ARP85G [7], in which it is specified that the air coming from the heat exchanger must be regulated to a temperature not exceeding 204 °C.

As for the other components defined in the previous sections, the specific heat at constant pressure $c_{p,i}$ is likewise calculated in the Mixing Unit.

Assumptions The main assumptions adopted for this component are:

- **Requirements:**
 - The pressure of the flow entering the cabin must be greater than or equal to that which would occur at an altitude of 8 000 ft, i.e., 2 438 m; this requirement is assumed from the SAE Standard ARP85G [7];
 - The air entering the cabin must have a temperature between 2°C and 71°C, as specified in the SAE Standard ARP85G [7];
- **Thermodynamic assumptions:**

- The mixing of the flows occurs through an adiabatic process, i.e., one without heat exchange with the external environment;
- Air is treated as an ideal gas, and consequently the universal gas constant $R = 287$ J/(kg K) is considered constant;
- The flow is in steady-state conditions, so no temporal variations of the quantities defining its thermodynamic state are considered;
- The pressure of the mixed flow is assumed to be equal to the minimum among the pressures of the three incoming flows, i.e., equal to the pressure that would occur at an altitude of 8000 ft;
- The recirculation flow temperature is assumed equal to the cabin temperature, $T_{rec} = T_{cab}$, since no additional heat exchange is modelled between the cabin and the mixing unit inlet;
- The recirculation flow pressure is assumed equal to the cabin pressure, $p_{rec} = p_{cab}$, consistent with the cabin pressure requirement (Section 1.4);

• **Sizing assumptions:**

- The velocity of the cabin recirculation flow is assumed to be equal to 15 m/s;
- The bypass coefficient x_{hx} of the air coming from the Primary Heat Exchanger is limited, by definition, to the interval $[0, 1]$.

Equations The basic thermodynamic balance presented below, relating to the mixing of two flows, follows the relation described by Moran and Shapiro [51]:

$$\dot{m}_{ACM} c_{p,ACM} T_{ACM} + \dot{m}_{rec} c_{p,rec} T_{rec} = \dot{m}_{mix} c_{p,mix} T_{mix} \quad (3.75)$$

From the previous equation, it is possible to derive the total flow rate $\dot{m}_{mix}$ as the simple sum of the flow rates:

$$\dot{m}_{mix} = \dot{m}_{ACM} + \dot{m}_{rec} \quad (3.76)$$

The temperature, on the other hand, is obtained as:

$$T_{mix} = \frac{\dot{m}_{ACM} c_{p,ACM} T_{ACM} + \dot{m}_{rec} c_{p,rec} T_{rec}}{\dot{m}_{mix} c_{p,mix}} \quad (3.77)$$

The two input flows, defined in Equation 3.75, are:

- Air flow rate $\dot{m}_{ACM}$ coming from the Air Cycle Machine, i.e., from the turbine. This value takes into account the percentage of air bypassed from the Primary Heat Exchanger x_{hx} (at the first iteration it is equal to 0);
- Air flow rate $\dot{m}_{rec}$ coming from the passenger cabin. It is calculated as a function of:
 - Flow rate coming from the ACM, $\dot{m}_{ACM}$;
 - A recirculation percentage φ , referred to the total flow rate:

$$\varphi = \frac{\dot{m}_{rec}}{\dot{m}_{ACM} + \dot{m}_{rec}} \quad (3.78)$$

$$\dot{m}_{rec} = \dot{m}_{ACM} \frac{\varphi}{1 - \varphi} \quad (3.79)$$

The temperature resulting from the mix of the two input flows must comply with the supply temperature calculated as a function of the value of the Heat Loads to be compensated in order to keep the cabin temperature constant and equal to T_{cab} .

$$T_s = T_{cab} - \frac{HL_{tot}}{\dot{m}_s c_{p,s}} \quad (3.80)$$

The terms appearing in the previous equation are:

- T_s : required temperature of the flow entering the cabin in order to compensate for the heat loads;
- HL_{tot} : total heat loads, defined in Section 3.2;
- T_{cab} : cabin temperature;
- $\dot{m}_s$: total flow rate entering the cabin, given by the sum of the fresh air flow rate and the cabin air recirculation flow rate;

$$\dot{m}_s = \dot{m}_{fresh} + \dot{m}_{rec} \quad (3.81)$$

- $c_{p,s}$: specific heat at constant pressure of the total flow.

In the case where the mix temperature T_{mix} , calculated in Equation 3.77, is lower than the supply temperature T_s , it is then essential to consider the presence of the hot bypass air flow rate coming from the Primary Heat Exchanger.

Equation 3.76 is modified to accommodate the third flow, referred to as $\dot{m}_{hx}$:

$$\dot{m}_{ACM} c_{p,ACM} T_{ACM} + \dot{m}_{rec} c_{p,rec} T_{rec} + \dot{m}_{hx} c_{p,hx} T_{hx} = \dot{m}_s c_{p,s} T_s \quad (3.82)$$

The supply temperature is therefore defined as:

$$T_s = \frac{\dot{m}_{ACM} c_{p,ACM} T_{ACM} + \dot{m}_{rec} c_{p,rec} T_{rec} + \dot{m}_{hx} c_{p,hx} T_{hx}}{\dot{m}_s c_{p,s}} \quad (3.83)$$

It is important to define the bypass air flow rate from the PHX as:

$$\dot{m}_{hx} = x_{hx} \dot{m}_{fresh} \quad (3.84)$$

This flow rate represents a percentage, defined by x_{hx} , of the flow rate entering the system through the diffuser $\dot{m}_{fresh}$. Then, by definition, the flow rate coming from the ACM $\dot{m}_{ACM}$ is defined as:

$$\dot{m}_{ACM} = \dot{m}_{fresh} (1 - x_{hx}) \quad (3.85)$$

Furthermore, by construction, it can be shown that:

$$\begin{aligned} \dot{m}_{ACM} + \dot{m}_{hx} &= \dot{m}_{fresh} (1 - x_{hx}) + \dot{m}_{fresh} x_{hx} = \\ &= \dot{m}_{fresh} - \cancel{\dot{m}_{fresh} x_{hx}} + \cancel{\dot{m}_{fresh} x_{hx}} = \\ &= \dot{m}_{fresh} \end{aligned} \quad (3.86)$$

Equation 3.86 ensures the conservation of the flow rate within the system and within the mixing unit.

The calculation of the percentage of bypass air from the Primary Heat Exchanger is carried out starting from the following relation:

$$\dot{m}_{ACM} c_{p,ACM} T_{ACM} + \dot{m}_{rec} c_{p,rec} T_{rec} + \dot{m}_{hx} c_{p,hx} T_{hx} = \dot{m}_s c_{p,s} T_s \quad (3.87)$$

Substituting Equations 3.84 and 3.85, the following is obtained:

$$\dot{m}_{fresh} (1 - x_{hx}) c_{p,ACM} T_{ACM} + \dot{m}_{rec} c_{p,rec} T_{rec} + \dot{m}_{fresh} x_{hx} c_{p,hx} T_{hx} = \dot{m}_s c_{p,s} T_s \quad (3.88)$$

Then, by solving explicitly for x_{hx} , the percentage of air that needs to be bypassed at the outlet of the Primary Heat Exchanger is found:

$$x_{hx} = \frac{\dot{m}_s c_{p,s} T_s - \dot{m}_{rec} c_{p,rec} T_{rec} - \dot{m}_{fresh} c_{p,ACM} T_{ACM}}{\dot{m}_{fresh} (c_{p,hx} T_{hx} - c_{p,ACM} T_{ACM})} \quad (3.89)$$

Sizing The mixing manifold is defined as a component consisting of three inlets and one outlet. The three inlets correspond to the three flows defined in the previous sub-section, and have a circular cross-section, as does the outlet.

The sizing phase essentially consists of calculating the inlet and outlet diameters.

The diameter of the inlet section of the flow coming from the Air Cycle Machine, d_{ACM} [m], is equal to the diameter of the turbine outlet section, which is also equal to the diameter of the duct that allows the air to pass between the two components.

The diameter of the duct carrying the recirculation flow coming from the cabin is calculated as follows:

- Calculate the flow density ρ_{rec} [kg/m³] using the ideal gas equation:

$$\rho_{rec} = \frac{p_{rec}}{R T_{rec}} \quad (3.90)$$

The terms in the equation are:

- p_{rec} [Pa]: static pressure of the recirculation flow;
- R [J/(kg K)]: ideal gas constant, assumed to be equal to $R = 287$ J/(kg K);
- T_{rec} [K]: static temperature of the recirculation flow;
- Calculate the inlet section A_{rec} [m²], using the air flow rate $\dot{m}_{rec}$ [kg/s] and the flow velocity v_{rec} [m/s]:

$$A_{rec} = \frac{\dot{m}_{rec}}{\rho_{rec} v_{rec}} \quad (3.91)$$

- The diameter d_{rec} [m] is then derived from the following equation:

$$d_{rec} = 2 \sqrt{\frac{A_{rec}}{\pi}} \quad (3.92)$$

The diameter of the inlet section of the bypass flow coming from the Primary Heat Exchanger, d_{hx} [m], is equal to the diameter of the duct placed between these components.

Subsequently, the following assumptions are made:

- Thickness of the outlet section t [m] assumed to be equal to $t = 0.8$ mm; this value is an engineering assumption and is not derived from a structural sizing analysis, and it is discussed as a model limitation in Section 5.2;
- The material of which the component is made is Al-2024-T3 aluminium [52], widely used in aerospace applications and specifically identified as the baseline fuselage sheet alloy for Bombardier aircraft [53], defined by the following density $\rho_{Al} = 2780$ kg/m³;
- Presence of a corrective weight factor that accounts for the presence of fitting and joint elements, useful for connecting the component to the ducts of the respective flows, equal to $k_{fit} = 1.3$.

The diameter of the main body of the component, defined as d_{body} [m], is assumed to be equal to the maximum value among the diameters of the ducts connected to the mixing manifold.

$$d_{body} = \max(d_{ACM}, d_{hx}, d_{rec}) \quad (3.93)$$

This assumption proves to be essential, since it is intended to ensure that the cross-section of the mixing unit is always equal to or greater than that of the connected ducts, so that this component does not represent a bottleneck for any incoming flow.

The body length L_{body} [m] is estimated as:

$$L_{body} = 1.5 (d_{rec} + d_{hx} + d_{ACM}) \quad (3.94)$$

In particular, it is estimated in this way because it is intended to ensure that the fittings of the ducts connected to it have physical space along the lateral surface of the cylindrical body of the part. Therefore, it is assumed that the three ducts occupy, on the lateral surface, a space exactly equal to their own diameter. Furthermore, the factor equal to 1.5 is arbitrary.

Mass Calculation The mass estimation of the component is based on the calculation of the total surface area, composed of the following contributions:

- The lateral surface of the cylindrical body and the two circular bases, which correspond to the structural elements capable of conveying the flow resulting from the sum of the three inlet flows toward a single outlet section:

$$A_{body} = \pi d_{body} L_{body} + 2 \frac{\pi}{4} d_{body}^2 = \pi d_{body} L_{body} + \frac{\pi}{2} d_{body}^2 \quad (3.95)$$

- The lateral surfaces of the three inlet fittings are calculated as:

$$S_{ACM} = \pi d_{ACM} \cdot 1.5 d_{ACM} \quad (3.96)$$

$$S_{hx} = \pi d_{hx} \cdot 1.5 d_{hx} \quad (3.97)$$

$$S_{rec} = \pi d_{rec} \cdot 1.5 d_{rec} \quad (3.98)$$

The factor equal to 1.5 is equal to the assumed length of the fitting, obtained according to the same assumption used for the length of the mixing unit.

The total area A_{tot} [m²] is then equal to:

$$A_{tot} = A_{body} + S_{ACM} + S_{hx} + S_{rec} \quad (3.99)$$

Finally, the mass of the mixing unit m_{mu} [kg] is calculated by multiplying the material density ρ_{Al} by the minimum thickness t and by the total area A_{tot} , applying a local corrective factor for the component k_{fit} :

$$m_{mu} = k_{fit} \cdot \rho_{Al} A_{tot} t \quad (3.100)$$

Limitations The model adopted for the Mixing Unit assumes instantaneous and complete mixing of the three inlet flows, ignoring the phenomenon of incomplete mixing that may occur in a real component. Furthermore, the effects related to the different pressure of the three flows are neglected, assuming that the resulting flow has the pressure of one of the three flows, typically the lowest. Finally, the process is assumed to be adiabatic, and consequently heat exchanges with the surrounding structure during mixing are not considered.

3.3.2.8 Duct

Ducts are the components that allow the air flow to pass between the different components of the system.

The thermodynamic model follows [54], whilst the calculation of the dimensions and the mass constitutes an original contribution of this thesis.

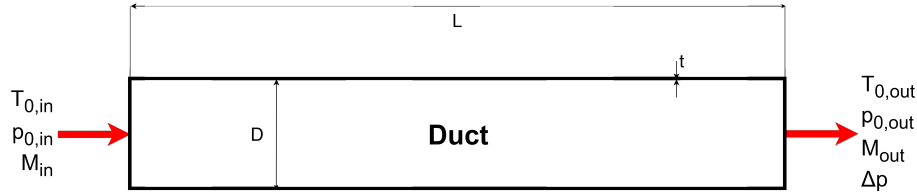


Figure 3.9: Duct Schematic

The behaviour of the ducts has been modelled by considering Fanno Flow [54]. This is a mathematical model that allows the calculation of the outlet conditions of a duct of length L [m] under adiabatic conditions ($q = 0$ [W]) and in the presence of wall viscous effects ($F_\tau \neq 0$ [N]).

The effects of viscosity translate into a distribution of wall friction stress along the entire duct. This effect results in a variation of the thermodynamic conditions of the outlet flow, with respect to the inlet conditions, in terms of temperature, pressure, and velocity. The viscous effects are quantified through the friction factor f [–], defined as $f = 4\bar{C}_f$, where $\bar{C}_f$ is the mean wall friction coefficient.

Assumptions The assumptions used for the definition of this component are:

- **Fluid dynamic assumptions:**

- The flow is considered compressible;
- The flow is considered adiabatic: $q = 0$; this assumption implies that the total temperature is conserved: $T_{0,2} = T_{0,1}$;
- The flow is considered viscous: $\tau \neq 0$;
- The flow is steady, and consequently there are no temporal variations of the quantities describing it;

- **Geometric assumptions:**

- The duct cross-section A is constant;

Equations Considering a duct of length L [m] and diameter D [m], given the inlet conditions, it is possible to calculate the outlet conditions using the following methodology.

The governing function of this component is defined by the normalised critical length of the duct. This quantity, expressed as a function of either the inlet or the outlet Mach number, represents the length that would make the duct critical:

$$\frac{fL^*}{D} = \frac{1 - M^2}{\gamma M^2} + \frac{\gamma + 1}{2\gamma} \ln \left[\frac{(\gamma + 1) M^2}{2 + (\gamma - 1) M^2} \right] \quad (3.101)$$

Knowing the inlet Mach number M_1 [–], it is possible to calculate the normalised critical length $\left(\frac{fL^*}{D}\right)_1$ and, knowing the geometry of the duct, the normalised length of the given duct $\left(\frac{fL}{D}\right)$. In order to calculate the outlet Mach number M_2 [–], it is important to define the relationship between the normalised critical lengths associated with the duct:

$$\left(\frac{fL}{D}\right) = \left(\frac{fL^*}{D}\right)_1 - \left(\frac{fL^*}{D}\right)_2 \quad (3.102)$$

Consequently, knowing the terms $\left(\frac{fL^*}{D}\right)_1$ and $\left(\frac{fL}{D}\right)$, it is possible to calculate the term $\left(\frac{fL^*}{D}\right)_2$:

$$\left(\frac{fL^*}{D}\right)_2 = \left(\frac{fL^*}{D}\right)_1 - \left(\frac{fL}{D}\right) \quad (3.103)$$

Then, using the Newton-Raphson method, it is possible to determine the value of the outlet Mach number M_2 .

This is carried out iteratively, by defining the derivative with respect to the Mach number, $\frac{dF}{dM}$, of the function $F(M)$ derived from Equation 3.101, so that the outlet Mach number M_2 can be calculated as follows:

$$M_i = M_{i-1} - \frac{F(M_{i-1})}{dF(M_{i-1})} \quad (3.104)$$

Where M_i is the current Mach number, and M_{i-1} is the Mach number calculated at the previous iteration.

The derivative, $\frac{dF}{dM}$, is presented below:

$$\frac{dF}{dM} = -\frac{2}{\gamma M^3} + \frac{\gamma+1}{2\gamma} \left(\frac{2}{M} - \frac{(\gamma-1)M}{1 + \frac{\gamma-1}{2}M^2} \right) \quad (3.105)$$

Once the outlet Mach number M_2 has been defined, it is possible to calculate the outlet thermodynamic quantities.

In particular, these are calculated by means of ratios referred to the critical conditions. The ratios are defined below:

- Ratio between the static temperatures:

$$\frac{T}{T^*} = \frac{\gamma+1}{2 + (\gamma-1)M^2} \quad (3.106)$$

- Ratio between the static pressures:

$$\frac{p}{p^*} = \frac{1}{M} \sqrt{\frac{\gamma+1}{2 + (\gamma-1)M^2}} \quad (3.107)$$

The thermodynamic quantities are therefore calculated by means of chains of ratios:

$$T_2 = \frac{T_2}{T^*} \frac{T^*}{T_1} T_1 \quad (3.108)$$

$$p_2 = \frac{p_2}{p^*} \frac{p^*}{p_1} p_1 \quad (3.109)$$

Where the ratios $\frac{T_i}{T^*}$ and $\frac{p_i}{p^*}$ are calculated by substituting the Mach number M_i for the Mach number M , respectively, in the formulas in Equations 3.106 and 3.107.

The total pressure is calculated using the ratio between the total pressures referred to the critical condition:

$$\frac{p_0}{p_0^*} = \frac{1}{M} \left[\frac{2 + (\gamma-1)M^2}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \quad (3.110)$$

Then, by means of a chain of ratios, it is possible to define the outlet total pressure $p_{0,2}$ [Pa] as:

$$p_{0,2} = \frac{p_{0,2}}{p_0^*} \frac{p_0^*}{p_{0,1}} p_{0,1} \quad (3.111)$$

Mass Calculation The mass of the duct is calculated by considering the duct as a hollow cylinder.

First, knowing the diameter D , the outer radius r_{out} [m] is derived:

$$r_{out} = \frac{D}{2} \quad (3.112)$$

The inner radius r_{in} [m], on the other hand, has been calculated considering a thickness t [m]:

$$r_{in} = r_{out} - t \quad (3.113)$$

Finally, the mass m_{duct} [kg] is calculated using the formula for the volume of a hollow cylinder and the density of the material of which it is made:

$$m_{duct} = \pi (r_{out}^2 - r_{in}^2) L \rho_{Al} \quad (3.114)$$

In Equation 3.114, the term L is the length of the duct and ρ_{Al} is the density of the material, assumed to be Al-2024-T3 [52], consistent with its established use as the baseline fuselage sheet alloy for Bombardier aircraft [53]. The duct thickness is assumed equal to $t = 1.5$ mm, representative of thin-walled aerospace aluminium ducting; this value, together with the mixing unit thickness (Section 3.3.2.7), is discussed as a model limitation in Section 5.2.

Limitations The model adopted for the characterisation of the ducts assumes a straight duct with a constant cross-section and a uniform friction factor along the entire length. Consequently, the additional pressure losses due to bends, elbows, or fittings typical of real ducts on board an aircraft are not considered, as these typically do not follow a straight path.

3.3.2.9 Air Cycle Machine Shaft

As defined in Section 1.2.2.2, the Air Cycle Machine is composed of three distinct turbomachines: the compressor, the turbine, and the fan, mechanically connected by means of a common shaft. The turbine supplies the work, obtained from the expansion of the air, necessary to drive the compressor and the fan through this shaft.

Assumptions The assumptions that have been adopted for the modelling of the shaft are reported below.

- **Mechanical assumptions:**

- The mechanical efficiencies $\eta_{t,m}$, $\eta_{c,m}$, and $\eta_{f,m}$, relating respectively to the turbine, the compressor, and the fan, are considered constant and account for the friction losses in the bearings;
- The net power at the shaft is considered to be zero, ensuring the balance between the power supplied by the turbine and that absorbed by the compressor and the fan.

Equations The power balance at the shaft requires that the power supplied by the turbine be equal to the sum of the power absorbed by the compressor and the fan:

$$\eta_{t,m} P_t = \frac{P_c}{\eta_{c,m}} + \frac{P_f}{\eta_{f,m}} \quad (3.115)$$

where $\eta_{t,m}$, $\eta_{c,m}$, and $\eta_{f,m}$ are the mechanical efficiencies of the turbine, the compressor, and the fan, respectively, which account for the friction losses in the bearings.

In other words, the net power at the shaft is zero:

$$P_{net} = \eta_{t,m} P_t - \left(\frac{P_c}{\eta_{c,m}} + \frac{P_f}{\eta_{f,m}} \right) = 0 \quad (3.116)$$

If this condition is not met, the following two situations may occur:

- The net power at the shaft is positive and different from zero $P_{net} > 0$: in this case, uncontrolled acceleration of the shaft occurs;
- The net power at the shaft is negative and different from zero $P_{net} < 0$: in this case, deceleration occurs.

In both conditions, the turbomachines are subjected to off-design operating conditions, resulting in an increase in stresses on the bearings and possible fatigue failure.

Limitations Although this component has not been treated as a standalone component, its presence in a real system is non-negligible in terms of mass and of the transient and inertial effects it entails. This model, in practice, neglects these effects by assuming that the rotational speed is constant; consequently, the acceleration/deceleration transients during regime variations are neglected, as are vibrations or shaft flexibility effects. In this model, the mass is calculated by means of a corrective factor, which is not representative of the true mass of the real component, and the power balance is assumed to be instantaneous and steady-state, with constant mechanical efficiencies for the turbine, compressor, and fan.

3.3.3 Total System Mass

The total mass of the ECS system m_{tot} [kg] is obtained as the sum of the masses of the individual components, corrected by a factor k_m [–] that accounts for elements not explicitly modelled, such as fastening elements (screws, bolts), support brackets, gaskets, electrical wiring, and the Air Cycle Machine shaft:

$$m_{tot} = k_m \sum_{i=1}^N m_i \quad (3.117)$$

In Equation 3.117, the term N is the total number of components of the ECS system, and the value of k_m was assumed to be equal to $k_m = 1.5$.

3.3.4 Model Validation

The validation of the model was carried out using data available in the literature, in particular from the analysis by Negi and Ranganayakulu [55] on the ECS system of an Airbus A320.

The model presented by the authors considers:

- The presence of humidity only in the calculation of the Reheater and Water Separator components, which have been neglected within the scope of this model;
- The absence of pressure loss within the ducts, which this model takes into account, as defined in sub-section 3.3.2.8;
- It considers the specific heat at constant pressure c_p [J/(kg·K)] as a constant parameter, whereas in this model it is calculated as a function of temperature and pressure;
- The thermodynamic model of the components is carried out using the same equations, with the exception of the calculation of the turbine outlet conditions, which is assumed to be the same as that defined by the same authors in [56].

Overall, the data proposed by the authors in [55] can be used because, in the same components defined within the scope of this thesis, the presence of humidity is not considered; the pressure loss is low, and the variation of the specific heat at constant pressure c_p with respect to the standard value $c_p = 1005 \text{ J/(kg}\cdot\text{K)}$ is minimal.

In Table 3.4, the data used to carry out the comparison are presented.

Table 3.4: Parameters Used for the Validation of the A320 ECS Model

Category	Parameter	Symbol	Value
Pressure ratios	Compressor pressure ratio	π_c	1.3
	Turbine pressure ratio	π_t	2.1
	Fan pressure ratio	π_f	1.012
	Electric compressor pressure ratio	π_{e-CMP}	3.2
Isentropic efficiencies	ECS turbine	η_t	0.75
	ECS compressor	η_c	0.75
	Fan	η_f	0.25
	Diffuser	η_d	0.95
HX effectiveness	P-HX	ε_{P-HX}	0.55
	S-HX	ε_{S-HX}	0.55
Air flowrates	Bleed-air flowrate (kg/s)	$\dot{m}_{\text{bleed}}$	0.4
	Ram air flowrate (kg/s)	$\dot{m}_{\text{ram}}$	0.818

Below, the charts extrapolated from [55] can be examined. The data were extracted using the WebPlotDigitizer software [57].

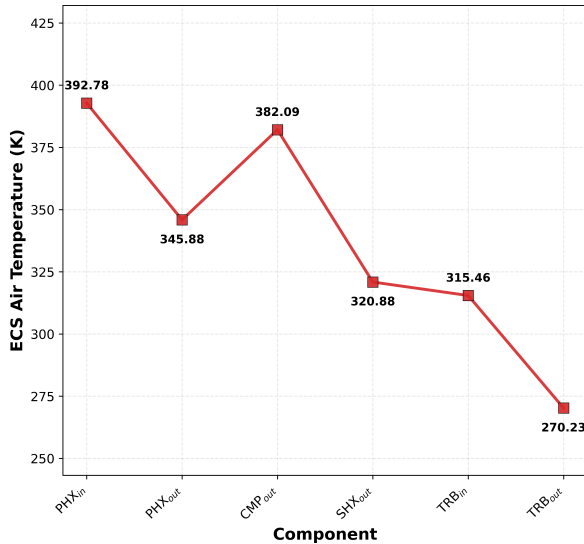


Figure 3.10: Reference Temperature Values Digitised from the Validation Chart in [55]

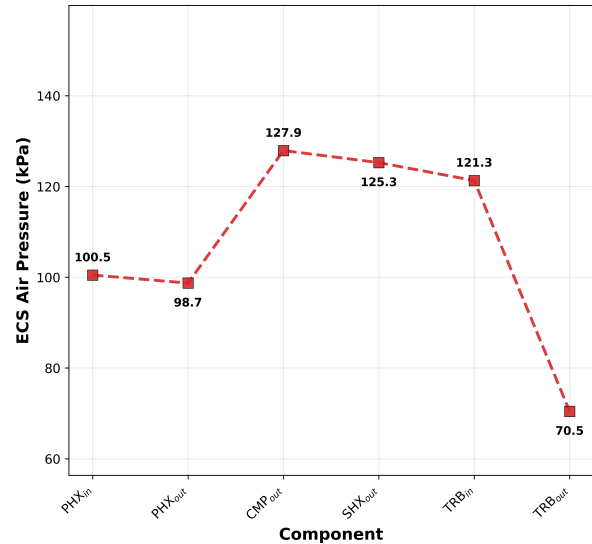


Figure 3.11: Reference Pressure Values Digitised from the Validation Chart in [55]

In Table 3.5, the inlet and outlet values for the components considered in the thermodynamic validation are presented, along with the percentage error with respect to what was extrapolated from the charts of the reference paper.

Table 3.5: Comparison Between Experimental Data and Model: Pressure and Temperature at the Main Cycle Stations

Station	Pressure [kPa]			Temperature [K]		
	Ref.	Model	Err. [%]	Exp.	Model	Err. [%]
Primary HX Inlet	100.48	100.48	0.00	392.78	392.78	0.00
Primary HX Outlet	98.72	98.47	0.25	345.88	342.46	0.99
Compressor Outlet	127.92	128.34	0.33	382.09	381.78	0.08
Secondary HX Outlet	125.26	125.36	0.08	320.88	321.11	0.07
Turbine Inlet	121.31	121.31	0.00	315.46	315.46	0.00
Turbine Outlet	70.45	57.77	18.00	270.23	270.27	0.01
Mean Abs. Error [%]	3.11			0.19		

As can be seen from Table 3.5, the mean absolute error of the temperatures is very low, while that of the pressures is significantly higher, attributable to an inconsistency in the data extrapolated from the chart of the reference paper, rather than to an error in the model proposed in this thesis, as demonstrated below.

In particular, the expansion ratio π_t implicit in the pressure values read from the chart ($p_{0,in}/p_{0,out} \simeq 121.31/70.45 \simeq 1.72$) does not match the value of $\pi_t = 2.1$ defined in Table 3.4. Using Equation 3.66, considering the turbine inlet temperature $T_{0,in}$ equal to that of the Secondary Heat Exchanger outlet (already validated with an error of 0.07%) and the declared efficiency $\eta_t = 0.75$, the value of π_t consistent with the observed outlet temperature can be determined: using $\pi_t = 2.1$ yields an error of 0.01% on $T_{0,out}$, whereas using the value implicit in the chart, $\pi_t \simeq 1.72$, the error rises to 4.15%. This confirms that $\pi_t = 2.1$ is the value consistent with the rest of the paper's data, and that the discrepancy in the turbine outlet pressure is attributable to a representation error in the original chart rather than a limitation of the model developed in this thesis.

The validation of the masses and dimensions of the components was not carried out, since no reference data are available in the literature for this comparison.

The model can be considered validated with a mean absolute error of less than 1% on the fundamental thermodynamic quantities, with the exception of the turbine outlet pressure, whose discrepancy, as discussed previously, is attributable to the reference data and not to the model itself.

3.4 Fuel-Cells Powertrain Modelling

The objective of this section is to provide a complete overview of the Fuel Cell model implemented in this project. The model was derived from that produced by Cavini [8, 9], available within the research group in which this thesis work was carried out and already validated through comparison against commercial Fuel Cell datasets.

The model described here is used in Chapter 4 to estimate the hydrogen, oxygen, and water consumption of the Fuel Cell in the different flight phases, and to evaluate its impact in terms of weight on the components of the bleedless ECS system.

3.4.1 Assumptions

The presented model is based on the following assumptions:

- The fuel cell is treated as a black box. The thesis builds on the fundamental mass balance relations reported by Cavini in [9] for the hydrogen flow rate $\dot{m}_{H_2}$ [kg/s], the oxygen flow rate $\dot{m}_{O_2}$ [kg/s], the air flow rate $\dot{m}_{air}$ [kg/s], and the water flow rate $\dot{m}_{H_2O}$ [kg/s], expressed as a function of the Fuel Cell current I_{fc} [A], and derives their closed-form expressions as a function of the sole required electrical power P [W] and the cell efficiency η [-]. The internal electrochemical modelling developed by Cavini in [8, 9] is not reproduced in this thesis;
- The model is steady-state: the transients related to the start-up of the Fuel Cell or to rapid electrical load variations are not considered;
- The working fluid is modelled as an ideal gas with constant properties:
 - $\gamma = 1.4$;
 - $R = 287 \text{ J}/(\text{kg} \cdot \text{K})$;
- The temperature of the hydrogen entering the cell is considered to be between 60 and 80 °C; this value can either be set directly or derived from heat exchange through the heat exchangers of the system, in which hydrogen is used as the cooling fluid;
- The temperature of the air entering the cell is considered to be between 0 and 40 °C;
- The pressure of the incoming air is considered equal to atmospheric pressure: $p_{air} = 1 \text{ atm}$;
- The reaction enthalpy of hydrogen HHV is considered constant and equal to $\Delta h_{HHV} = 141.8 \text{ MJ/kg}$, regardless of the temperature and pressure conditions of the fluid;
- The efficiency of the Fuel Cell is obtained exclusively as a function of the ratio P/P_{max} , without considering the effects due to operating temperature and pressure on the curve;
- The air excess coefficient λ_{O_2} is considered constant and equal to 1.8;
- The molar fraction of oxygen in the air y_{O_2} is considered constant and equal to 0.21;
- The presence of humidity in the air is not considered, consistently with the ECS model, in which humidity is likewise not modelled in any component, as defined in Section 3.3.1.

The constants used in the model are presented in Table 3.6.

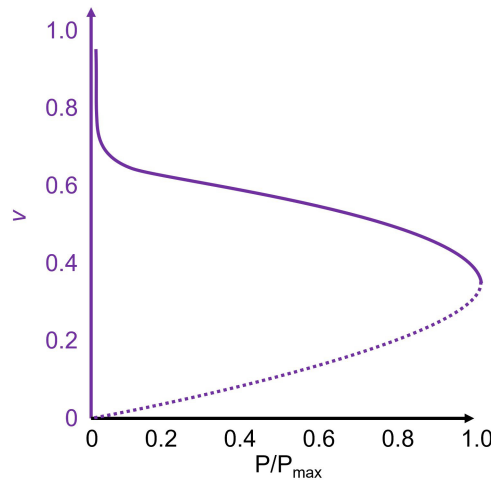
3.4.2 Equations

Efficiency The efficiency of the Fuel Cell was derived starting from the chart presented in Figure 3.12, obtained from [9]. This thesis neglects the points for efficiencies lower than 0.4, in line with the same choice made by Cavini [9] to exclude the unstable branch of the bistable curve.

The data in Figure 3.12 were extrapolated using the WebPlotDigitizer software [57] and interpolated using a Python function defined in the model. This approach makes it possible, by setting the value of P/P_{max} , to obtain the efficiency of the Fuel Cell, which is useful for defining the consumable flow rates in the following sections.

Table 3.6: Parameters Used for the Fuel Cell Model

Category	Parameter	Symbol	Value
Fundamental constants	Faraday constant	F	96485 A s/mol
	Hydrogen HHV	Δh_{HHV}	141.8 MJ/kg
Molar masses	Hydrogen	M_{H_2}	2.01568 g/mol
	Oxygen	M_{O_2}	31.9988 g/mol
	Water	M_{H_2O}	18.01528 g/mol
	Air	M_{air}	28.96 g/mol
Air composition / excess	O ₂ molar fraction in air	y_{O_2}	0.21
	Stoichiometric air excess ratio	λ_{O_2}	1.8
Operating temperatures	Hydrogen inlet temperature	T_{H_2}	60–80 °C
	Air inlet temperature	T_{air}	0–40 °C
Operating pressure	Air inlet pressure	p_{air}	1 atm

Figure 3.12: $\eta - P/P_{\max}$ [9]

Calculation of the $P/P_{\max}$ ratio In order to define the $P/P_{\max}$ ratio, useful for calculating the efficiency, this thesis first defines the value of the maximum required power $P_{\max}$ [W]. The value of $P_{\max}$ is constant for the specified flight phase and operating condition, and is obtained from the following equation:

$$P_{\max} = P_{\text{prop}_{\max}} + P_{\text{ECS}_{\max}} + P_{\text{avi}_{\max}} \quad (3.118)$$

An explanation of the terms appearing in Equation 3.118 is provided below:

- $P_{\text{prop}_{\max}}$ is the maximum power of the single engine, referring to the Honeywell HTF-7000 of the Bombardier Challenger 300;
- $P_{\text{ECS}_{\max}}$ is the maximum power required by the ECS system, relating to the condition in which the maximum energy expenditure occurs. In particular, it refers to the power required by the electric motor, which supplies power to the electric compressor;
- $P_{\text{avi}_{\max}}$ is the power required by the avionics.

The value of P is calculated for the single operating condition and is given by the sum of the same factors, as indicated below:

$$P = P_{\text{prop}} + P_{\text{ECS}} + P_{\text{avi}} \quad (3.119)$$

Finally, the value of P/P_{max} is defined as follows:

$$\frac{P}{P_{\text{max}}} = \frac{P_{\text{prop}} + P_{\text{ECS}} + P_{\text{avi}}}{P_{\text{prop,max}} + P_{\text{ECS,max}} + P_{\text{avi,max}}} \quad (3.120)$$

Hydrogen Flow Rate The hydrogen flow rate necessary to produce sufficient electrical power P [W], as defined in the previous sub-section, is defined below.

Starting from the efficiency formula:

$$\eta = \frac{2 F V_{fc}}{N \Delta h_{HHV}} \quad (3.121)$$

In Equation 3.121, F is the Faraday constant ($F = 96485 \frac{\text{As}}{\text{mol}}$), V_{fc} is the voltage of the fuel cell, N is the number of cells in series, and Δh_{HHV} is the molar enthalpy of formation of hydrogen. The power is defined as:

$$P = V_{fc} I_{fc} \quad (3.122)$$

In Equation 3.122, I_{fc} is the current of the fuel cell.

It can be shown that the hydrogen flow rate $\dot{m}_{\text{H}_2}$ can be obtained with the following relation, following Cavini [9]:

$$|\dot{m}_{\text{H}_2}| = M_{\text{H}_2} N \frac{I_{fc}}{2 F} \quad (3.123)$$

In Equation 3.123, M_{H_2} is the molar mass of hydrogen ($M_{\text{H}_2} = 2.01568 \frac{\text{g}}{\text{mol}}$).

Consistently with the convention adopted by [9], the hydrogen and oxygen flow rates are negative, as they represent mass removed from the gas channels (in fact, they are consumed reactants), while the water flow rate is positive, as it is the reaction product introduced into the system. In this thesis, reference is made to the absolute value of the flow rates $|\dot{m}_i|$, since the relevant aspect is the magnitude of the exchanged mass rather than the direction of the flow.

From the previous relation, Equation 3.123, I_{fc} is derived as:

$$I_{fc} = \frac{2 |\dot{m}_{\text{H}_2}| F}{M_{\text{H}_2} N} \quad (3.124)$$

From Equation 3.121, on the other hand, V_{fc} is derived:

$$V_{fc} = \frac{N \Delta h_{HHV} \eta}{2 F} \quad (3.125)$$

Substituting I_{fc} and V_{fc} into Equation 3.122:

$$P = \frac{|\dot{m}_{\text{H}_2}| \Delta h_{HHV} \eta}{M_{\text{H}_2}} \quad (3.126)$$

Therefore, the molar hydrogen flow rate can be obtained as a function of the known parameters:

$$|\dot{m}_{\text{H}_2}| = \frac{P M_{\text{H}_2}}{\eta \Delta h_{HHV_{\text{molar}}}} \quad (3.127)$$

Equation 3.127 can be rewritten as a function of the mass-specific enthalpy, knowing that:

$$\Delta h_{HHV_{\text{molar}}} = M_{\text{H}_2} \cdot \Delta h_{HHV_{\text{mass}}} \quad (3.128)$$

Finally, it is possible to convert from the molar flow rate to the mass flow rate according to the following relation:

$$|\dot{m}_{\text{H}_2}| = \frac{P M_{\text{H}_2}}{\eta M_{\text{H}_2} \Delta h_{HHV_{\text{mass}}}} = \frac{P}{\eta \Delta h_{HHV_{\text{mass}}}} \quad (3.129)$$

Oxygen Flow Rate The oxygen flow rate necessary to ensure the reaction is defined, following Cavini [9], as a function of the following relation:

$$\dot{m}_{O_2} = -M_{O_2} N \frac{I_{fc}}{4 F} \quad (3.130)$$

Multiplying and dividing by the molar mass of hydrogen M_{H_2} , the following is obtained:

$$|\dot{m}_{O_2}| = \frac{M_{O_2}}{2 M_{H_2}} \underbrace{M_{H_2} N \frac{I_{fc}}{2 F}}_{|\dot{m}_{H_2}|} \quad (3.131)$$

Finally, it is possible to calculate the oxygen flow rate $\dot{m}_{O_2}$ as a function of the previously defined hydrogen flow rate $\dot{m}_{H_2}$, reflecting the stoichiometry of the reaction:

$$|\dot{m}_{O_2}| = |\dot{m}_{H_2}| \frac{M_{O_2}}{2 M_{H_2}} \quad (3.132)$$

As can be seen from Equation 3.132, the oxygen flow rate can be calculated as a function of the previously defined hydrogen flow rate and the molar mass of oxygen M_{O_2} and hydrogen M_{H_2} .

Water Flow Rate As defined in the introduction of the chapter, the product of the reaction is water.

In particular, reflecting the stoichiometry of the reaction and following Cavini [9], the water flow rate $\dot{m}_{H_2O}$ can be defined as:

$$\dot{m}_{H_2O} = M_{H_2O} N \frac{I_{fc}}{2 F} \quad (3.133)$$

Multiplying and dividing by M_{H_2} :

$$\dot{m}_{H_2O} = \frac{M_{H_2O}}{M_{H_2}} \underbrace{M_{H_2} N \frac{I_{fc}}{2 F}}_{|\dot{m}_{H_2}|} \quad (3.134)$$

Finally, the following is obtained:

$$|\dot{m}_{H_2O}| = |\dot{m}_{H_2}| \frac{M_{H_2O}}{M_{H_2}} \quad (3.135)$$

As can be seen from Equation 3.135, the water flow rate can be calculated as a function of the previously defined hydrogen flow rate and the molar mass of water M_{H_2O} and hydrogen M_{H_2} .

Air Flow Rate The reaction requires the availability of hydrogen and oxygen. Clearly, within the scope of civil aviation, it is unthinkable to consider carrying pure oxygen on board the aircraft to ensure the correct reaction, since, when flying within the troposphere, it is possible to obtain it from the air.

The maximum air flow rate is defined as:

$$\dot{m}_{air_{max}} = \frac{N I_{max} \lambda_{O_2} M_{air}}{4 F y_{O_2}} \quad (3.136)$$

Equation 3.136 can be rewritten by multiplying and dividing by M_{O_2} :

$$\dot{m}_{air} = \underbrace{\frac{N I_{fc} M_{O_2}}{4 F}}_{|\dot{m}_{O_2}|} \frac{\lambda_{O_2} M_{air}}{y_{O_2} M_{O_2}} \quad (3.137)$$

Then,

$$|\dot{m}_{air}| = |\dot{m}_{O_2}| \frac{M_{air}}{M_{O_2}} \frac{\lambda_{O_2}}{y_{O_2}} \quad (3.138)$$

As can be seen from Equation 3.138, the air flow rate $\dot{m}_{air}$ depends on two fundamental parameters:

- The molar (or mass) fraction y_{O_2} of oxygen in the air, i.e., how much of it is actually made up of oxygen. The value considered is $y_{O_2} \simeq 0.21$. Consequently, knowing the required oxygen flow rate, it is essential to scale the air flow rate so as to extract the amount required from it;
- The air excess coefficient λ_{O_2} , which indicates how much additional oxygen, with respect to the minimum stoichiometric amount required by the reaction, is actually supplied to the Fuel Cell. Typically, the value of λ_{O_2} is greater than 1, since it is intended to ensure that:
 - The oxygen is well distributed over the cathode;
 - Zones in which the oxygen is insufficient are avoided, thereby preventing the degradation of performance.

3.4.3 Model Limitations

The presented model, being simplified, entails the following limitations:

- It does not allow the analysis of transient phenomena, such as start-up or rapid load variations;
- It does not account for the effects related to the temperature and pressure of the cell on the efficiency curve;
- It considers the Balance of Plant (BoP) in a reduced form.

These simplifications and limitations have been deemed acceptable within the scope of a preliminary analysis of the ECS system, since the main objective is to evaluate the consumption and the mass impact, rather than the detailed characterisation of the cell.

4 Case Studies

The objective of this chapter is to define the sizing procedure of the bleedless ECS system, the different integrations envisaged for the Fuel Cell, the sizing of the integrated ECS system, the comparison between the different integrations, and the estimation of hydrogen H_2 and air consumption, and water H_2O production during a simple mission.

4.1 System Sizing Methodology

Having defined the ECS system with its components and their connections, this section defines the sizing methodology of the system. This work initially considers three worst-case conditions, following the approach proposed by Fioriti and Di Fede [14]; Table 4.1 describes these conditions.

Table 4.1: Design Cases for the Thermal Analysis

Case Name	Condition	Flight Phase	Altitude	ISA Deviation	Number of Passengers	Day Condition
Hot Day Ground	Cooling	Stationary on Ground	Sea-level	$\Delta T = +25$ K	Maximum	Day-time
Cold Day Ground	Heating	Stationary on Ground	Sea-level	$\Delta T = -35$ K	Minimum	Night-time
Cold Day Cruise	Heating	In Flight	FL250	$\Delta T = -20$ K	Minimum	Night-time

Following the crew estimation formula in Equation 3.4, the Maximum and Minimum number of passengers correspond to:

- Maximum: 10 passengers + 1 cabin crew + 2 flight crew;
- Minimum: 0 passengers + 0 cabin crew + 2 flight crew.

These conditions represent the extremes of the thermal demand of the system, capturing the worst case during both cooling and heating, on the ground and in flight.

For each worst condition defined in Table 4.1, this work carries out an independent sizing of the ECS system, obtaining, for each component, the mass and dimension values corresponding to that operating condition. Since each component may be sized under a different condition from the others (for example, the electric compressor may be critical in the Cold Day Cruise condition, since the external ambient pressure is low and greater power is required), this work combines the three results into a single design envelope, selecting, for each component, the sizing corresponding to the most critical condition among the three.

Table 4.2 presents the conditions used to size each component, selected as the most critical among the three worst-case conditions.

Table 4.2: Envelope Sizing Conditions

Component	Variable	Condition
Diffuser Fresh Air	Flow rate $\dot{m}_{fresh}$ [kg/s]	Maximum flow rate required
Diffuser Ram Air	Flow rate $\dot{m}_{ram}$ [kg/s]	Maximum flow rate required
Electric Compressor	Compressor power P_{e-CMP} [W]	Maximum power required
Primary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
Secondary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
ACM Compressor	Compressor power $P_{ACM CMP}$ [W]	Maximum power required
ACM Turbine	Turbine power $P_{ACM TRB}$ [W]	Maximum power required
ACM Fan	Fan power $P_{ACM FAN}$ [W]	Maximum power required

In this context, sizing a single component can also determine the dimensions and mass of other components not listed in Table 4.2, such as the ducts.

Table 4.3 defines these dependencies.

Table 4.3: Response Variables and Driven Components

Response	Driven Component / Duct
Electric Compressor Power	Electric Compressor
	Electric Motor
	Duct: E-Compressor $\rightarrow$ PHX
Compressor Power (ACM)	ACM Compressor
	Duct: Compressor $\rightarrow$ SHX
Turbine Power (ACM)	ACM Turbine
	Duct: Turbine $\rightarrow$ Manifold
Fan Power (ACM)	ACM Fan
PHX Effectiveness	Primary Heat Exchanger
	Duct: PHX $\rightarrow$ Compressor
	Duct: PHX $\rightarrow$ SHX
	Duct: PHX $\rightarrow$ Manifold
SHX Effectiveness	Secondary Heat Exchanger
	Duct: SHX $\rightarrow$ Turbine
	Duct: SHX $\rightarrow$ Fan
Diffuser Fresh Air Flow Rate	Fresh Air Diffuser
	Duct: Diffuser $\rightarrow$ E-Compressor
	Mixing Manifold
	Duct: Manifold $\rightarrow$ Cabin
Diffuser Ram Air Flow Rate	Ram Air Diffuser
	Duct: Diffuser $\rightarrow$ PHX

This work assumes that the fresh air diffuser drives the sizing of the Mixing Unit, since every

air flow rate value passing through it (i.e., the air coming from the cabin and the bypass air from the PHX) depends on the external air $\dot{m}_{fresh}$. Finally, this sizing procedure establishes the baseline ECS against which the Fuel Cell integration configurations, presented in the following sections, are compared.

4.2 Fuel Cell Integration

This section explores possible ways to integrate Fuel Cells on a Business Jet category aircraft, evaluating whether the cooling/heating power of the system itself and/or the compressed air can supply the cell.

The following subsections present the individual integrations.

4.2.1 Integration Concept 1 (IC1): compressed air bypass after ECS electric compressor

The schematic of the system is represented in Figure 4.1.

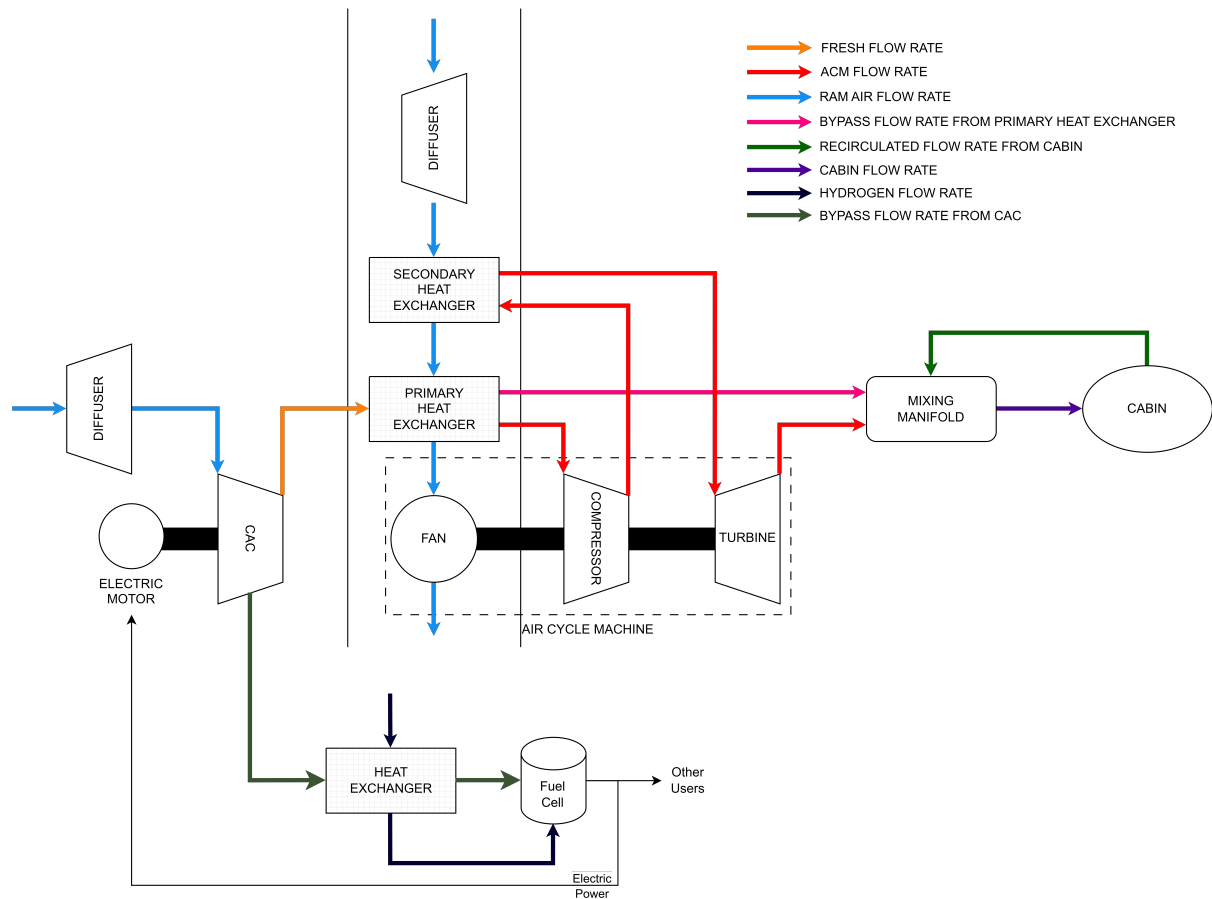


Figure 4.1: IC1: Compressed Air Bypass After ECS Electric Compressor

The integration involves modifying the system as follows:

- The electric compressor compresses the air drawn from the outside through the intake, in order to ensure that a satisfactory pressure value is reached, typically higher than atmospheric pressure;
- The system bypasses part of the air toward the fuel cell, while the rest is directed to the ECS system and will be used for cabin conditioning, as is the case for the conventional

ECS;

- The air bypassed and directed to the cell, although it has a pressure sufficient for the operation of the cell itself, has a very high temperature, outside the ranges defined in Table 3.6. Consequently, this configuration integrates a heat exchanger that uses hydrogen as the cooling fluid;
- As in the ECS system, this configuration also includes the ducts between components.

This configuration therefore makes it possible to avoid increasing the number of rotating components of the system, at the cost of introducing an additional component for the thermal management of the air directed to the cell.

In this configuration, the Fuel Cell supplies electrical power to the following components:

- Propulsion, the system is sized under One Engine Inoperative condition¹;
- Onboard avionics and electrical components;
- ECS system: in this integration, the only component that requires electrical power is the electric motor connected to the electric compressor.

4.2.1.1 Envelope Sizing Methodology

Table 4.4 defines the envelope sizing conditions of the ECS system for this configuration, accounting for both the ECS components and those related to the Fuel Cell integration. The results below first isolate the ECS system before presenting the overall system.

Table 4.4: Envelope Sizing Conditions (IC1)

Component	Variable	Condition
Diffuser Fresh Air	Flow rate $\dot{m}_{fresh}$ [kg/s]	Maximum flow rate required
Diffuser Ram Air	Flow rate $\dot{m}_{ram}$ [kg/s]	Maximum flow rate required
Electric Compressor	Compressor power P_{e-CMP} [W]	Maximum power required
Primary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
Secondary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
ACM Compressor	Compressor power $P_{ACM CMP}$ [W]	Maximum power required
ACM Turbine	Turbine power $P_{ACM TRB}$ [W]	Maximum power required
ACM Fan	Fan power $P_{ACM FAN}$ [W]	Maximum power required
Fuel Cell Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required

Table 4.5 defines these dependencies.

¹One Engine Inoperative (OEI), in the aeronautical field, is a standard design condition that requires, in the event of a failure of one of the two engines, the remaining engine to be considered capable of providing the power necessary for the safe continuation of the flight or for landing.

Table 4.5: Response Variables and Driven Components (IC1)

Response	Driven Component / Duct
Diffuser Fresh Air Flow Rate	Fresh Air Diffuser
	Mixing Manifold
	Duct: Diffuser $\rightarrow$ E-Compressor
	Duct: Manifold $\rightarrow$ Cabin
Diffuser Ram Air Flow Rate	Ram Air Diffuser
	Duct: Diffuser $\rightarrow$ PHX
Electric Compressor Power	Electric Compressor
	Electric Motor
	Duct: E-Compressor $\rightarrow$ Fuel Cell Heat Exchanger
	Duct: E-Compressor $\rightarrow$ PHX
PHX Effectiveness	Primary Heat Exchanger
	Duct: PHX $\rightarrow$ Compressor
	Duct: PHX $\rightarrow$ SHX
	Duct: PHX $\rightarrow$ Manifold
SHX Effectiveness	Secondary Heat Exchanger
	Duct: SHX $\rightarrow$ Turbine
	Duct: SHX $\rightarrow$ Fan
Compressor Power (ACM)	ACM Compressor
	Duct: Compressor $\rightarrow$ SHX
Turbine Power (ACM)	ACM Turbine
	Duct: Turbine $\rightarrow$ Manifold
Fan Power (ACM)	ACM Fan
FCHX Effectiveness	Fuel Cell Heat Exchanger
	Duct Air: FCHX $\rightarrow$ PEMFC
	Duct Hydrogen: FCHX $\rightarrow$ PEMFC

4.2.2.1 Envelope Sizing Methodology

Table 4.6 defines the envelope sizing conditions of the ECS system for this configuration, accounting for both the ECS components and those related to the Fuel Cell integration. The results below first isolate the ECS system before presenting the overall system.

Table 4.6: Envelope Sizing Conditions (IC2)

Component	Variable	Condition
Diffuser Fresh Air	Flow rate $\dot{m}_{fresh}$ [kg/s]	Maximum flow rate required
Diffuser Ram Air	Flow rate $\dot{m}_{ram}$ [kg/s]	Maximum flow rate required
PEMFC Diffuser	Flow rate $\dot{m}_{FC}$ [kg/s]	Maximum flow rate required
Electric Compressor	Compressor power P_{e-CMP} [W]	Maximum power required
FC Dedicated Compressor	Compressor power $P_{Ded.CMP}$ [W]	Maximum power required
Primary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
Secondary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
ACM Compressor	Compressor power $P_{ACM CMP}$ [W]	Maximum power required
ACM Turbine	Turbine power $P_{ACM TRB}$ [W]	Maximum power required
ACM Fan	Fan power $P_{ACM FAN}$ [W]	Maximum power required

Table 4.7 defines these dependencies.

Table 4.7: Response Variables and Driven Components (IC2)

Response	Driven Component / Duct
Diffuser Fresh Air Flow Rate	Fresh Air Diffuser
	Mixing Manifold
	Duct: Diffuser → E-Compressor
	Duct: Manifold → Cabin
Diffuser Ram Air Flow Rate	Ram Air Diffuser
	Duct: Diffuser → PHX
Diffuser FC Flow Rate	PEMFC Diffuser
	Duct: FC Diffuser → Dedicated Compressor
Electric Compressor Power	Electric Compressor
	Electric Motor
	Duct: E-Compressor → PHX
Dedicated Compressor Power	FC Dedicated Compressor
	FC Dedicated Motor
	Duct: Dedicated Compressor → PEMFC
PHX Effectiveness	Primary Heat Exchanger
	Duct: PHX → Compressor
	Duct: PHX → SHX
	Duct: PHX → Manifold
SHX Effectiveness	Secondary Heat Exchanger
	Duct: SHX → Turbine
	Duct: SHX → Fan
Compressor Power (ACM)	ACM Compressor
	Duct: Compressor → SHX
Turbine Power (ACM)	ACM Turbine
	Duct: Turbine → Manifold
Fan Power (ACM)	ACM Fan

4.2.3 Integration Concept 3 (IC3): fuel cell dedicated compressor and ECS air cooling using hydrogen

The schematic of the system is represented in Figure 4.3.

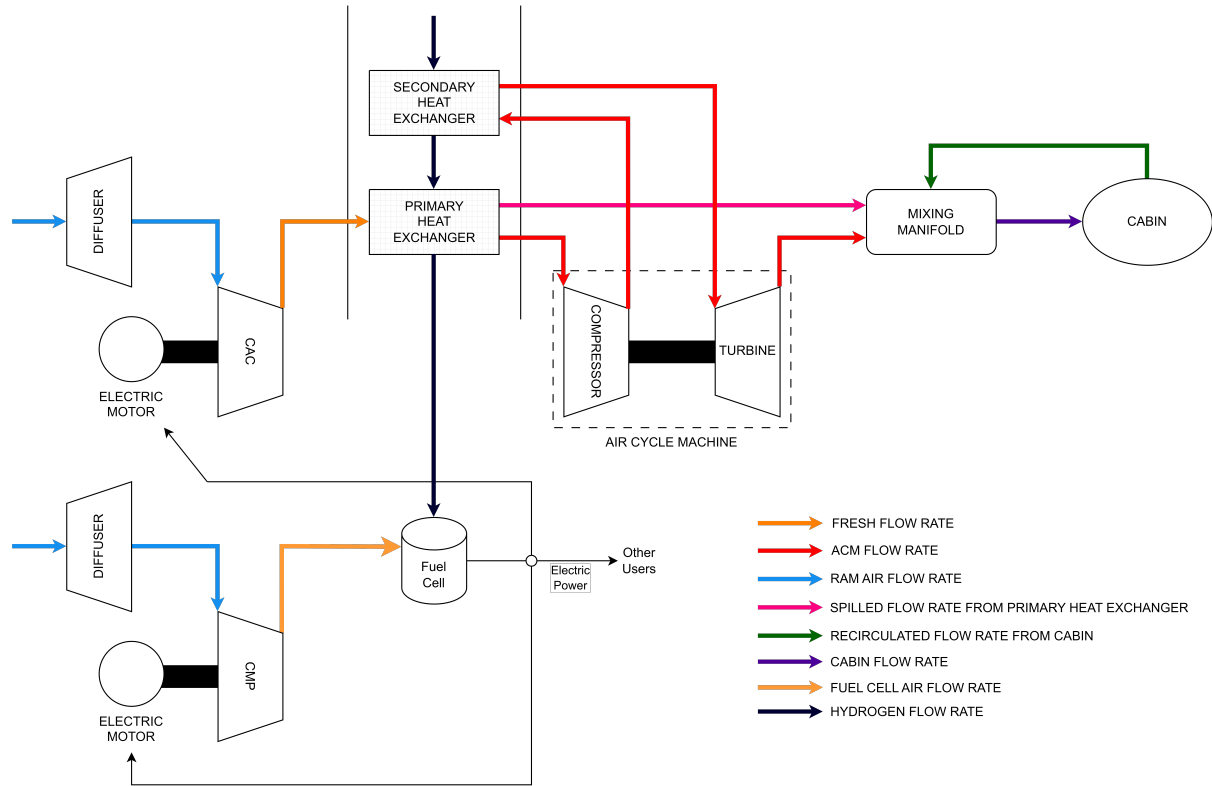


Figure 4.3: IC3: Fuel Cell Dedicated Compressor and ECS Air Cooling Using Hydrogen

This configuration entails the most substantial modifications to the architecture of the system compared to the previous ones. Indeed, this configuration eliminates the ram air channel entirely and, consequently, the fan within the Air Cycle Machine (ACM), thus transforming the system from a Three-Wheel to a Two-Wheel configuration. The hydrogen, in fact, cools the hot air within the ECS, which, by passing through the Primary and Secondary Heat Exchangers, heats up until it reaches the operating limits defined by the cell and shown in Table 3.6. Therefore, unlike IC2, where the hydrogen is considered to already be at a sufficient temperature at the cell inlet, in this one the ECS heat exchangers instead thermally condition the hydrogen.

This entails an important advantage: this configuration combines the ECS cooling function with the hydrogen thermal conditioning into a single operation, simplifying the architecture of the system and avoiding the separate management of the temperature and pressure of the cooling fluid.

The main disadvantage is that the complexity of simultaneously managing the thermal constraints of the ECS and the Fuel Cell increases, since the hydrogen must satisfy both requirements at the same time.

In this configuration, the Fuel Cell supplies electrical power to the following components:

- Propulsion, the system is sized under One Engine Inoperative condition;
- Onboard avionics and electrical components;
- ECS system: the electric compressor is powered by an electric motor;
- Fuel Cell dedicated electric compressor, which is likewise powered.

4.2.3.1 Envelope Sizing Methodology

Table 4.8 defines the envelope sizing conditions of the ECS system for this configuration, accounting for both the ECS components and those related to the Fuel Cell integration. The results below first isolate the ECS system before presenting the overall system.

Table 4.8: Envelope Sizing Conditions (IC3)

Component	Variable	Condition
Diffuser Fresh Air	Flow rate $\dot{m}_{fresh}$ [kg/s]	Maximum flow rate required
PEMFC Diffuser	Flow rate $\dot{m}_{FC}$ [kg/s]	Maximum flow rate required
Electric Compressor	Compressor power P_{e-CMP} [W]	Maximum power required
FC Dedicated Compressor	Compressor power $P_{Ded.CMP}$ [W]	Maximum power required
Primary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
Secondary Heat Exchanger	Effectiveness ε [-]	Maximum effectiveness required
ACM Compressor	Compressor power $P_{ACM CMP}$ [W]	Maximum power required
ACM Turbine	Turbine power $P_{ACM TRB}$ [W]	Maximum power required

Table 4.9 defines these dependencies.

Table 4.9: Response Variables and Driven Components (IC3)

Response	Driven Component / Duct
Diffuser Fresh Air Flow Rate	Fresh Air Diffuser
	Mixing Manifold
	Duct: Diffuser $\rightarrow$ E-Compressor
	Duct: Manifold $\rightarrow$ Cabin
Diffuser FC Flow Rate	PEMFC Diffuser
	Duct: FC Diffuser $\rightarrow$ Dedicated Compressor
Electric Compressor Power	Electric Compressor
	Electric Motor
	Duct: E-Compressor $\rightarrow$ PHX
Dedicated Compressor Power	FC Dedicated Compressor
	FC Dedicated Motor
	Duct: Dedicated Compressor $\rightarrow$ PEMFC
PHX Effectiveness	Primary Heat Exchanger
	Duct: PHX $\rightarrow$ Compressor
	Duct: PHX $\rightarrow$ SHX
	Duct: PHX $\rightarrow$ Manifold
SHX Effectiveness	Secondary Heat Exchanger
	Duct: SHX $\rightarrow$ Turbine
	Duct: SHX $\rightarrow$ PEMFC
Compressor Power (ACM)	ACM Compressor
	Duct: Compressor $\rightarrow$ SHX
Turbine Power (ACM)	ACM Turbine
	Duct: Turbine $\rightarrow$ Manifold

4.2.4 Comparison between the configurations

This sub-section presents the results obtained from the three integrations defined above, expressed as relative difference Δ with respect to the baseline bleedless ECS configuration (Section 4.1).

4.2.4.1 System mass comparison

Table 4.10 presents the results for the different configurations analysed.

Table 4.10: Mass Comparison Between ECS Baseline and the Three Fuel Cell Integration Concepts

Component	ECS (kg)	IC1		IC2		IC3	
		FC (kg)	Δ (%)	FC (kg)	Δ (%)	FC (kg)	Δ (%)
Compressor (ACM)	4.2	4.2	+0.04%	4.2	0.0%	4.6	+10.0%
Turbine (ACM)	2.5	2.5	+0.02%	2.5	0.0%	2.6	+3.7%
Fan (ACM)	1.5	1.5	+1.5%	1.5	+1.5%	0.0	-100.0%
Electric Compressor	9.6	14.2	+47.2%	9.6	0.0%	9.2	-4.1%
Electric Motor	14.1	97.3	+589.9%	14.1	0.0%	13.2	-6.5%
Primary Heat Exchanger	24.9	24.9	-0.01%	24.9	0.0%	11.6	-53.6%
Secondary Heat Exchanger	17.5	17.5	-0.07%	17.5	0.0%	13.4	-23.5%
Fresh Air Diffuser	32.0	220.8	+589.9%	32.0	0.0%	36.0	+12.5%
Ram Air Diffuser	24.0	24.0	0.0%	24.0	0.0%	0.0	-100.0%
Mixing Manifold	0.69	0.95	+36.3%	0.69	0.04%	1.9	+169.1%
Ducts (ECS)	2.1	2.6	+27.1%	2.1	0.01%	2.3	+13.5%
TOTAL ECS	133.1	410.4	+208.4%	133.1	+0.02%	94.8	-28.8%

Table 4.10 shows the following results for each configuration:

- IC1:
This configuration entails few modifications to the system, which mainly result in the definition of the bypass used to extract the air downstream of the electric compressor in order to supply the fuel cell. However, due to this aspect, the total flow rate entering the intake of the ECS system is significantly higher than the one needed for the baseline under the same worst condition ($\dot{m}_{tot} = \dot{m}_{ECS} + \dot{m}_{FC}$). This means that the intake is larger, as are the electric compressor and the electric motor: this results in a considerable increase in the mass of these components, which leads the ECS system to a mass increase of 208.4 %;
- IC2:
This configuration, on the other hand, does not entail any modification to the system, since a separate and independent channel is defined to supply the fuel cell. As evident in the table, the weight of the system does not change;
- IC3:
This configuration introduces the greatest changes to the system, compared to IC1 and IC2. Indeed, it removes the ram air diffuser and the fan, and it introduces a separate channel for the supply air to the fuel cell. The use of gaseous hydrogen as the cooling fluid within the heat exchangers considerably decreases their weight, because the cooling power of hydrogen is approximately 14 times higher than that of air, since $c_{p_{H_2,g}} \simeq 14 c_{p_{air}}$. Overall, a 28.8% reduction in the total weight of the system is obtained, making this configuration the lightest among the three.

Finally, Table 4.11 presents the weights of the additional components required for the different integrations, together with the relative difference of the total weight of the system.

Table 4.11: Grand Total Mass Comparison: ECS Baseline vs. the Three Fuel Cell Integration Concepts

Configuration	ECS (kg)	FC (kg)	Grand Total (kg)	Δ ECS (%)	Δ Grand Total (%)
ECS Baseline	133.1	–	133.1	–	–
IC1	410.4	3.2	413.6	+208.4%	+210.8%
IC2	133.1	209.5	342.6	+0.02%	+157.5%
IC3	94.8	212.4	307.1	-28.8%	+130.8%

In Table 4.11, the column indicated as FC includes the components related to the fuel cell: dedicated diffuser, dedicated electric compressor and motor, dedicated heat exchanger, and dedicated ducts.

Compared to the baseline, the following differences emerge for each configuration:

- For IC1, the weight of the additional components is lower than in the other configurations, but overall the grand total is higher than the baseline by approximately +210.8%. Although the number of additional components is minimal, their weight remains non-negligible, because the ducts must handle a hotter fluid at higher pressure, and the heat exchanger must ensure high and optimal performance to manage a large amount of heat;
- For IC2, on the other hand, the increase in total weight is greater than for IC1, since this configuration includes components such as the diffuser, the compressor, and the electric motor: these are components with a considerable mass, as the required flow rates and powers are high. Consequently, although the ECS remains unchanged, the definition of the independent channel has nonetheless resulted in a non-negligible increase in the grand total mass: +157.5%;
- IC3 is also the optimal configuration in terms of the grand total. Indeed, as can be seen from the table, a -28.8% decrease in the weight of the ECS alone is obtained, together with a total increase of +130.8%. Compared to the other configurations, IC3 ensures a reduced increase in the mass of the system. This result is due to what was discussed just above.

Figure 4.4 shows the mass breakdown of the baseline ECS for the three different configurations as a function of the worst conditions defined in Table 4.1. The components highlighted in red are the critical ones selected for the sizing of the system, for that specific worst condition and for that specific configuration.

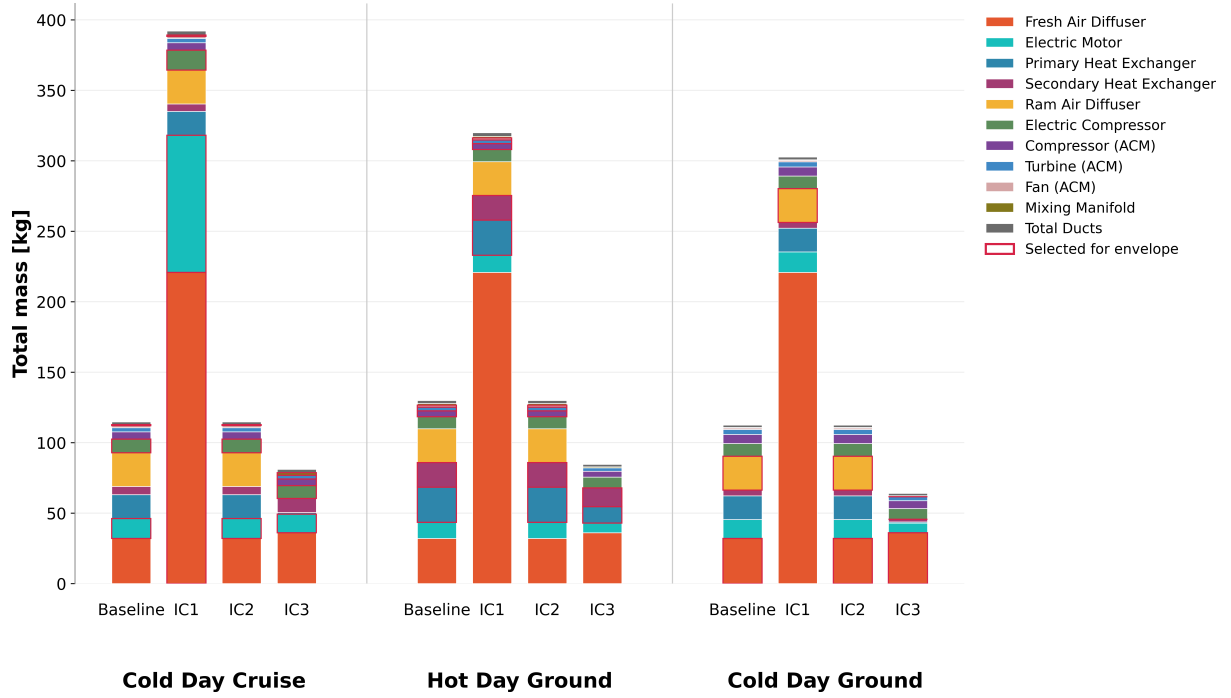


Figure 4.4: ECS Component Mass Breakdown for the Three Worst-Case Sizing Conditions (Cold Day Cruise, Hot Day Ground, Cold Day Ground)

4.2.4.2 Drag comparison

The objective of this section is to define the drag comparison.

As defined in sub-section 3.3.2.1, the presence of the intake leads to a certain contribution to the total drag of the aircraft. As can also be seen from Equation 3.27, as the air flow rate entering the intake increases, the drag contribution F_D [N] increases.

Table 4.12 shows the relative difference introduced by the different configurations with respect to the drag produced by the baseline of the system.

Table 4.12: Drag Comparison Between ECS Baseline and the Three Fuel Cell Integration Concepts

Component	IC1 Δ (%)	IC2 Δ (%)	IC3 Δ (%)
Fresh Air Diffuser	+589.9%	0.0%	+12.5%
Ram Air Diffuser	0.0%	0.0%	-100.0%
PEMFC Diffuser	–	+303.4%	+304.2%
Total Drag	+337.1%	+303.4%	+268.5%

Note that the percentage values in Table 4.12 do not share the same basis: the individual component rows use one reference value, whilst the Total Drag row uses a different one, and they are therefore not directly summable. The following paragraphs clarify this distinction.

Indeed, for the individual components, the relative difference Δ follows the same definition used for the mass comparison, with the mass replaced by F_D , and expresses the variation in aerodynamic drag for that specific component with respect to its own baseline value. For example, the value of +589.9% reported for the Fresh Air Diffuser in IC1 indicates that the drag generated by that single component is +589.9% higher than the drag generated by the

same component in the baseline configuration alone. This approach applies to the Fresh Air Diffuser and the Ram Air Diffuser, since for both there exists an equivalent component in the baseline configuration.

With regard to the PEMFC Diffuser, on the other hand, no equivalent component is present in the baseline configuration, since in the reference bleedless ECS there is no air intake dedicated to the Fuel Cell. Consequently, the variation in aerodynamic drag induced by this component cannot be calculated using the same relative difference definition, as the corresponding baseline value would be equal to zero. In this case, the contribution is instead expressed as the relative difference of the PEMFC-dedicated intake drag ($F_{D,PEM}$) with respect to the total baseline drag ($F_{D,0}$). This is also the reason why no value is reported for the PEMFC Diffuser in IC1 column in Table 4.12: in that configuration, the air supplied to the Fuel Cell is not drawn through a dedicated air intake, as is the case for IC2 and IC3, but rather downstream of the ECS electric compressor, as discussed in Section 4.2.1.

The Total Drag row instead reports the relative difference between the summed drag of all components in the analysed configuration ($F_{D,tot}$) and the summed drag of all components in the baseline configuration ($F_{D,0}$).

The results in Table 4.12 show that:

- IC1, which has the same number of intakes as the baseline, entails a considerable increase in drag compared to it. The significant increase in the drag of the Fresh Air Diffuser in IC1 (+589.9%) occurs because, in this configuration, the entire air flow rate required to supply the Fuel Cell is drawn downstream of the same dynamic intake used for cabin conditioning, rather than through a dedicated intake. Consequently, the overall mass flow rate $\dot{m}_{fresh}$ processed by the diffuser increases considerably compared to the baseline, and according to the continuity equation (3.21) this entails a proportional increase in the frontal inlet section A_{in} , from which the large increase in the aerodynamic drag generated by the component derives. The contribution of the dedicated dynamic intake is absent, whereas it appears in the other configurations, because this configuration does not include an intake of this type, consistently with Section 4.2.1;
- IC2, which was defined to be identical to the baseline, results in the drag generated by the diffusers of the ECS system remaining unchanged. This configuration, however, introduces a dynamic intake dedicated to the fuel cell, which indeed results in a drag increase of +303.4%;
- IC3, on the other hand, shows a slight increase in drag due to the Fresh Air Diffuser, caused by a slight increase in the conditioning flow rate $\dot{m}_{fresh}$ entering the system. This configuration also features a dynamic intake dedicated to the fuel cell supply channel, which results in a drag increase of +304.2%. Overall, this configuration represents the smallest increase in drag (+268.5%), because the Ram Air Diffuser is absent and therefore contributes zero drag.

4.3 Mission Profile

This analysis considers a simple mission profile, consisting of the following phases and corresponding durations:

Table 4.13: Mission Profile Phases

Phase	Duration [s]	Thrust [%]	Cabin Temperature [K]
Ground	1200	0.0	300.15
Taxi Out	600	5.0	300.15
Climb	1800	90.0	294.15
Cruise	7200	40.0	294.15
Descent	1500	15.0	294.15
Taxi In	600	5.0	294.15

The selected route does not correspond to an actual, existing route, but has been considered to be short-range and is representative of a Business Jet category aircraft, with propulsive characteristics similar to those of the Bombardier Challenger 300. The thrust percentage assumed for each phase of the mission profile was defined arbitrarily, unlike the engine's maximum thrust, which was derived from its actual technical specifications.

The total mission duration is 3 hours and 35 minutes.

Appendix B, Table B.5 reports the general mission parameters, such as cruise altitude, Mach number, passenger load, day/night condition, and ISA deviation.

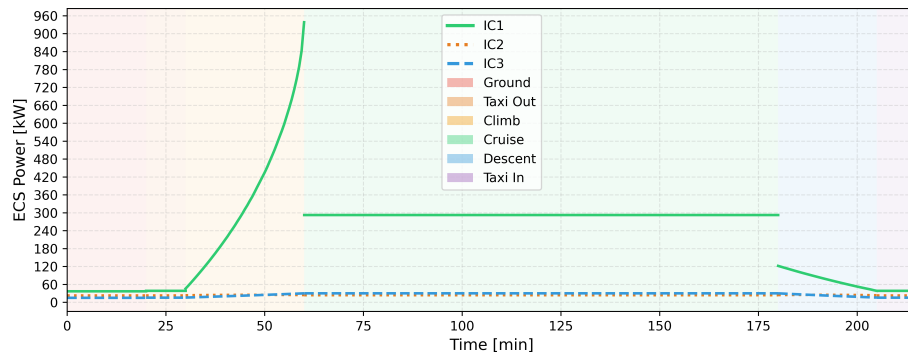


Figure 4.5: ECS Power Profile

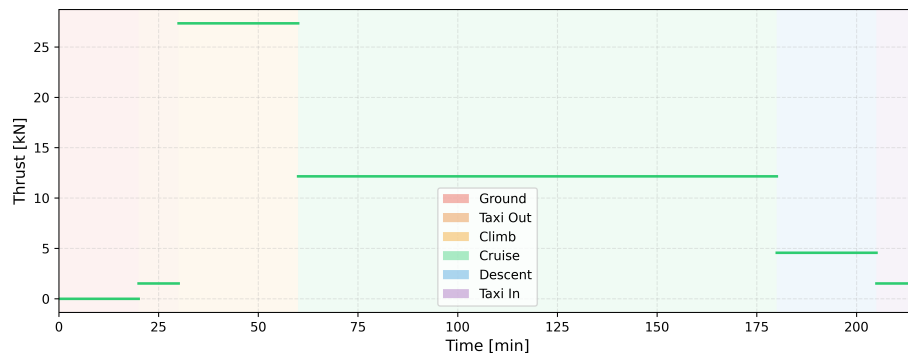


Figure 4.6: Thrust Profile

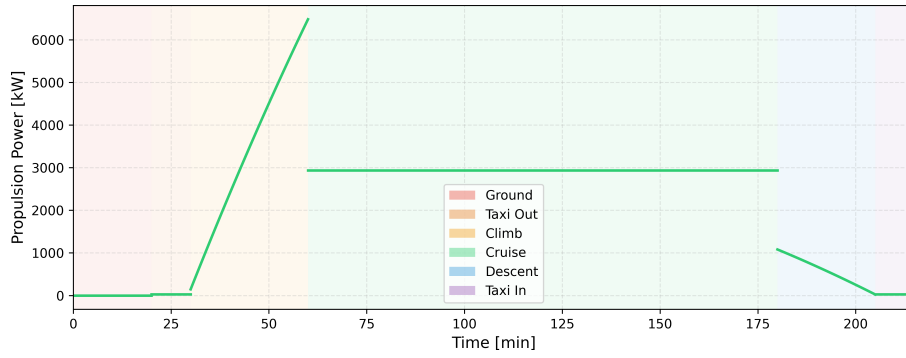


Figure 4.7: Propulsion Power Profile

Figure 4.5 shows the power required by the ECS. This thesis sizes the electric compressor, and consequently the electric motor as well, based on three static worst-case conditions, defined in Table 4.1, none of which corresponds to the climb phase. Figure 4.6 and Figure 4.7 show that the climb phase represents for IC1 the point of maximum electrical power demand. The peak of IC1 in this phase therefore exceeds the sizing point, unlike IC2 and IC3, which do not exhibit this behaviour thanks to the independent air channel, and reflects the high compression required at altitude to simultaneously supply the ECS and the fuel cell. This simply confirms a limitation discussed in Section 5.2, which states that the sizing conditions do not cover the entire flight envelope.

Figure 4.6 shows the thrust profile, expressed in [kN], of the single engine along the mission. It is derived from the thrust percentage defined in Table 4.13 and the maximum thrust of the Honeywell HTF-7000 engine, reported in Appendix A.

Figure 4.7 shows the electrical power P_{prop} supplied by the Fuel Cell for propulsion, as defined in Equation 3.119.

This work estimates the consumption following the system sizing, for each defined configuration. Since the sizing defines the maximum capacity of each component, this analysis uses nominal operating conditions of the system, within the criticality limits imposed during sizing.

4.3.1 Consumption Trends

This section presents the trends of the consumables during the mission defined in Table 4.13.

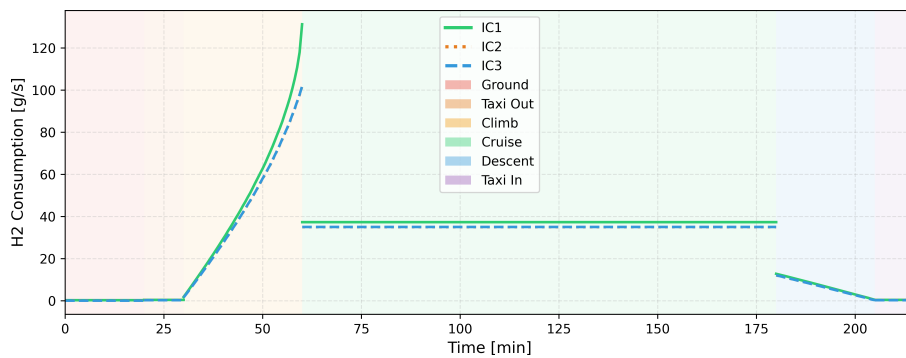


Figure 4.8: Hydrogen Consumption

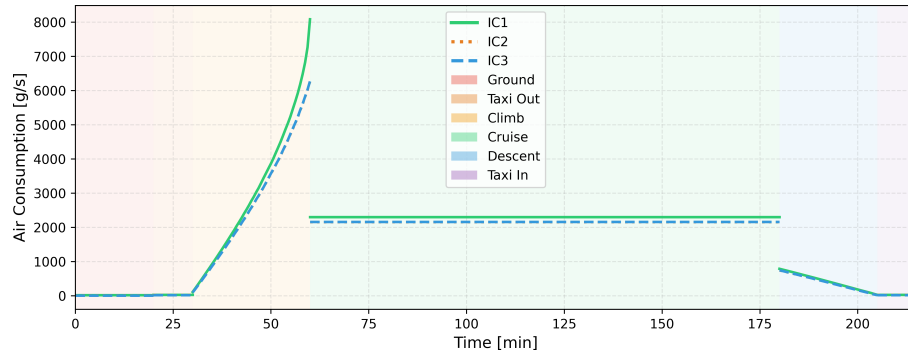


Figure 4.9: Air Consumption

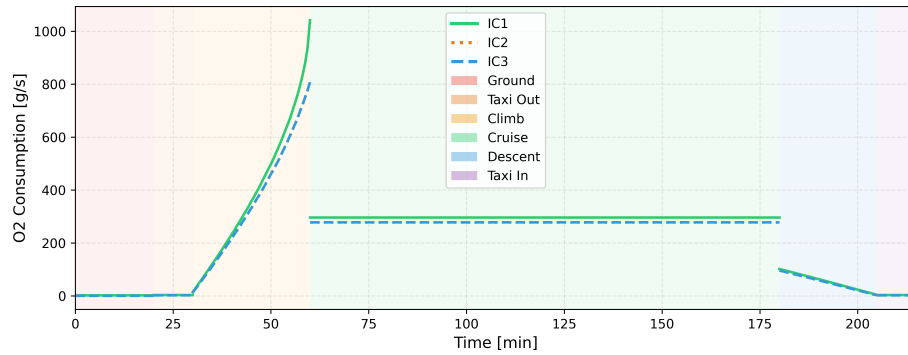


Figure 4.10: Oxygen Consumption

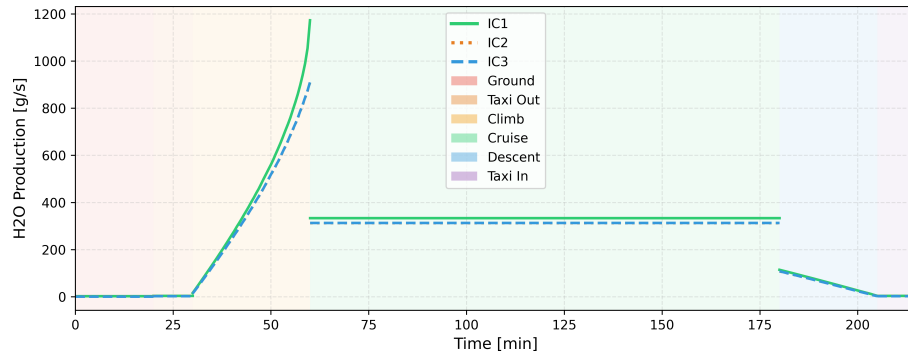


Figure 4.11: Water Production

The trends show that:

- IC1 shows a significant increase in hydrogen and air consumption during the climb phase compared to the other two cases. This occurs because a single electric compressor pressurises and heats the air for both the ECS and the fuel cell simultaneously. Clearly, this aspect entails a waste: in this case, the pressure reached by the air flow rate supplying the fuel cell will be higher than necessary. Overall, the electrical power to be supplied to the electric motor is higher than what is required for IC2 and IC3, resulting in higher consumption;
- The increase in consumption during the climb phase also occurs because, as altitude increases, the air flow rate requires greater compression, which translates into a higher electrical power demand;

- IC2 and IC3, on the other hand, feature an independent channel for managing the air flow rate supplying the fuel cell: consequently, in order to meet the inlet requirements, a lower compression is sufficient, which translates into a lower electrical power demand, allowing consumption to be reduced. Furthermore, their consumption trends overlap;
- During the cruise phase, IC1 entails a higher consumption, which is, however, more limited compared to the climb phase.

The final conclusions are presented in the next chapter.

5 Conclusions

This chapter aims to evaluate the achievement of the objectives defined in Chapter 1, discuss the methodological limitations of the work carried out, and propose possible future developments.

5.1 Evaluation of the objectives

The objective declared in the introduction to this thesis was to define a model of an Environmental Control System (ECS) and of a Proton Exchange Membrane Fuel Cell (PEMFC), in order to evaluate the impact of the integration of the cell on the architecture of the system itself, in terms of the percentage variation in mass and aerodynamic drag, and of the trends of hydrogen and air consumption, as well as water production, along a realistic mission profile.

This objective can be considered achieved. Indeed, a modular model of a bleedless ECS has been developed, consisting of a Three-Wheel Air Cycle Machine (ACM) configuration, including the calculation of the heat loads acting in the cabin and a detailed modelling of each component of the system. The validation of the model was carried out against literature data from an Airbus A320, achieving a mean error of less than 1% for temperatures and 3.11% for pressures, confirming the thermodynamic accuracy of the model.

With regard to the fuel cell, this work clarifies that the objective declared in Chapter 1 referred to defining a model of the PEMFC. As specified in Chapter 3, this thesis adopts a black box model already developed and validated in the literature, rather than defining a new one. This choice was guided by the fact that the primary objective of the work was to analyse the impact of its integration on an Environmental Control System (ECS), rather than on the electrochemical characterisation of the cell itself, which has already been the subject of other works. The objective relating to the fuel cell can be considered achieved, as this model was effectively integrated into the framework proposed in this work.

Regarding the analysis of the impact of the integration, the work has, in fact, gone beyond the minimum scope of the objective: indeed, rather than limiting itself to the analysis of a single generic integration configuration, three different architectures were defined, sized, and compared, each according to a precise envelope of critical design conditions. This made it possible to quantify the impact of the integration, offering a structured comparison of alternative architectural solutions, of greater utility for a trade-off phase in the preliminary design of a civil aviation aircraft. Furthermore, all four metrics required by the objective, namely the variation in mass and aerodynamic drag, the trends of hydrogen and air consumption, and water production, were calculated and discussed in Chapter 4 for each of the three configurations.

With regard to the results, IC1 entails the greatest increase in terms of mass and aerodynamic drag (respectively +208.4% and +337.1% with respect to the baseline ECS), as the electric compressor and the diffuser must handle the combined air flow rate required by both the ECS and the Fuel Cell. IC2, on the other hand, leaves the mass and aerodynamic drag of the ECS almost unchanged (respectively +0.02% and 0.0%), although the grand total mass of the system increases by +157.5% and the aerodynamic drag by +303.4%, due to the addition of a dedicated electric compressor, the related electric motor, and a dedicated diffuser for the supply of the Fuel Cell. IC3 is the only configuration in which the mass of the ECS decreases with respect to the baseline (−28.8%) and presents the smallest overall increase in aerodynamic drag (+268.5%), thanks to the elimination of the ram air diffuser and of the ACM fan, and to the greater cooling capacity of hydrogen compared to air; furthermore, it entails lower hydrogen and air consumption during the climb and cruise phases, since the independent air channel requires a lower compression ratio compared to the shared compressor of IC1, which instead results in a higher power demand and higher consumption.

5.2 Limitations

5.2.1 Model Limitations

The model developed satisfies the accuracy requirements of the preliminary design phases of an aircraft. However, it presents some methodological limitations, consciously assumed in order to maintain the focus of the work on the system-level analysis rather than on the detailed physical characterisation of each component.

With reference to the ECS model, the following limitations are important to consider:

- Humidity in the air is not considered in any of the simulated components, as its modelling entails greater complexity, although its management is one of the system functions defined in Chapter 2;
- The mass of auxiliary elements, such as bolts, support brackets, electrical wiring, and the Air Cycle Machine (ACM) shaft, was not calculated individually, but was instead estimated through a global corrective factor applied to the overall mass of the modelled components;
- The thickness values of the ducts and of the Mixing Unit are the result of engineering assumptions; a more rigorous approach would therefore involve the calculation of the thicknesses on the basis of the pressure loads experienced;
- The validation of the model was carried out exclusively on the thermodynamic quantities of the cycle, as no reference experimental data are available in the literature for the validation of the mass and dimensions of the individual components.

The fuel cell, on the other hand, was modelled as a black box. Consequently, the following aspects should be considered:

- Aspects related to transient phenomena were not considered, such as the start-up of the cell or rapid variations of the electrical load;
- The effect of temperature and pressure on the efficiency curve was not modelled, as it is considered to depend solely on the ratio $\frac{P}{P_{max}}$;
- The Balance of Plant (BoP) is represented in a simplified form, limited to the dedicated electric compressor and heat exchanger, without including other components such as the humidifier or regulating valves.

5.2.2 Limitations of the Analyses

In addition to the model limitations described above, the comparative analysis carried out in this work presents the following limitations:

- This thesis defines the mission profile as representative and not corresponding to a real route. Furthermore, this work chose the thrust percentage for each phase arbitrarily, unlike the maximum engine thrust, which follows the technical specifications of the Bombardier Challenger 300. The transitions between consecutive mission phases are also modelled as instantaneous, neglecting the real thrust and electrical power transients that would occur between them;
- The sizing of the three integration concepts was carried out on three discrete worst-case condition points, rather than on an entire flight envelope; more critical intermediate conditions may exist with respect to the three discrete points considered, which remain unexplored within the scope of this thesis. A concrete instance of this limitation is observed

in Section 4.3 for IC1, whose electric compressor power demand during climb exceeds the sizing envelope defined by the three worst-case conditions;

- This work compared the three integration concepts on a single reference aircraft; the results, and the relative ranking of the three concepts, may not be generalisable to aircraft of different category or size;
- Only three architectures were investigated; a trade-off across a larger number of concepts could provide further detail to the analysis.

5.3 Future Developments

The limitations indicated in the previous section represent natural development directions for the present work.

With regard to the Environmental Control System (ECS) model, the next steps may be:

- Considering humidity management, in order to add the missing components deriving from its integration, making the model consistent with all the ECS functions defined by the SAE ARP85G standard [7];
- Characterising the components defined in the model with greater precision, so as to obtain more detailed specifications, such as the number of stages present in the compressor or in the turbine;
- Obtaining real industrial or experimental data to validate the mass of the ECS components, so as to consolidate the quantitative reliability of the results presented in Chapter 4. Furthermore, this would make it possible to extrapolate the corrective factor useful for calculating the mass of the auxiliary elements with greater precision;
- Building a simulation model of the ECS to evaluate the time trends of the thermodynamic quantities and the achievement of the specified cabin temperature.

The fuel cell model, on the other hand, could be extended by considering the following aspects:

- Transient conditions and the effect of operating temperature and pressure conditions on the efficiency curve;
- A more complete modelling of the Balance of Plant (BoP), including the humidification and flow regulation system: this can be carried out only if the presence of humidity is also considered in the ECS system, so as to ensure consistency of assumptions;
- The addition of a model relating to the Solid Oxide Fuel Cell would make it possible to evaluate not only different integration architectures, but also different cell types, making the trade-off phase of the preliminary design of an aircraft even more comprehensive.

This work could also be extended based on the identified limitations of the analysis:

- Extending the sizing methodology to the entire flight envelope, and not only to the three worst-case conditions, in order to verify that all the most critical conditions are effectively identified;
- Extending the comparative analysis to reference aircraft of different category and size, in order to verify whether the comparison between the three integration concepts identified in this work is generalisable beyond the Bombardier Challenger 300;
- Exploring a wider set of integration concepts than those analysed in this work, potentially evaluating integration variants or hybrid solutions.

In addition, another development would concern the application of the model to a certified and representative mission profile of a route actually operated, with documented propulsive specifications, in order to obtain results under conditions closer to the real operational conditions of a Business Jet aircraft.

5.4 Concluding Remarks

The framework developed in this work currently constitutes a quantitative tool for the direct comparison between different integration architectures of an Environmental Control System (ECS) with a fuel cell in the preliminary design phases of an aircraft.

In today's context, in which the electrification of onboard systems and the use of hydrogen represent central development directions for the reduction of the environmental impact of aviation, the possibility of rapidly evaluating the trade-offs between mass, aerodynamic drag, and energy consumption of different integration concepts addresses a concrete need of the initial design phases, where the decisions made decisively condition the subsequent development of the aircraft.

A Bombardier Challenger 300

This section presents the aircraft used as a reference in this project: the Bombardier Challenger 300.



Figure A.1: Bombardier Challenger CL-300 [\[58\]](#)

This aircraft is produced by the Canadian company Bombardier, and is a business jet category aircraft typically used on transcontinental routes.

It is characterised by long, slender wings, with low-mounted winglets. The engines are of the turbofan type, mounted in the tail section, and correspond to the Honeywell HTF-7000. The tailplane is defined in a T-tail configuration with large horizontal surfaces.

The technical characteristics of the aircraft are presented in Table [A.1](#).

Table A.1: Bombardier Challenger CL-300 – Technical Specifications [59]

Category	Parameter	Value
General	Type	Business jet
	Crew	2 pilots + 1 flight attendant
	Manufacturer	Bombardier Aerospace (Canada)
	First flight	August 14, 2001
	Entry into service	January 2004
	Units built	ca. 300
Development	Unit cost	ca. \$20 million
	Developed from	Challenger CL-600
Dimensions and weights	Length	20.92 m
	Wingspan	19.46 m
	Height	6.20 m
	Wing area	48.50 m ²
	Empty weight	10,591 kg
	Loaded weight	11,839 kg
	Max takeoff weight	17,463 kg
	Passengers	8 to 9
	Payload	1,247 kg / 522 kg*
	Fuel capacity	5,693 kg
Propulsion	Engine	2 Honeywell HTF-7000 turbofans
	Thrust	30.4 kN
Performance	Max speed	Mach 0.82 (ca. 870 km/h)
	Cruise speed	Mach 0.80 (ca. 850 km/h)
	Takeoff distance	1,463 m at MTOW
	Landing distance	792 m at MLW
	Range	5,741 km at Mach 0.80
	Service ceiling	12,497 m
	Absolute ceiling	13,716 m

* 522 kg with maximum fuel load.

B Simulation Parameters

This appendix reports the numerical parameters relating to the different components used for the OpenMDAO simulations of the ECS system, which are common to all the analysed configurations (ECS Baseline and the three Fuel Cell Integration Concepts), as well as the specific parameters relating to each defined worst condition and integration concept.

B.1 Common Parameters

Table B.1 reports the fixed parameters of the ECS system, valid independently of the worst condition and the configuration considered.

B.2 Fuel Cell Common Parameters

Table B.2 reports the parameters relating to the PEMFC-type Fuel Cell, common to all three integration concepts in which it is present.

Table B.3 reports the specific parameters of each integration, relating to the additional components introduced with respect to the baseline.

B.3 Worst-Case Sizing Conditions

For each of the three worst conditions defined in Table 4.1, the following values of the component parameters, reported in Table B.4, have been assumed.

B.4 General Mission Parameters

Table B.5 reports the parameters relating to the mission profile, common to all three integrations in which it is present.

Table B.5: General Mission Parameters

Parameter	Value
Cruise altitude [m]	7620
Cruise Mach number [-]	0.78
Number of passengers	10
Day flight	Yes
ISA deviation [°C]	0

Table B.1: Common ECS Fixed Parameters

Category	Parameter	Value
Heat Loads	Glass surface per window [m ²]	0.12
	Fuselage length [m]	20.9
	Fuselage width [m]	2.19
	Number of windows [-]	6
	Number of engines [-]	2
	Internal air velocity [m/s]	3.3
Fresh Air Diffuser	Efficiency η_d [-]	0.95
	Outlet Mach number [-]	0.3
Ram Air Diffuser	Efficiency η_d [-]	0.95
	Outlet Mach number [-]	0.3
ACM Compressor	Outlet Mach number [-]	0.3
	Reference mass [kg]	4.5
	Reference radius [m]	0.055
ACM Turbine	Outlet Mach number [-]	0.1
	Reference mass [kg]	3.5
	Reference radius [m]	0.045
e-CMP Compressor	Outlet Mach number [-]	0.3
	Reference mass [kg]	18.0
	Reference radius [m]	0.12
ACM Fan	Outlet Mach number [-]	0.3–0.4 [*]
	Reference mass [kg]	5.0
	Reference radius [m]	0.18
Electric Motor	Power-to-mass ratio ϕ [kW/kg]	5.0
Ducts (ECS)	Length, all ducts [m]	0.2 (0.4 for Manifold → Cabin)
	Thickness, all ducts [m]	1.5×10^{-3}
Heat Exchangers	Hot-side fluid (PHX, SHX)	Air
	Cold-side fluid (PHX, SHX), Baseline & IC1/IC2	Air

^{*} 0.3 in ECS Baseline and IC2/IC3; 0.4 in IC1.

Table B.2: PEMFC Common Parameters

Parameter	Value	Unit
Maximum thrust (OEI)	30360.0	N
Maximum velocity	245.0	m/s
Maximum ECS power	74557.14	W
Maximum electrical power	781.74	W
Weight-to-power ratio	0.625	kg/kW
Reference Fuel Cell power	2000	W
Hydrogen inlet temperature	22	K
Hydrogen outlet temperature	353.15	K
Hydrogen inlet pressure	360.0	kPa

Table B.3: Fuel-Cell-Related Component Parameters by Integration Concept

Component	Parameter	IC1	IC2	IC3
Fuel Cell Dedicated Diffuser	Efficiency η_d [-]	–	0.95	0.95
	Outlet Mach number [-]	–	0.3	0.3
Fuel Cell Heat Exchanger	Hot-side fluid	Air	–	–
	Cold-side fluid	Hydrogen	–	–
PHX / SHX cold side	Hot-side fluid (PHX, SHX)	Air	Air	Air
	Cold-side fluid (PHX, SHX)	Air	Air	Hydrogen
FC Dedicated Compressor	Outlet Mach number [-]	–	0.3	0.3
	Reference mass [kg]	–	18.0	18.0
	Reference radius [m]	–	0.12	0.12
Dedicated Electric Motor	Power-to-mass ratio [kW/kg]	–	5.0	5.0
Ducts	Length [m]	0.2	0.2	0.2
	Thickness [m]	0.003	0.003	0.003/0.04*

*0.04 for Hydrogen Ducts; 0.003 for Air Ducts.

Table B.4: Nominal Parameters for the Three Worst-Case Sizing Conditions

Parameter	CDC	HDG	CDG	Unit
Altitude	7620	0	0	m
Mach number	0.78	0	0	–
Number of passengers	0	10	0	–
Cabin temperature	294.15	300.15	294.15	K
ISA deviation	-20	+25	-35	°C
Day condition	No (night)	Yes	No (night)	–
PHX effectiveness	0.55	0.65	0.55	–
PHX pressure drop	8.0	8.0	8.0	%
SHX effectiveness	0.55	0.65	0.55	–
SHX pressure drop	8.0	8.0	8.0	%
e-CMP compression ratio	5.0	3.0	4.5	–
e-CMP efficiency	0.90	0.90	0.90	–
e-CMP rotational speed	80000	80000	80000	rpm
ACM Compressor efficiency	0.75	0.75	0.75	–
ACM Turbine efficiency	0.75	0.75	0.75	–
ACM Fan compression ratio	1.012	1.012	1.012	–
ACM Fan efficiency	0.25	0.25	0.25	–
ACM rotational speed	65000	65000	65000	rpm
Recirculation percentage	50.0	50.0	50.0	%
Fresh air flow rate (nominal)	0.40	0.40	0.40	kg/s
Ram air flow rate (nominal)	0.30	0.70	0.30	kg/s

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