Analytical Design of Conventional and Electrical Aircraft Environmental Control Systems

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Abstract. Environmental control systems hold vital importance as they are responsible for aircraft cabin air ventilation and passenger comfort. This paper presents an analytical design of both Conventional & Electrical environmental control systems. The result of the estimated design is represented in a geometrical model that gives freedom to visualize various options in the conceptual design process, using Knowledge-based engineering application as a base for the design and methodology. Flexibility in the model enables the user to control the size and positioning of the system and sub-systems associated with it. The number of passengers serves as the driving input and the three-dimensional model gives the exact representation concerning the volume occupied and dependencies on the number of passengers. It also provides a faster method to alter the system to user needs with respect to the number of air supply pipes, number of ducts, and pipe length.

1. Introduction
The Environmental Control System (ECS) is a critical system that ensures that passengers in the airplane cabin have a comfortable and safe environment. The primary goal of the ECS system is to maintain cabin pressure and temperature. As air pressure and temperature vary with altitude, ECS works to regulate the air by taking in bleed air and mixing it with recirculating air to ensure that the pressure and temperature of air are safe for breathing. Also, the system provides de-misting, anti-icing functions for the aircraft [1].

The Conventional ECS is an open-loop system with air as the refrigerant and bleed air is conditioned and fed into the aircraft. Low-Pressure Water Separation System (LPWS) and High-Pressure Water Separation System (HPWS) are the two classifications for this system. Air is passed through heat exchangers, Turbines, condensers, and water extraction loop to give the conditioned air, shown in Figure 1. Ram air is used as a coolant while the bleed air tapped from the engine is the source air. The difference between LPWS and HPWS is the water extraction loop, consisting of a Reheater and Condenser in the latter system as shown in Figure 2. Although LPWS has fewer components and lesser weight, the absence of a water extraction loop unit is the limiting factor and can lead to icing near the Turbine unit. This icing is not a desirable effect, therefore HPWS becomes the better choice and is used commercially on a large scale.

On the other hand, electrical ECS operates by reducing the power consumption, using electric power instead of pneumatic power. Air is taken as the ram-air substitute and conditioned before feeding into the fuselage. Electrical ECS comprises two air conditioning packs, which are
electrically powered and motor-driven. Electrical ECS is gaining importance due to the lesser fuel consumption and eco-friendliness compared to the conventional ECS. Because there is no bleed air inlet, electrical compressors are used to pressurize the cabin. These compressors also act as the source of air for the ECS, illustrated in Figure 3. All the equations necessary/used to design the ECS systems are presented in the preprint available at engrXiv preprint [2].

2. Aims and Objectives
The goal of this work is to design and sizing conventional & electrical ECS and later build the geometrical model of the ECS along with air supply piping, as well as diffusers. These could be used for a variety of aircraft sizes and types, as well as a variety of passenger counts. The user has the option of selecting an ECS system (conventional or electric) as well as air supply pipework and diffusers (single-aisle). The following objectives are taken into account while achieving the goals:

- Design the ECS and its components based on the type of aircraft or number of passengers.
- Compute inlet & outlet temperatures and pressures of individual components and Validating the output temperature (K) and pressure (Pa) of bleed air.
- Calculate the pressure losses in pipes based on the number of bends & length of the piping.
- Realize the analytical design in the geometrical model along with air supply piping for single and double aisle configurations instantiated along the length of the fuselage.
3. Methodology
The various components that comprise an ECS are sized/modeled and presented below. Also, the assisting equations are illustrated with numerical values along with the assumptions made in the design process in [2]. Initial assumptions are based on Moir & Seabridge [1]:

- Cruising altitude of 11277m
- Mach number of 0.78
- Inlet bleed air temperature at PHX ($T_{\text{bleed}}$) is 473.15 K
- Ram air temperature ($T_{\text{ram}}$) is 217.15 K

3.1. Analytical component sizing
Heat exchangers form the backbone of ECS. Cross-flow heat exchangers are considered and only dry bleed air is made to pass through the ECS [3]. The sizing calculations, as well as the assumptions, are shown for each component of ECS are as presented in [2]. These equations increase the flexibility and adaptability of the system. These equations boost the system’s adaptability and flexibility. The driving input for ECS sizing is the number of passengers ($N_{\text{Pax}}$). During the sizing/modeling of the different ECS components, other constraints like as stresses, size, servicing, material, and cost were ignored.

3.1.1. Heat Exchanger: The Primary heat exchanger (PHX) & Main heat exchanger (MHX) are not the only heat exchangers in ECS, even Reheater & Condenser are also cross-flow type heat exchangers. Thus, PHX, MHX, Reheater, and Condenser have the same sizing equations.

3.1.2. Compressor: It is essential to find the work done by the compressor and the radial speed of the impeller as part of the air cycle machine that takes in cold bleed air from the engine pressurizes, and increases the temperature of the bleed air.

3.1.3. Turbine: Another essential component of the air cycle machine is the Turbine. The temperature of the air drops as the air expands through the Turbine. Work done by the Turbine and the radial speed of the impeller is to be calculated for the model.

3.1.4. Pressure Losses in Pipes: In general, pressure loss is considered for all types of fully developed flows i.e., laminar or turbulent, circular or non-circular, smooth or rough surfaces, horizontal or inclined pipes constitute to different kinds of pressure losses.

4. Results
Numerical data obtained for the different components of the conventional Electrical ECS is analyzed and validated in this section. Also, results obtained for the three different aircraft types that were considered are being evaluated. The performance of ECS varies with the user input called the number of passengers. The bleed air mass flow rate required for the aircraft type is calculated as product of Number of passengers ($N_{\text{pax}}$) and required mass flow of cabin fresh air ($m_{\text{pax}}$) [1]. Table 1, illustrates the amount of bleed and ram air mass flow required for the three different passenger configuration aircraft’s considered. The results obtained along with the assumptions made for the different components of the system are provided below.

\[ m_{\text{bleed}} = N_{\text{pax}} \times m_{\text{pax}} \] (1)
Table 1: Bleed and ram air mass flow rate.

| Aircraft Type (-) | Number of passengers ($N_{pax}$) | Bleed air mass flow rate ($kg/sec$) | Ram air mass flow rate ($kg/sec$) |
|-------------------|-----------------------------------|------------------------------------|----------------------------------|
| 1                 | 150                               | 0.50                               | 0.8                               |
| 2                 | 250                               | 0.83                               | 1.1                               |
| 3                 | 350                               | 1.17                               | 1.4                               |

4.1. Conventional Environmental Control System

The results of Conventional Environmental Control System are presented in Table 2 & in this section along with validation of inlet and outlet Temperature of components with respect to Liebherr data [4] shown in Figure 4.

Table 2: Results of Aircraft Types - Conventional ECS

| Aircraft Type (-) | PHX & MHX | Compressor & Turbine Impeller | Reheater & Condenser Impeller |
|-------------------|-----------|-------------------------------|-------------------------------|
|                   | La (m)    | Lb (m) | Lc (m) | Outlet Diameter | Inlet Diameter | Outlet Diameter | Inlet Diameter |
| 1                 | 0.25      | 0.23  | 0.15   | 0.076          | 0.038          | 0.10           | 0.10           | 0.14           | 0.07           |
| 2                 | 0.30      | 0.25  | 0.15   | 0.098          | 0.049          | 0.14           | 0.14           | 0.14           | 0.18           | 0.09           |
| 3                 | 0.32      | 0.20  | 0.18   | 0.11           | 0.055          | 0.18           | 0.18           | 0.18           | 0.21           | 0.105          |

4.1.1. Heat Exchangers - PHX and MHX: The Primary heat exchanger (PHX) & Main heat exchanger (MHX) are typically cross-flow type heat exchangers. Depending on the inlet mass flow rate of the air the size of the component varies. As the aircraft type changes i.e., as the number of passengers increase the mass flow rate of hot bleed air increases and vice-versa. For both PHX and MHX, the fin tube height and fin tube thickness are taken as 0.006 m and 0.0002 m respectively for all the three aircraft types [3]. The inside cross-sectional area ($A_t$) and perimeter of the tube ($P_t$) is taken as 0.002 $m^2$ and 0.54 m respectively [3]. The thermal conductivity of the fin ($K_{fin}$) is considered to be 177 $W/m^2K$ [5] for all the aircraft and Prandtl number is used from [6] for air on cold and hot side of the heat exchanger.

4.1.2. Air Cycle Machine - Compressor & Turbine: The compressor, Turbine, and fan are all mounted on the same shaft, and the Turbine drives the compressor. The bleed air from the Reheater cold side (CS) flows into the Turbine. The pressure ratio of the compressor ($\pi_c$) is considered to be 1.4 [3]. The specific heat of bleed air at constant pressure and volume is considered to be $c_p=1.005 (kj/kg.K)$ and $c_v=0.716 (kj/kg.K)$ [7]. The compressor efficiency ($\eta_{cmp}$) is assumed to be 0.7 [3]. Slip factor of the compressor ($S_{fcmp}$) is taken as 0.9 [8]. The impeller rotations per minute (rpm) ($N_{cmp}$) is considered to be 45000 [9]. The diffuser inlet
diameter \((D_{\text{comp}})\) was assumed to be half of the \((D_{2\text{cmp}})\). The assumptions considered for the Turbine are as follows, the expansion ratio of the Turbine for all the three aircraft types is assumed to be 2. The slip factor of the Turbine is assumed to be 0.9. The isentropic efficiency of the Turbine is assumed to be 0.8 for all three aircraft types.

4.1.3. High Pressure Water Separation Loop: The high-pressure water separation loop consists of Reheater, Condenser, Water extractor, and Turbine. The bleed air temperature and pressure at the cold side of the Reheater are assumed to be 320 K and 260000 Pa [3].

4.1.4. Reheater (Cold & Hot Side) & Condenser (Low pressure side (LPS) & High pressure Side (HPS)): Reheater (REH) and Condenser are cross-flow type heat exchangers. The bleed air from the MHX flows through the hot side of the Reheater. Bleed air from the high pressure side of the condenser flows into cold side of the Reheater. From Reheater hot side (HS), the bleed air flows into the high pressure side (HPS) of the condenser. Here, the Turbine outlet bleed air acts as the coolant air and passes to the low pressure side of the condenser. At high pressure side of the condenser, bleed air from Turbine outlet acts as the coolant and passes at the low pressure side of the condenser. The heat transfer takes place between the bleed air flowing at the condenser high pressure side (HPS) and bleed air flowing at the low pressure side (LPS).

4.1.5. Validation of inlet and outlet temperature of ECS components: The summarizes of the inlet and outlet temperatures of different components of the conventional ECS are shown in Figure 4. The values are validated with Liebherr ECS data [4].

![Validation of Conventional ECS temperature data with Liebherr ECS data](image)

Figure 4: Validation of inlet and outlet Temperature of components vs Liebherr data [4]

4.2. Electrical ECS

The results for Electrical ECS, the sizing values with respect to individual components of the system are tabulated. Comparing with conventional ECS, components like Reheater, Condenser and Water extractor are absent. Components like compressors and fans are powered by motors running on AC power.
### Table 3: Results of Aircraft Types - Electrical ECS

| Aircraft Type (-) | PHX & SHX | Compressor impeller | Turbine Impeller |
|-------------------|-----------|---------------------|------------------|
|                   | La (m)    | Lb (m)              | Lc (m)           | Outlet Diameter (m) | Outlet Diameter (m) | Outlet Diameter (m) | Outlet Diameter (m) |
| 1                 | 0.33      | 0.11                | 0.11             | 0.16                | 0.08                | 0.12                | 0.06                |
| 2                 | 0.22      | 0.20                | 0.20             | 0.20                | 0.10                | 0.16                | 0.08                |
| 3                 | 0.27      | 0.25                | 0.25             | 0.24                | 0.12                | 0.19                | 0.095               |

#### 4.2.1. Ram Air Compressors: In Electric ECS, bleed air from the engine is absent. Instead, ram air is used from atmosphere as the source of air to electric ECS, fed by electric ram air compressors. Compressed air passes through the ozone separator and flows into the Primary heat exchanger (PHX). The primary heat exchanger is a cross-flow type heat exchanger same as the conventional HPWS-ECS. The compressed hot ram air from ram air compressors passes at one side of PHX and cold ram air passes from the other side of the PHX from plenum.

The inlet pressure of the ram air is obtained using the inlet pressure Equation. The Mach number of the aircraft is considered to be 0.75 and is flying at an altitude of 11277.6 m. The atmospheric pressure \(P_{atm}\) at 11277.6 m is 8100 Pa [1]. The pressure ratio of the two ram air compressors is considered to be 5 [10]. The slip factor of the ram air compressors is considered to be 0.9 [8]. The isentropic efficiency of the ram air compressors is considered to be 0.7 [10].

#### 4.2.2. Primary Heat Exchanger & Secondary Heat Exchanger: Compressed air passes through the ozone separator and flows into the primary heat exchanger (PHX). The primary heat exchanger is a cross-flow type heat exchanger. The compressed hot ram air from ram air compressors is passed into the one side of the PHX and cold ram air from plenum passes on the other side of the PHX.

#### 4.2.3. Air Cycle Machine - Compressor: The dimensional and thermal results are illustrated in Table 3. These results are obtained analytically by solving the equations considered Turbine sizing. The air inlet pressure of the Turbine is equal to the outlet air pressure from the SHX. The is-entropic efficiency of the compressor \(\eta_{trb}\) is considered to be 0.8. The slip factor of the compressor \(S_{fcmp}\) is 0.9.

From PHX the air flows into the ACM. In compressor, air gains the pressure and temperature. The pressure ratio of the compressor \(\pi_c\) is assumed to be 5. The specific heat of bleed air at constant pressure and volume is considered to be \(c_p=1.005\ (kJ/kg.K)\) and \(c_v=0.716\ (kJ/kg.K)\) [7]. The compressor efficiency \(\eta_{cmp}\) is assumed to be 0.7. The slip factor of the compressor \(S_{fcmp}\) is assumed to be 0.9. The impeller rotations per minute (rpm) \(N_{cmp}\) is considered to be 45000 rpm. The impeller inlet diameter \(D_{1cmp}\) is assumed to be half of the \(D_{2cmp}\).

#### 4.2.4. Air cycle machine - Turbine: The dimensional results are illustrated in Table 3. These obtained by analytically solving the equations considered in Turbine sizing. The air inlet pressure of the Turbine is equal to the outlet air pressure from the SHX. The is-entropic efficiency of the Turbine \(\eta_{trb}\) is considered to be 0.8. The slip factor of the Turbine \(S_{ftrb}\) is 0.9.
4.3. Pressure Losses in Pipes:

The hydraulic diameter \( (D_h) \) of each pipe differs for each type of aircraft, \( (D_h) \) for aircraft’s type 1, type 2 and type 3 are 30 mm, 35 mm and 40 mm. The pipe is assumed to be made up of aluminum (Al). The absolute roughness of the pipe is considered to be \( 0.001*10^{-3} \) m [11]. Aluminum pipes are assumed for the calculations as they are cheap, the surface roughness ranges from \( 0.001*10^{-3} \) m to \( 0.002*10^{-3} \) m and are lesser in weight compared to the pipes made up of other metals. These characteristics of aluminum contribute economically and increase the efficiency of the system [11]. The pipe length between each component is considered to be 0.3 m. It is constant for both conventional and electrical ECS and does not vary with the type of aircraft. The bend angle considered for each pipe connection for both conventional and electrical ECS is 90° and the bend type is flanged smooth bend. For the bend with an angle of 90° the flow is across bends, so the frictional factor value \( (K_L) \) is considered to be 0.3 [11]. Figure 5

![Pressure loss in pipes between electric ECS components](image)

Figure 5: Pressure loss (PL) in pipes between electric ECS components

![Pressure loss in pipes between conventional ECS components](image)

Figure 6: Pressure loss (PL) in pipes between conventional ECS components
& Figure 6, illustrate the pipe pressure losses for all the components of both conventional and electrical ECS.

5. Geometric models and RAPID Integration
Knowledge-based Engineering approach is employed in CATIA [12], the knowledge is stored in the form of templates also known as User Defined Features (UDF), these UDF’s are instantiated repeatedly with the help of a catalog and Knowledge pattern feature, to obtain the desired result. The geometric models of the two pack conventional and electrical ECS are represented in Figure 7a and 7b, respectively. These are the geometric models of ECS, that would be instantiated into the aircraft in RAPID [13] [14] and the choice of the system is controlled manually using a parameter. Essentially, the user can choose which system would be required for the particular aircraft. The diffusers are connected to the main system through a mixing manifold. This air is then fed into the aircraft through the diffusers. The user has a controlling parameter to chose the type of ECS from and the sizing is done automatically based on the number of passengers that serves as the driving input.

Figure 7: Left: Geometrical representation of Conventional & Electric ECS Systems. Right: Automated instantiation of pipes & ducts in RAPID.

The geometric model of the air diffusers is shown in Figures 7d & 7c that is integrated into the RAPID [13] [14]. Single-aisle configuration has the ducts that would be instantiated as shown. The number of diffusers to be instantiated into the aircraft can be controlled manually by a string parameter named "numberOfInstances" by the user as per the requirements. This parameter is controlled by the knowledge pattern code. Double aisle configuration is different compared to single-aisle, instead of diffusers, the system incorporates a different design. The air
supply pipes are designed to ensure the supply of air to the cabin directly. Figure 7e shows the air
diffuser pipes, that would also act as the ducts for the double aisle configuration. This eliminates
the need for the ducts, in turn reducing the piping cost and the gross weight of tubing. The
user gets a parameter, which can be used to switch between the configurations for the aircraft.
Figure 7d, illustrate the ECS instantiated automatically into the RAPID. This automation is
achieved by knowledge pattern scripting. The product knowledge template workbench is used
for the implementation of knowledge pattern script into the CATIA model. The scripting is
faster and flexible when compared with VBA [15]. The number of air ducts for the single-aisle
configuration can be adjusted or controlled by a few parameters. The design being really flexible
can be customized easily for either single or double aisle configuration.

6. Conclusion & Future work
Analysis and working of conventional and electrical ECS are addressed along with temperature
and pressure data for different aircraft configurations. These systems are designed and tested
for different aircraft types with a different number of passengers. The temperature and pressure
data obtained from the system for a specific cruise altitude are compared with the standard
data for accuracy. Results show a minor variation from the standard values, although this could
be accounted for the constants that are assumed during the course of the calculation. This
work can be taken as the first step in ECS and can serve as the base for further improvements,
including increasing the size for an extremely high or low number of passengers. Future work
include using SSP support as presented in [16] for coupling with other domains & possibility of
a hybrid environmental control system.

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