Exergy-Based Analysis of Aircraft Environmental Control Systems – Integration into Model-Based Design and Potential for Aircraft System Evaluation

Daniel Bender
Institute of System Dynamics and Control, DLR German Aerospace Center, Oberpfaffenhofen, Germany
Daniel.Bender@dlr.de

Abstract:
The analysis of complex thermodynamic systems with exergetic and 2nd law methods is continually performed for various fields of engineering. This also applies to environmental control systems (ECS) of aircraft. This paper focuses on methods of exergy and energy analysis applied to ECS. It gives a survey of the published material and identifies the state of the art. Furthermore, this analysis includes an example with a conventional ECS cycle on how these methods can be integrated into a corresponding model-based design process. Conventional exergy methods allow the location of exergy destruction throughout a system, but ignore the mutual interdependencies of the system components. Advanced exergy analysis provides a splitting of the exergy destruction in each component into different parts. This method enables a realistic assessment of the potential for improving the thermodynamic efficiency of each component. The different methods are discussed with an evaluation of a conventional ECS cycle regarding their optimization potentials and conclusions are drawn.

Keywords:

1. Introduction
About 2-3% of the whole energy consumption of a conventional civil aircraft applies to the environmental control system. In times of intense competitive pressure for the airlines to survive at the global market, the demand for more efficient aircraft is enormous. Efficiency means primarily the reduction of fuel consumption. Less fuel means less cost and less weight and consequently more remaining payload (such as passengers or cargo). An aircraft is a very complex system with hundreds of subsystems - all of which consume energy. So where should one start optimizing? Fuel is the only energy source on a plane. Most of this energy is needed to propel the aircraft. But besides the thrust, the engines produce electrical, hydraulic and pneumatic power that is needed to run all the other systems such as avionics, flight controls, flight deck systems, cabin entertainment and the environmental control system. Among all these systems, the ECS is the second largest consumer of energy besides the propellant and thus an important candidate for optimization. Model-based design methods gain more and more importance in today’s development of environmental control systems for aircraft - whether to support trade-off studies during the pre-design phase or for detailed performance simulation of system models. Thanks to increasing computing power, such simulations can be performed on single workstations. Equation-based object-oriented modelling languages allow the modelling of multi-physic systems without the need to be a computer/programming expert. Modelica [1] is a free language that has been developed by the Modelica Association since 1996 and is used in industry since about the year 2000. Its goal is to provide the modelling of technical systems and their dynamic behaviour in a convenient way.
The models are described by differential-algebraic and discrete equations. Models of similar technical fields can be organized in libraries. For example equipment such as heat exchangers, compressors, turbines, ducts, etc. can be modelled as single components and stored in a library. Using these component models, a system model can be assembled to simulate its behaviour. In this way different architectures do not have to be modelled from scratch as the single component models can be reused and slight modifications can easily be made with little effort. Many free and commercial libraries based on the Modelica language have been developed for different physical fields and applications\(^1\). For the application that is presented in this paper, a library [2] for the modelling of environmental control systems has been used.

Besides the pure modelling and simulation of system models, it is important to have instruments to analyse and evaluate the different designs in terms of efficiency and performance. As the ECS mainly consists of thermodynamic cycles, different analysis methods can be applied. These are the traditional trade factors (such as fuel burnt, specific fuel consumption (SFC), and take-off weight (GTW) [3]) and the thermodynamic second law concept.

1.1 Fuel burnt, SFC and GTW

Fuel burnt, SFC and GTW are based on the traditional first law energy conversion methods that are used in industry for analysis of integrated thermal systems. By weighting system performance and components weight, specific fuel penalties or gross take-off weight can be determined for each component of the system. These factors can be calculated with reference to standardized methods as presented in [3] and summed up for the whole system. The optimal design of the overall system can then be found by varying different parameters such as heat exchanger effectiveness and size, compressor and turbine performance or ECS coolant flow rates in order to minimize the total SFC or GTW. The found optimal design has to undergo a performance analysis to proof its satisfaction for all operating conditions of the aircraft.

The advantage of this conventional method is that it can easily be applied to an environmental control system and gives standardized results for trade-off analysis of different system designs. But this method does not give any information about the quality of the system design itself as the interactions of the different components are not considered.

1.2 Exergy based methods

Second law methods have already a long tradition in the aerospace sector - especially for the application on environmental control systems. Early works for ECS architecture optimization of advanced aircraft by using entropy generation analysis on system level are found two decades ago [4]. The efforts then increased significantly with the beginning of 2000, focusing on integrative thermodynamic optimization of environmental control systems. Single components, mostly heat exchangers, were optimized, i.e. regarding their geometry parameters, by minimizing entropy generation on system level [5,6]. Contrary to previous methods, components were optimized regarding aircraft-level performance, as opposed to an isolated view.

Exergy-based and conventional energy-based approaches were applied by several authors [7-9] to the same highly integrated aircraft thermal systems and compared in terms of their results. It emerged that both approaches led to similar outcomes, but are awkward for direct comparisons as they seek answers for different questions [9]. Instead of opposing the two evaluations, their combination was suggested in order to search for a pareto optimal design. Exergy-based analysis is seen advantageous as a decision making tool for aircraft systems design, but a solid proof of this hypothesis is still outstanding. It is a powerful method to compare and analyze systems and their components, but also raises the question, how non-exergy related aspects can be addressed in the exergy analysis framework [10].

\(^{1}\) A detailed overview can be found at: [https://modelica.org/ModelicaLibrariesOverview](https://modelica.org/ModelicaLibrariesOverview)
Conventional exergy methods allow the location of exergy destruction throughout a system, but ignore the mutual interdependencies of the system components. Advanced exergy analysis provides a splitting of the exergy destruction in each component into different parts [11]. This method enables a realistic assessment of the potential for improving the thermodynamic efficiency of each component. For the analysis and evaluation of aircraft environmental control systems the advanced exergy methods have not yet been applied until today. A conventional exergy analysis is performed within this paper and based on these results the need for advanced exergy methods is emphasized.

2. The Environmental Control System

The primary task of the ECS is to ensure an environment that fulfils the physiological needs and comfort demands of passengers and crew. These tasks require functionalities such as temperature, humidity control and regulation of cabin pressurization. De- or anti-icing capabilities and sufficient ventilation, fresh air supply and the removal of pollutants are furthermore provided. [2]

Figure 1: Conventional ECS architecture [2]

Figure 1 shows an overview of a conventional environmental control system. It consists of several subsystems: Air conditioning system (ACS), temperature control system (TCS), ventilation control system (VCS), air distribution system (ADS), and cabin pressure control system (CPCS). Systems such as combined ozone/ VOC converters (VPZC), humidification systems (HUM), or dry air generation systems (DAGS) can optionally be installed on an ECS. [2]

2.1 Overview

The key part of the ECS is the air generation unit (also called (air) pack). Within this devise, the air flow is conditioned. Usually there are two packs installed in an aircraft. Conventional systems use engine bleed air as the power source. The bleed air is drawn off from the compressor stages upstream the combustion chamber. There the air has high temperature (~220°C) and high pressure (~2.5bar) and must be conditioned before it is distributed into the cabin. First the air flow is lead to the air pack where it is cooled down and dehumidified. It passes several heat exchangers, a compressor, a turbine and valves before the flow has reached the right condition to be lead to the mixing unit. Now it merges with recirculated, filtered air from the cabin. From there the air is carried to the flight deck and different compartments of the cabin. A single isle aircraft contains about 3 different temperature controlled zones. These can increase up to eight zones for long range aircraft.
Unconventional ECS follow the more electric aircraft approach and are bleed-less architectures. That means that the fresh air is not sucked from the compressor stage of the engines but enters the system through air inlets installed at the fuselage. Contrary to the conventional system, the energy for the air pack is not provided in form of pneumatical power (such as air at high temperature and pressure conditions). The ambient air must be heated up and compressed by electrically driven machines. The electrical power is supplied through generators mounted at the engines. The unconventional ECS concept additionally includes a vapor compression cycle to cool down the recirculated, filtered air from the cabin before it meets the fresh air from the air cycle in the mixing unit. [12]

2.2 Air Cycles

Within the environmental control system, the air generation unit is the central part. The thermodynamic cycle of the air cycle is derived from the reverse Joule cycle for open systems. Air is compressed (at least in the engine compressor), heat is then rejected at high temperature and finally the air expands to cool down below ambient condition.

Figure 2: Typical air cycles used aboard commercial aircraft [2]

Figure 2 shows four typical air cycles that are or were installed in conventional ECS architectures using bleed air. They represent different levels of development. The cycle on the very left is the simplest of the four cycles and from today's point of view it works inefficiently. It is part of the ECS aboard the Fokker 100, for example. The next shown cycle is the bootstrap cycle. Contrary to the simple approach, the bleed air is first compressed before entering the heat exchanger where it is cooled against ram air. The higher inlet temperature at the hot side makes the process more efficient. Inside the turbine the air flow is expanded below ambient temperature. On ground the ram air flow is provided by the ground fan which is usually driven electrically (i.e. Boeing 727) or pneumatically (i.e. Boeing 737 Classic).

The third cycle, the three wheel bootstrap cycle, has a slightly lower efficiency compared to the classic bootstrap cycle as the fan (F) is mounted on the same shaft as the compressor (C) and the turbine (T). This arrangement has the advantage of being self-contained and does not depend on other power sources.

In the beginning of this section, humidity control was mentioned as one of the main tasks of the ECS. As cooling is mostly involved during the conditioning process of the air, the temperature can sink below the saturation point. Condensation and free water in the moist air flow would be the consequence. As this could theoretically happen in any component of the ECS (formation of ice) or the cabin (fogging), humidity control is crucial for the reliable operation of the ECS and thus the aircraft. To prevent the air flow from reaching the saturation point, water extractors are implemented to the system. Two concepts can be distinguished. The lowest temperature occurs downstream the turbine and free water can be found there. The approach to place a water separator at this point is called low pressure water separation. In the case of condensation, ice build-up cannot be prevented by other means than limiting the expansion process of the turbine to a minimum exit temperature of 0°C. This results in strong restrictions concerning the pack design and thus its
cooling capacity. The alternative is the location of the water separator upstream the turbine. This concept is called the high pressure water separation.

Coming back to the three wheel bootstrap cycle, two designs concerning water separation are used in ECS architectures. In the early version of the Boeing 747 the low pressure design was used. Using the high pressure water separation, the three wheel bootstrap cycle is probably the most common pack configuration today (used in the Airbus A320 and A330/A340 families, Boeing 757, 737NG, later version of the Boeing 747 and early versions of the 767).

The four wheel bootstrap cycle resembles the three wheel bootstrap cycle and differs mainly by an additional turbine stage on the shaft. The different requirements concerning humidity control for ground cases and cruising conditions at high altitude can be achieved by this architecture. A detailed description can be found in [2].

Whether the three or four wheel bootstrap cycle is used seems to be a matter of philosophy. It must be decided on a base of case to case trade-off. The latter cycle is used in today’s versions of the Airbus A380, Boeing 777 and later version of 767, and the Embrear EMB 170/190 family. [2]

2.3 System description

Figure 3 illustrates the detailed schematic of the air generation unit that is used for the exergetic analysis. It includes a conventional bleed air driven three wheel bootstrap cycle. The different flows are enumerated for a better allocation with the simulation results. In principle three different flows are considered. The bleed air arises from the compressor stage at the engine, passing at first the pneumatic distribution device (PDD) before it enters the ozone converter (O$_3$/O$_2$). Inside the primary heat exchanger (PHX) the hot air is cooled down against the ram air flow. Before entering the compressor stage (CMP), a part of the air flow is separated and bypassed through the temperature control valve (TCV). Downstream the compressor stage the heated and compressed air is cooled down a second time inside the main heat exchanger (MHX) against the cold ram air flow.

![Figure 3: Schematic diagram of the overall air generation unit.](image)

Here the most intense heat exchange takes place due to the large temperature difference. The air flow now enters the hot side of the reheater (REH) and is cooled down again before its temperature
is further decreased inside the condenser (CON) in order to dehumidify the air flow and prevent downstream conditions from reaching the saturation point. This configuration of the three wheel bootstrap cycle uses the concept of high pressure water separation. In case of condensation in the condenser, the free water is separated in the water extractor (WE) and carried to the injector (IN) located at the beginning of the ram air channel. The dehumidified air flow now passes the re heater a second time, this time at the cold side where it is re heater against its upstream air flow. Inside the turbine (TRB) the air is expanded to a sufficient pressure level. Concurrently the temperature decreases significantly below ambient conditions. At this point the air reaches its coldest condition. Meeting the separated air from the temperature control valve, the flow gains a higher temperature und finally is heated up inside the condenser again before it leaves the air pack to the mixing unit where it is mixed with recirculated and filtered air from the cabin.

The second flow occurring is the ram air flow. It functions as a heat sink and enters the aircraft through inlets outside the aircraft’s fuselage. The amount of air flow can be controlled by flaps installed at the inlet and outlet of the ram air channel. Water from the water extractor is now injected into the ram air flow where it evaporates and subsequently the temperature of the ram air flow is decreased. The cool air passes successively the main heat exchanger and primary heat exchanger before it leaves the ram air channel to the ambient. In ground operation the ram air flow is driven by the ram air fan that is mounted on the same shaft as the compressor and turbine.

3. Definitions
In the following some definitions are described that are used for the discussion part of this work.

3.1 Advanced exergy analysis
The advanced exergy analysis proposes a further splitting of exergy destruction for the \( k \)-th component [13]. The exergy destruction can be split into four parts. Avoidable and unavoidable exergy destruction provide a measurement instrument for the optimisation potential of the thermodynamic efficiency of the component. Endogenous and exogenous exergy destruction give information on how the components impact each other among the system.

3.2 Avoidable and unavoidable exergy destruction
The thermodynamic performance of a component is limited due to technological limitations such as availability and cost of materials, and manufacturing methods. In case of the application for the aircraft industry additional limitations such as weight, volume, noise and reliability must be considered. The exergetic destruction due to these limitations is defined as the unavoidable (\( \dot{E}_{Dk}^{UN} \)) part and cannot be reduced by optimization. The remaining part is called the avoidable (\( \dot{E}_{Dk}^{AV} \)) exergy destruction. The splitting in the \( k \)-th component \( \dot{E}_{Dk} = \dot{E}_{Dk}^{UN} + \dot{E}_{Dk}^{AV} \) gives a realistic assessment of the potential for optimization of the thermodynamic efficiency of a component.

3.3 Endogenous and exogenous exergy destruction
The endogenous (\( \dot{E}_{Dk}^{EN} \)) part of the total destroyed exergy in the \( k \)-th component results from the irreversibilities happening within the component under the assumption that all other components of the system operate in the ideal way and the \( k \)-th component operates with its current efficiency. The remaining exogenous (\( \dot{E}_{Dk}^{EX} \)) part can be reduced to the exergy destruction within the component that are caused by the irreversibilities of other components of the system. Together they yield the total exergy destruction \( \dot{E}_{Dk} = \dot{E}_{Dk}^{EN} + \dot{E}_{Dk}^{EX} \) of the \( k \)-th component.

3.4 Combination of the splitting
The combination of the four parts allows a detailed analysis of the total destroyed exergy within a component. The unavoidable endogenous and subsequently the unavoidable exogenous, the avoidable endogenous and avoidable exogenous exergy destruction can be considered separately.
The unavoidable endogenous ($\dot{E}_{D_{k}}^{UN,EN}$) exergy destruction cannot be reduced due to technical limitations of the $k$-th component. The unavoidable exogenous ($\dot{E}_{D_{k}}^{UN,EX}$) part will remain because of technical limitations related to all the other components of the system structure. The other two parts can be reduced through optimization. The avoidable endogenous ($\dot{E}_{D_{k}}^{AV,EN}$) part can be reduced by optimizing the thermodynamic efficiency of the $k$-th component. The remaining part, the avoidable exogenous ($\dot{E}_{D_{k}}^{AV,EX}$) exergy destruction can be reduced by improving the efficiency of the other components of the overall system.

4. Methodology

For the work presented in this paper, conventional exergy methods have been implemented into a model of a three wheel bootstrap cycle of a conventional environmental control system. The model was simulated and the results were extracted. The approach and used methodology is described in the following section.

4.1 Conventional exergy analysis

For the calculation of the air cycle it is assumed that the components do not interact with the ambient environment (such as surrounding structures, compartment, etc.). This brings the advantage that the exergy balance over one component includes only the entering and leaving flows. It can be expressed for the $k$-th component as:

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k}$$

where subscripts $F$, $P$ and $D$ represent the fuel exergy, product exergy and destroyed exergy of the $k$-th component.

For the total system this balance can be written as:

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \sum_k \dot{E}_{D,k} + \dot{E}_{L,tot}$$

with $tot$ representing the total amount of the overall system.

The exergetic efficiency $\varepsilon_k$ of the $k$-th component is defined by the following equation:

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}$$

The rate of the exergy destroyed related to the fuel exergy that enters the component is expressed by the exergy destruction ratio $y_{D,k}$:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}$$

4.2 Integration into model-based design

As already mentioned in the introduction of this paper, the equation-based, object-oriented modelling language Modelica has been used to set up the model of the three wheel bootstrap cycle. Dymola [14] was chosen as the modelling and simulation environment tool. Figure 4 shows the diagram layer of the modelled air pack as it was realized in Dymola.
Figure 4: Diagram layer of air pack system model with three wheel bootstrap cycle.

A graphical surface enables the user to plug the components into the model from the library by drag & drop. The component models are equipped with connectors and can easily be linked by connecting the outlet connector of one component with the inlet connector of the downstream component. Here the orange lines represent the air flow and the blue line represents the connection between the water extractor and the water injector. The ram air inlet and outlet, the engine as source of the bleed air and the exit to the mixing unit are represented by air sources and air sinks. The ambientConditions element on the lower right constitutes the ambient conditions and provides its thermodynamic properties. The shaft on which the compressor, the fan and the turbine are mounted, is modelled as a pseudo inertia element. All components are taken from the before mentioned ECS library [2].

The connectors represent the inlets and outlet interfaces of a component. They all contain thermodynamic information describing the air/water flow at the border of the component in order to communicate the variable values to the adjacent components. In case of the air flow, the connectors contain flow and stream variables for mass flow, specific enthalpy, water content and additional constituents, and a static variable for the pressure. From these variables other properties
such as the temperature and specific entropy can be calculated by functions that are provided by the Modelica Standard Library\(^2\).

The conventional exergy analysis is implemented to the model in a straightforward way. For each component and each air port the exergy flow is calculated inside the component. In case of a heat exchanger four flows are determined. Further equations for the destroyed exergy of each component are implemented to the programming code.

First the specific entropy and specific enthalpy are determined for the reference point \(T_0\), \(p_0\) and \(X_0\) and the specific entropy at the inlet and outlet. The exergy flows are calculated by the following equations:

\[
\dot{E}_{in} = \dot{m}_{in} \left[ h_{in} - h_0 - T_0 \times (s_{in} - s_0) \right]
\]

and

\[
\dot{E}_{out} = \dot{m}_{out} \left[ h_{out} - h_0 - T_0 \times (s_{out} - s_0) \right]
\]

where \(\dot{m}\) is the mass flow entering and leaving the component, \(h\) and \(s\) represent the specific enthalpy and specific entropy of the flow at the inlet, respectively outlet.

The destroyed exergy can then be determined by:

\[
\dot{E}_D = \dot{E}_{hot,in} - \dot{E}_{hot,out} + \left( \dot{E}_{cold,out} - \dot{E}_{cold,in} \right)
\]

Once the equations have been implemented for each component model, the variables are calculated during simulation for every single time step and can be accessed afterwards for evaluation and analysis.

### 5. Results

For the simulation of the air generation unit a flight segment has been chosen that could occur during climb or descend of a flight mission. Table 1 lists the conditions at the use case flight level for a standard ISA day. For the exergy analysis these conditions are defined as the reference values for the reference point \(T_0\), \(p_0\) and \(X_0\).

<table>
<thead>
<tr>
<th>Altitude [ft]</th>
<th>Temperature [°C]</th>
<th>Pressure [bar]</th>
<th>Relative humidity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.000</td>
<td>-4.81</td>
<td>0.696844</td>
<td>54.7</td>
</tr>
</tbody>
</table>

The main thermodynamic properties of the system are shown in Table 2. The numbers of the different flows are linked to the enumeration within the schematic diagram of Figure 3. The values for the pressure and temperature have been normalized for reasons of confidentiality. \(\dot{E}_{tot}\) is the total exergy flow of the appropriate flow following equations (5) and (6).

<table>
<thead>
<tr>
<th>No.</th>
<th>Working Fluid</th>
<th>(\dot{m}), [kg/s]</th>
<th>(p/p_{ref}), [-]</th>
<th>(T/T_{ref}), [-]</th>
<th>(\dot{E}_{tot}), [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Air</td>
<td>0.5</td>
<td>0.837</td>
<td>1.06</td>
<td>78.78</td>
</tr>
<tr>
<td>1</td>
<td>Air</td>
<td>0.5</td>
<td>0.824</td>
<td>1.06</td>
<td>78.17</td>
</tr>
<tr>
<td>2</td>
<td>Air</td>
<td>0.5</td>
<td>0.815</td>
<td>1.06</td>
<td>77.72</td>
</tr>
<tr>
<td>3</td>
<td>Air</td>
<td>0.5</td>
<td>0.788</td>
<td>0.92</td>
<td>63.90</td>
</tr>
<tr>
<td>4</td>
<td>Air</td>
<td>0.4</td>
<td>0.788</td>
<td>0.92</td>
<td>51.12</td>
</tr>
<tr>
<td>5</td>
<td>Air</td>
<td>0.4</td>
<td>1.000</td>
<td>1.00</td>
<td>63.90</td>
</tr>
</tbody>
</table>

\(^2\) A detailed description can be found on: [https://www.modelica.org/news_items/modelica-standard-library-3.2.1-released](https://www.modelica.org/news_items/modelica-standard-library-3.2.1-released)
The simulation results from the conventional exergy analysis at the component level are listed in Table 3.

The results show that for the fresh air flow 36% of the fuel exergy is destroyed in the temperature control valve. This could be reduced by reducing the mass flow that is bypassed among the cycle. The turbine shows the second largest exergy destruction, followed by the main heat exchanger and the fan. The water extractor and injector do not destroy any exergy. That is because in the current operating case no water condenses and is extracted. Regarding the perspective of the conventional exergy approach, the higher the exergy destruction, the higher is the potential for improvement of the overall system efficiency. According the results, the turbine should be addressed first for optimization. Followed by the main heat exchanger and the fan.

Table 3: Results from the conventional exergy analysis on component level.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{f,k}$, [kW]</th>
<th>$\dot{E}_{p,k}$, [kW]</th>
<th>$\varepsilon_k$, [-]</th>
<th>$\gamma_{D,k}$, [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDD</td>
<td>78.78</td>
<td>78.17</td>
<td>99.2%</td>
<td>0.78%</td>
</tr>
<tr>
<td>$O^3O^2$</td>
<td>78.17</td>
<td>77.72</td>
<td>99.4%</td>
<td>0.57%</td>
</tr>
<tr>
<td>PHX</td>
<td>88.24</td>
<td>85.82</td>
<td>97.3%</td>
<td>2.74%</td>
</tr>
<tr>
<td>CMP</td>
<td>65.66</td>
<td>63.90</td>
<td>97.3%</td>
<td>2.68%</td>
</tr>
<tr>
<td>MHX</td>
<td>63.90</td>
<td>57.58</td>
<td>90.1%</td>
<td>9.89%</td>
</tr>
<tr>
<td>REH</td>
<td>93.35</td>
<td>92.97</td>
<td>99.6%</td>
<td>0.40%</td>
</tr>
<tr>
<td>CON</td>
<td>73.47</td>
<td>72.71</td>
<td>99.0%</td>
<td>1.03%</td>
</tr>
<tr>
<td>WE</td>
<td>46.29</td>
<td>46.29</td>
<td>100.0%</td>
<td>0.00%</td>
</tr>
<tr>
<td>REH</td>
<td>93.35</td>
<td>92.97</td>
<td>99.6%</td>
<td>0.40%</td>
</tr>
<tr>
<td>TRB</td>
<td>46.28</td>
<td>37.70</td>
<td>81.5%</td>
<td>18.52%</td>
</tr>
<tr>
<td>CON</td>
<td>73.47</td>
<td>72.71</td>
<td>99.0%</td>
<td>1.03%</td>
</tr>
<tr>
<td>Injector</td>
<td>0.00</td>
<td>0.00</td>
<td>100.0%</td>
<td>0.00%</td>
</tr>
<tr>
<td>MHX</td>
<td>63.90</td>
<td>57.58</td>
<td>90.1%</td>
<td>9.89%</td>
</tr>
<tr>
<td>PHX</td>
<td>88.24</td>
<td>85.82</td>
<td>97.3%</td>
<td>2.74%</td>
</tr>
<tr>
<td>Fan</td>
<td>24.84</td>
<td>23.46</td>
<td>94.4%</td>
<td>5.56%</td>
</tr>
<tr>
<td>TCV</td>
<td>12.78</td>
<td>8.27</td>
<td>64.7%</td>
<td>35.96%</td>
</tr>
</tbody>
</table>

* normalized values in kW/kW
6. Discussion

The results listed in Table 3 are a first indicator which component should be primarily addressed for improving the overall system efficiency. This simulation is just a snapshot of one flight phase. A whole flight mission is a highly dynamic trajectory. Beginning from ground operation at the gate, taxiing, take off and climb to cruise, descend, landing and finally taxiing again, the environmental control system operates in many different conditions and must fulfil its tasks at any time.

Looking at the air generation unit architecture as the central part of an ECS, it is obvious that it is a highly integrative system where each component interacts strongly with the other components. Contrary to stationary energy conversion cycles such as for terrestrial applications, the ECS passes several operating points. The trade-off between high efficiency, reliability, low weight, restrictions concerning volume, cost and maintenance requires a very time-consuming design process.

Components for terrestrial energy conversion systems are designed for an optimal operating point. However, the components of an aircraft ECS need to meet several contradictory requirements. Let us look at the main heat exchanger (MHX) as an example. It is installed in the ram air channel (Figure 3) and cools down the bleed air. On the one hand it shall have high efficiency. On the other hand it shall cause only little drag in the ram air flow and have low weight. The heat that can be exchanged is proportional to the heat transfer surface. Larger surface area leads to higher heat transfer. But larger surface area concurrently causes higher drag. This illustrates the discrepancy for the design of the heat exchanger itself. Ascending to the next highest level, the primary heat exchanger (PHX) downstream the ram air flow is taken into account. The design of the MHX influences directly the condition of the exiting air flow. The conditioned air in turn enters the PHX and thus can be regarded as its operating point. These considerations are just about the design of two components. And only the cold side of the heat exchangers is regarded. The hot side air flow goes the opposite direction and passes the compressor between the two heat exchangers.

Considering now that the ram air flow enters the aircraft at varying ambient conditions, the two heat exchangers operate at several operating points. These thoughts shall give a slight impression about the complex challenges for the design of environmental control systems. However, these reflections underline the need for analysis methods that give more detailed information about the interactions within the system.

Current research (such as it is performed within the European FP7 project TOICA³) seeks for methods where the thermal design of future aircraft or improved systems is developed from a perspective at higher level and follows an overall thermal conception on aircraft level. Meaningful analysis methods are indispensable for the success of these integrative approaches. Advanced exergy methods seem to offer sufficient tools for future needs for the development within the aircraft industry.

7. Conclusion

Conventional exergy analysis methods have been applied to a conventional air generation unit of an environmental control system for commercial aircraft. The model of the considered three wheel bootstrap cycle was modelled using the Modelica language. The exergy methods were implemented to the components of the system model and the simulation for a reference point of a flight mission was performed. Once the methods have been applied to the components, the concept of model-based design allows a conventional exergetic analysis for any simulation performed with this system model or new architectures to be built with of these components. Nevertheless it is restricted to the components that contain the appropriate equations. The presented methodology requires detailed knowledge in modelling as direct adaption of the programme code is required. An evaluation of the system regarding exergy efficiency thus needs expertise in equation-based object-oriented modelling. The concept of a user-friendly method, respectively interface for conventional exergy analysis of energy conversion systems is proposed for future work. In the framework of

model-based design with the Modelica language an exergy analysis library could be a distinct possibility.

As the presented results of the conventional exergy analysis do not provide sufficient information about the interactions and impacts between the components, advanced exergy methods are proposed to apply to environmental control systems. This could bring a better understanding of the system behaviour and hence show a realistic potential for optimization.

8. Acknowledgments

The used library for modelling environmental control systems for aircraft was developed in collaboration and on behalf of Airbus Deutschland GmbH.

Nomenclature

\( \dot{E} \)  exergy rate, W  \\
\( h \)  specific enthalpy, J/(kg)  \\
\( \dot{m} \)  mass flow rate, kg/s  \\
\( p \)  pressure, bar  \\
\( s \)  specific entropy, J/(kgK)  \\
\( T \)  temperature, °C  \\
\( y \)  exergy destruction ratio, %

Greek symbols

\( \varepsilon \)  exergetic efficiency, %

Subscripts and superscripts

\text{0} \quad \text{thermodynamic state at reference point}  \\
\text{D} \quad \text{exergy destruction}  \\
\text{F} \quad \text{Fuel}  \\
\text{k} \quad \text{k-th component}  \\
\text{L} \quad \text{exergy losses}  \\
\text{P} \quad \text{exergy of product}  \\
\text{tot} \quad \text{total}

References


