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Integration of exergy analysis into model-based design and evaluation of aircraft environmental control systems

Daniel Bender

Institute of System Dynamics and Control, DLR German Aerospace Center, Muenchener Str. 20, 82234, Wessling, Germany

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ABSTRACT

The environmental control system of an aircraft is a complex energy intensive system and the most important non-propellant consumer of energy among all aircraft systems. Considering the highly competitive market for conventional aircraft, meaningful analysis methods for evaluation during conceptual design of ECS and effective modelling and simulation tools became more important. Hence, this paper focuses on energy and exergy analyses applied to the conventional aircraft environmental control system combined with the model-based design approach. The reported results are related to the different analysis methods for aircraft environmental control systems and cover the model-based design approach.

The exergy method is applied to a model of a conventional air generation unit of a commercial aircraft. This model was developed using a model-based design framework. Within this framework, the exergy analysis was performed for four phases of a standard flight mission: Take-off, cruise, landing and taxi. The results obtained from the detailed exergy analysis show highly varying performances for the components at the different simulation cases. The exergy efficiencies range from 1% to 88%. A discussion about the special requirements for aircraft environmental control system analysis methods concludes the paper.

1. Introduction

About 3–5% [1,2] 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. Besides the reduction of aircraft weight and fuel consumption, reducing the CO_2 emission is an additional major step towards the ACARE Environmental Goals for future aircraft design [3]. An aircraft is a very complex system with dozens of subsystems. All of them are energy intensive. Fuel is the only energy source on a conventional aircraft. Most of this energy is used to propel the aircraft. But besides the thrust, the engines produce electrical, hydraulic and pneumatic power that is needed to operate all the systems such as avionics, flight controls, flight deck systems, cabin entertainment and the environmental control system. Among all these systems, the environmental control system (ECS) is the largest non-propellant 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, like the support of trade-off studies during the conceptual design phase [4] or thermal management functions on system level [5,6]. Thanks to increasing computing power and more efficient modelling techniques, 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. The goal is to provide the modelling of technical systems and their dynamic behaviour in a convenient way [7]. 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. For the application that is presented in this paper, the modelling

E-mail address: Daniel.Bender@dlr.de.
URL: http://www.dlr.de

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Nomenclature

$\dot{E}$	exergy rate (W)
e	specific exergy (J/W)
h	specific enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (bar)
s	specific entropy (J/kg K)
T	temperature (°C)
$\dot{W}$	Work (W)
y	exergy destruction ratio (%)
X	water content (kg/kg)

Greek symbols

ε	exergetic efficiency (%)

Subscripts

0	dead state point
ch	chemical exergy
D	refers to exergy destruction
F	fuel exergy
k	k-th component
P	product exergy
ph	physical exergy
tot	total

Abbreviations

CMP	Compressor
CON	Condenser
CR	Cruise
ECS	Environmental control system
GTW	Gross take-off weight
IN(J)	Injector
LA	Landing
MHX	Main heat exchanger
PHX	Primary heat exchanger
REH	Reheater
SFC	Specific fuel consumption
TA	Taxi
TCV	Temperature control valve
TO	Take-off
TRB	Turbine
WE	Water extractor

language Modelica [8] has been used. For the modelling of the environmental control system, an existing library [4] was taken and modified for the needs of the exergy analysis.

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 burn, specific fuel consumption (SFC), and gross take-off weight (GTW) [9]) and the thermodynamic second law concept.

Fuel burn, SFC and GTW are based on the first law energy conversion method that is used in industry for analysis of integrated thermal systems [10]. By weighting system performance and components weight, specific fuel penalties or GTW can be determined for each component of the system. These factors can be calculated with reference to standardized methods as presented in Ref. [9] 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 [11,12]. 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 the simple application to any environmental control system and the standardized results gained 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.

The second law method has 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 can be found two decades ago [13]. The efforts then increased significantly with the beginning of 2000s, focusing on integrative thermodynamic optimization of environmental control systems. Single components, mostly heat exchangers, were optimized regarding their geometry parameters by minimizing entropy generation on system level [14,15]. Contrary to previous methods, components were optimized regarding aircraft-level performance, as opposed to an isolated view.

Conventional energy-based and exergy-based approaches were applied by several authors [10,16,17] to the same highly integrated aircraft thermal systems and compared in terms of their significance. It emerged that both approaches led to similar outcomes, but are awkward for direct comparisons as they seek answers for different questions [17]. Instead of opposing the two evaluations, their combination was suggested in order to search for a pareto optimal design, i.e. the found solution $d \in D$, with D being the set of all solutions, is not dominated by any other existing solution $v \in D$. 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 [18].

Conventional exergy methods allow the location of exergy destruction throughout a system, but ignore the mutual interdependencies of the system components. Advanced exergy analysis is a realistic assessment of the potential for improving the thermodynamic efficiency of each component [19]. 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 of a conventional air generation unit of a commercial aircraft is performed within this paper. The air generation unit is modelled using the equation-based object-oriented modelling language Modelica [8]. An adaption of the component models were necessary and a framework was developed to enable the exergy analysis. The analysis is then performed by simulating the model of the unit for the given flight cases. Based on the simulation results, the need for further application of the advanced exergy methods is emphasized.

The following section gives a brief introduction to aircraft environmental control systems and air cycle machines including the considered system. Following, the methodologies of the applied

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