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Exergy Analysis in Aircraft Applications – A Review

Gosukonda Bhavani Sankar

Research Scholar, JNTUA, Ananthapuramu – 515002, A.P. INDIA.

ABSTRACT

Exergy analysis came into prominence in the 70s for its application in the power sector to overcome the energy crisis. Many engineering applications benefitedwith the feasibility and the directionality provided by the analysis.Aircraft is a system of integrated complex systems. Each system has a role to play in every successful mission of the aircraft. In recent years, the aviation business has entered a major growth period with increased air transportation demand projected for the future. On the other hand, the rising awareness of environmental issues on a global scale necessitates a reduction in substances of concern. Furthermore, as the international demand for fuel increases, fuel prices are rising, and the aviation business urgently needs better fuel efficiency for economic reasons as well. With the projected increase of about 40% consumption of jet fuel from 2016 to 2040 due to the exponential growth of the air travel in the coming years, any improvement in the aircraft efficiency will result in huge savings during the life cycle of their operation. Thus, the energy consumption of each system is an area that is scrutinized closely. Going a step ahead, exergy analysis to minimizethe entropy generation by these systems and to curtail the endogenous avoidable and exogenous avoidable parts of the exergy destruction occurring in each component are extensively used in aircraft development.This paper presents a review of the application of the exergy analysis in aircraft applications. Published references are taken from journal papers, books, research work, conference proceedings and technical reports.

KEYWORDS: Exergy Analysis, Aircraft, Mechanical Systems, Environmental Control System, Compact Heat Exchangers

***Corresponding author**

G, BhavaniSankar

Research Scholar,

JNTUA, Ananthapuramu,

A.P. INDIA.

Email: gbspro@gmail.com, Mob No - 9482561000

INTRODUCTION

Energy conservation in any field is necessary for the economics of operation and is mandatory from the environmental issues. In the aircraft industry, with every year seeing a healthy growth ratethat is expected to continue for years to come, every watt of energy saved adds up cumulatively to a big number. While the energy optimisation using the first law of thermodynamics takesinto account all types of energies to satisfy the conservation of the total amount of it in any process, the second law gives the directionality and the quality of the energy and its degradation. So, it is not surprising that the exergy analysis (EA) was first applied to the power source of the aircraft, the engine, in 1956 by Glansdroff[1]. Since then, it had been used extensively for optimization of all types of aircraft engines. A. Bejan, a major contributor to this field of analysis, outlines[2] the need to pursue this approach in aircraft development. As the EA gives the theoretical limit attainable in terms of performance, the application of EA and thermodynamic optimisation at the conceptual level will lead to optimum configuration at all levels in the development of an aircraft which is treated as a complex system of systems[3]. This review paper is an attempt to look at the progress made in this direction and the opportunities that exist to use this powerful technique in the design and development of aircraft.

REVIEW PAPERS

Important review papers that appeared about application of EA for aircraft design and development are given in the following paragraphs. Most of these review papers give a brief history of the exergy and the mathematical models of EA, which are not repeated in this paper.

D.J. Moorhouse along with D.B. Paul and D.M. Pratt[4] discuss the Multi-Disciplinary Optimization (MDO) methodologies employed in design of an aircraft from the view point of a system of systems. The use of energy-based methods is presented, and it was concluded that these methods can be used during conceptual stage in a revolutionary design. An evolutionary design using traditional methods can be audited by these energy-based methods at any stage of the design process to identify the use and wastage of energy.

David Hayes, Mudassir Lone, James F Whidborne and Etienne Coetzee reviewed methods toEntropy Generation Minimization (EGM) and EA for aerospace applications[5]. They concluded that the EA is an excellent tool for optimizing individual sub-systems, however the true potential of the method is harnessed by applying it for top-level system of systems optimization. It can be done at any stage of the design over the entire mission profile to highlight the locations of exergy destruction. Along with José Camberos the authors have further reviewed[6] the use of EA in Aerospace. This review justifies how thermodynamic EA has the potential to facilitate a breakthrough in the optimization of aerospace vehicles based on a system of energy systems, through studying the exergy-based multidisciplinary design of future flight vehicles.

Onder Altuntas, T. Hikmet Karakoc and Arif Hepbasli[7] reviewed EA and the sustainability aspects of piston-prop aircraft engines in 2012. They have applied the analysis and the tools for calculating the exergy rates of an aircraft piston-prop engine during the landing and take-off phases of flight. The review by Meryem Gizem Sürer, Hüseyin Turan Arat[8] in 2018 on the exergy studies on jet engines emphasized the importance of energy and exergy analysis for efficient use of energy in jet engines. Zeyu Dong, Li D, Wang Z and Sun M.[9] observed that the penetration of EA application for aerospace systems is far less than its application in traditional thermodynamic systems. They point out that majority of the EA studies on aerospace propulsion systems are done on simplified systems and the studies on real-life complex combined cycle systems are yet to be done. They also observe that EA in this area should also take into consideration the dynamics along with the regular steady state analysis studies.

And finally in a review paper, Daniel Bender[10] focused on the methods of exergy and energy analysis applied to applied ECS splitting 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. His research thesis[11] is on this subject.

BROAD CATEGORY OF LITERATURE

Books and Online Resources

There are many books on the theory of Exergy. However, the following books are very relevant to the EA in Aircraft Applications.

The first one is edited by David John Moorhouse&José A. Camberos[12]titled "Exergy Analysis and Design Optimisation for Aerospace Vehicles" demonstrates the necessity and power of applying the exergy methods to advanced aerospace vehicle design, system decomposition and optimization. The book is intended to provide an understanding of basic thermodynamic theory to enable the readers to apply it for all the levels of aerospace vehicle design.

There are two books edited by Mark F. Ahlers titled "Aircraft Thermal Management: Systems Architectures"(SAE PT-177) &"Integrated Energy Systems Analysis"(SAE PT-178). There are papers in PT-177 that deal with optimization of the Aircraft thermal management (ATM) architectures to minimize airplane performance impacts which could be applied to commercial or military aircraft. PT-178 discusses approaches to computer simulation of the simultaneous operation of all systems affecting thermal management on an aircraft. A condensed precursor to these books was the paper by Ahler[13] in the Encyclopaedia ofAerospace Engineering.

Silvio de Oliveira Jr.'s book[14] has a chapter detailing the exergy method for conception and assessment of aircraft systems.Ibrahim Dincer & Marc A. Rosen[15]authored a chapter on EA of aircraft flight systems detailing the application of EA to a turbojet engine for a particular flight condition.

Thesis

The topic of EA in aircraft application is the subject of many theses. The notable among them are given in the table below:

Table 1 List of Thesis on Aircraft Applications of EA

[Ref]	Year	Type	Researcher	Guide/Reviewer	Title
16	1998	MS	David A. Gleeson	Conrad F. Newberry	Second law approach in the aircraft conceptual design
17	2000	PhD	Jules Ricardo Muñoz Guevara	Michael von Spakovsky	Optimization strategies for the Synthesis / Design of Highly Coupled, Highly Dynamic Energy Systems
18	2005	MS	Vijayanan Periannan	Michael von Spakovsky	Investigation of the Effects of Various Energy and Exergy-Based Objectives/Figures of Merit on the Optimal Design of High-Performance Aircraft System
19	2005	MS	Kyle Charles Markell	Michael von Spakovsky	Exergy Methods for the Generic Analysis and Optimization of Hypersonic Vehicle Concepts
20	2006	MS	Keith Merritt Brewer	Michael von Spakovsky	
21	2012	MS	Peter Carl Weise	Michael R. von Spakovsky, Walter F. O'Brien, Alan A. Kornhauser	Mission-Integrated Synthesis/Design Optimization of Aerospace Systems under Transient Conditions
22	2012	PhD	Michael Sielemann	Gerhard Schmitz, Martin Otter	Device-Oriented Modeling and Simulation in Aircraft Energy Systems Design
23	2013	PhD	Frederick Timothy Neil Berg	Patrick Keogh Martin Balchin	Principles for Aircraft Exergy Mapping
24	2014	Degree	Kunwar Kochar	Tunde Bello-Ochende	Optimum Design of a Compact Heat Exchanger for Environmental Control of an Aircraft at Cruising Conditions
25	2016	PhD	Ingo Staack	Petter Krus	Aircraft Systems Conceptual Design - An object oriented approach from <element> to <aircraft>
26	2016	Licentiate Degree	Oskar Thulin	Tomas Grönstedt, Jean-Michel Rogero	On Exergy and Aero Engine Applications
11	2018	PhD	Daniel Bender	Tetyana Morozyuk, Dirk Zimmer	Exergy-Based Analysis of Aircraft Environmental Control Systems and its Integration into Model-Based Design

The report of M.R. Von Spakovsky[27] summarises the works of three MS theses[18–20] referred above.

EA application in Aircraft Optimization

In Aircraft/Aerospace design and development, from aerodynamic optimization of aerofoil to optimization of propulsion system, EA has found many applications. Many systems and components can be optimized using EA.

The Exergy and thermoeconomics which were applied in the design of ground power stations were extended as a methodology for the design of the complete integrated system of systems of an aircraft by David J. Moorhouse[28].

Due to change in flight conditions and operation at different altitudes, the environmental conditions vary vastly in case of operation of an aircraft and its systems. Exergy balance of a general system with variations of environmental conditions was brought about by Yalcin A. Göğüş, Çamdali Ü, Kavsaoğlu MŞ. in[29].

EA application in Aerodynamics and Aerofoil design

In a report authored by R.A. Gaggioli and D.M. Paulus Jr.[30] the optimization of subsystem integration via the second law of thermodynamics is discussed. To illustrate the relevance of exergy of lift, two exergy flow diagrams were presented for a light aircraft, one for level flight, and one for climb by these authors in[31].

In a report, Figliola[32] studied the aerodynamic correlation in an exergy based design methodology. Along with Haipeng Li and Jason Stewart[33], he used this method on 2D aerofoil and 3D wing platforms to study its impact on the aerodynamic designs.

Ken Alabi, Ladeinde F, Moorhouse DJ, Camberos JA, Brook S. et. al.[34–36]presented CFD-based exergy calculation iterative local global optimization (ILGO) procedures for MDO of complex aircraft system decomposed into several sub-systems. Calculations were done on a B747-200 aircraft for a range of values of the angle of attack, assuming transonic flight and for a tactical fighter.

The report of J.A. Camberos[37] tried to relate work-potential losses (exergy destruction) to the aerodynamics forces to validate a new design methodology based on the second law of thermodynamics.

EA application in Aero Systems

The aircraft is an integrated system of many complex systems. The conventional method of development is by trade offstudiesthat rely heavily on the past design information. EA was suggested as a decision-making tool by Luiz Felipe Pellegrini and Gandolfi Richard[38] in aircraft system design. The authors have gone ahead and applied it to a complete flight mission of a commercial aircraft[39]. They have shown that the engine contributes to around 95% of the exergy destruction and that mainlycomes from the combustion chamber. The bleed air system contributes to the majority of the remaining and all other systems contributing to less than 1% of the exergy destruction. They have also looked at the exergy destruction during different phases of flight, the majority happening during cruise when the anti-ice is turned on. But the climbing and holding phases, though considered as 20-minute duration, contribute almost similar percentage to exergy destruction and in a real-world scenario, might be contributing the most. In yet another paper that complements the above results, the authors applied EA to a more electric aircraft (MEA) consisting of electric ECS and electric ice protection systems[40]. It was shown that the engine contributes to more than 99% of the exergy destruction during the two flight phases that were analysed. Because of the elimination of dependence of the MEA systems on the bleed air their combined contribution to the exergy destruction is less than 0.15% and their exergy efficiencies are better than their counterparts on a conventional aircraft. More recently Yitao Liu, Deng J, Liu C and Li S.[41] also studied the application of EA to MEA.

Propulsion System

EA was extensively used for optimization of the propulsion systems of aircraft as these are the prime source of energy and the economics of operation rely heavily on the optimum design of this system.

Exergy analysis applications and the methodology development needs of aerospace systems were discussed by M. A. Rosen[42], a paper co-authored by J. Etele. The results were expected to assist aerospace-engine design work, where exergy methods provide a more comprehensive assessment of performance, allowing an engine to be better tailored to the types of flights and operating conditions it will encounter.

There are papers on application of EA in optimization of various types of aero engines like Jet[40], Turbofan[45–48], Piston Turboprop[49], Turboprop[50], Scramjet[51] engines.

Tomas Grönstedt, Irannezhad M, Lei X, Thulin O and Lundbladh A.[52] give a first and second law analysis of future aircraft engines like open rotor engine, intercooled recuperated engine and an engine working with a pulse detonation combustion core.Aurélien Arntz, Atinault O, Destarac D and Merlen A[53,54] presented the performance assessment of aero propulsion taking into consideration the boundary layer ingestion for future aircraft configurations.

Thermal Management (TM)

TMensures that the aircraft systems' performance is met at all environments, from desert heat to arctic cold. It is also becoming imperative to be optimal in the present and future power-hungry manned and unmanned flight vehicles. Some of its typical applications are:

- Cabin/Cockpit TM by ensuring required heating/cooling at optimum airflow, maintaining the humidity to meet comfort requirements
- Cargo space control to ensure the required conditions
- TM of avionics, where the power densities are always on rise and cooling has a direct bearing on their reliability
- TM of aircraft braking system
- Fuel TM
- TM of flight control actuators

The solutions are dependent on the aircraft platform and the environment that it would operate in its life cycle. For this, the optimization should start from the system architecture studies and continue till the components are realised.

ECS that takes care of most of the aircraft TM has different configurations with variety of equipment. Various types of Air cycle machines, compact heat exchangers and valves, which are the primary components of ECS,need to be optimized at system and component levels based on energy and exergy-based analyses. Resorting to analytical solutions like exergy analysis at the start of the development to arrive at novel system architecture is an emerging trend in development of aircraft ECS[55], to meet the increasing functionalities with minimum penalty to the aircraft in terms of energy requirement.

Adrian Bejan studied the irreversibility concept for heat exchanger design in 1977 and went on to apply the entropy generation and the second law analysis in various applications. He presented a paper on the role of EA aircraft system design and optimization in 1999[56] and in 2001 along with D. Siems[2] emphasised the need for EA and the thermodynamic optimization in the design and development of an aircraft. Along with Shiba[57] he presented this analysis application to a counter flow heat exchanger of an aircraft ECS.

Thermodynamic optimization of finned crossflow heat exchangers for aircraft ECS[58] and Integrative thermodynamic optimization of the ECS of an aircraft[59] were presented by the same authors. In yet another review paper, Bejan had given the examples of optimizing the geometry of heat exchangers of a power plant and stated the complete structure of ECS heat exchangers can be derived based on this principle[60]. In these papers, the authors have shown optimization at component level and at an integrated system level. The thermodynamic optimization of the flow geometry, applicable to any system that runs based on a limited amount of fuel (exergy) installed onboard, was presented. EGM in a crossflow heat exchanger used in aircraft ECS is with ram air on the cold side was optimised for its geometric features by A. Alebrahim along with A. Bejan[61]. They further studied[62] several architectural features deduced from the same principle: the relative position of the two heat exchangers, their relative sizes, and all the geometric aspect ratios of the two heat exchanger cores. Thermodynamic optimization of geometric structure in the counterflow heat exchanger for an ECS was reported by T. Shiba and A. Bejan[57]. The minimum power requirements for environmental control of aircraft was given in the paper of J.J.C. Ordonez and A. Bejan[63].

EA brings out the system losses qualitatively and quantitatively and, in the process, the individual contributions from the sub-systems and the components become clear. Gandolfi R, Pellegrini LF, Lima da Silva GA and de Oliveira Junior S.[64] carried out the EA of conventional and more electric architectures of ECS to evaluate the exergy efficiency, exergy destroyed rate and exergy destroyed cost for each architecture.

R.S. Figliola and R. Tipton[65] detail the concept of using the exergy based method for designing an integrated aircraft thermal system. This conference proceeding was again published in the Journal of Aircraft in 2003, which was referred by Sciubba and Wall[1] in their marathon review paper on exergy analysis citing more than 2600 references.

While investigating the effect of humidity in the thermal performance of ECS, Tuzemen S, Altuntas O, Sogut MZ and Karakoc TH.[66] found that EA had given more reliable results. Similarly Yang Juan's study[67] applied to a civil aircraft showed that EA is of great practical significance to the integrated design of the ECS. Hongsheng Jiang, Dong S and Zhang H.[68] used EA to compare the air bleeding from the engine for conventional ECS with the electric power off-take of an electric ECS.EA of ECS and LSS of an International Space Station was studied by Kirk A. Clem, Nelson GJ, Mesmer BL, Watson MD and Perry JL.[69].

There are EA studies at the component level also. Li Hong-bo, Xin-min D, Jun G, Yong C and Ting-ting L.[70] optimised the heat exchanger by studying the effect of the ratio between the charge side flow length, coolant side flow length and height on the ECS entropy generation. Bello-Ochende T, Simasiku EM and Baloyi J.[71] used the EGM technique to optimize the heat exchanger of a typical bootstrap ECS. EA of air cycle machines was studied by Ayaz Süleyman Kağan, Önder A, Karakoc TH, Bilecik EA.[72] and Marcus Bracey, Nuzum SR, Roberts RA and Wolff M, Zumberge J.[73].

DISCUSSION

EA was extensively used for the thermal optimization of the propulsion system and its sub-systems and components as detailed earlier for the obvious reasons of achieving the low operating costs and improving the efficiency of operation. Though the penetration of EA is slow in design of other systems, ECS being the maximum consumer of the secondary power developed by the engine, is the prime candidate for the application of EA from its system architecture definition to the optimization of its components. Thermoeconomic analysis and optimization of a simple aircraft environmental control system was detailed by T.J. Leo and I. Perez-Grande in[74&75]. The study was extended for configuration studies involving the complexities from practical applications was studied by the present authors [76&77].

Further studies to evaluate the effect of moisture at other flight conditions, and further configuration studies to include the high-pressure water separation are possible to yield better optimization results. The MDO with EA can also be extended to VCS configurations of ECS to optimize the components involving phase change.

EA can effectively be used at the system architecture level for the configuration studies as well as optimization of the components of the system. Parametric studies and sensitivity analysis to study the effect of various parameters including the geometric values of the components can be carried out leading to the MDO of the system and the components.

CONCLUSIONS

Aircraft is a system of complex and highly integrated energy intensive systems. In conventional aircraft, the main source of this energy is from the fuel carried around and in other non-conventional and experimental aircraft it could be solar or from other sources. There is always an upper limit to the energy availability, be it the amount of fuel carried or the surface area for solar energy absorption. The energy conservation equations of the first law are the necessary conditions to be satisfied by the systems. However, combining with the second law in these systems optimization, the EA provides the sufficient conditions for system feasibility, directionality and performance. Over the years, EA had been extensively used in optimization of the aircraft propulsion system. Adoption of this technique for other systems on the aircraft is slow but is picking up.

All system design activities start with the configuration studies. To optimize the complex systems, several possible configurations are to be analysed through multidisciplinary optimization. In any aircraft system design, weight of the system plays an important role and the goal is always to minimise this after meeting the functional and safety requirements. Coupled to this, the EA of the system to minimise the entropy generation leads us to the best feasible solution to give energy savings over the life cycle of the aircraft.

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