

Optimization of an Unconventional Environmental Control System Architecture

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ABSTRACT

The Environmental Control System is a relevant element of any conventional or More Electric Aircraft (MEA). It is either the key consumer of pneumatic power or draws a substantial load from the electric power system. The objective of this paper is to present a tool for the design of Environmental Control Systems and to apply it to an unconventional system. The approach is based on a recently proposed methodology, which is improved with respect to flexibility and ease-of-use. Furthermore, modeling and simulation of vapor compression cycles is discussed, which are candidate technological solutions for More Electric Aircraft concepts. A steady-state moving boundary method is presented to model heat exchangers for such applications. Finally, the resulting design environment is applied to optimization of an unconventional ECS architecture and exemplary results are presented.

INTRODUCTION

Increasing prices for jet fuel have led to higher cost for airline operations. In addition with the increasing sensitivity for carbon dioxide as one cause of global climate change there is a high pressure for the airlines and for aircraft manufactures to search for the most fuel-efficient aircraft. Environmental Control Systems (ECS) contribute approximately 2-3% to the overall fuel burn with today's technologies [1]. To reduce this share a worldwide search for new technologies has started. One way to meet this challenge could be an introduction of

unconventional technologies instead of bleed air driven air-conditioning systems.

To evaluate and assess such air-conditioning architectures early in the development phase a design environment for ECS is required. It has to provide at least a modeling and simulation capability and additional optimization functionality. For modeling and simulation, a user has to be able to choose from all components potentially required in environmental control architectures using e.g. electric technologies. Based on them, both state-of-the-art and unconventional system architectures can be built up.

In order to be useful for optimization, all components in the modeling and simulation environment have to be implemented as parametric elements. Then, parameters relating component performance and weight can be varied within an optimization platform to converge towards a set of optimal designs. Ideally, such an optimization platform additionally provided instruments to capture the contradicting requirements that constitute each design problem of airborne systems. After all, when striving for both energy efficiency and weight reduction on system level, some trade-off has to be made. Furthermore, an optimization platform for unconventional system architectures has to address the definition of control logic. This is necessary because an ECS plant model by itself is not a well-defined (i.e. square) problem, unless control variables such as valve positions are defined. Whenever unconventional architectures are investigated, such control logic is not known a priori and a

sequential approach of first establishing and implementing appropriate control logic and then optimizing the architecture is considered impractical.

This article presents such a design environment for ECS. It consists of the suggested elements (modeling and simulation tool and optimization platform), which each meet the requirements introduced above. The modeling and simulation tool was developed from scratch as replacement of the one described by the authors in [2]. It differs from its predecessor primarily with respect to two key areas. First, the overall modeling and simulation methodology followed during the implementation with the equation-based object-oriented language Modelica was developed further. The changes include non-evolutionary ones and result in higher flexibility and ease-of-use. The second key area is steady-state simulation of vapor compression cycles, which are potential technological solutions for unconventional ECS architectures. Here, we focus on the modeling and simulation methodology of the heat exchangers, for which suggest a steady-state moving boundary method. Heat exchanger models for various pairs of fluids have been developed including refrigerant-to-air, refrigerant-to-liquid and air-to-liquid. In addition parameterized models for vapor cycle compressors are included. The optimization platform in turn utilizes the methodology proposed by the authors in [3], which is implemented in this work without fundamental changes.

The resulting design environment is then applied to an unconventional ECS architecture. We discuss a control strategy for energy efficient control as well as sizing of the major components. Furthermore, we address a key question of optimization of such architectures, namely, the trade-off between using electrical energy and ram air as primary heat sink.

DESIGN ENVIRONMENT FOR ECS

In this section we describe key elements of a design environment for ECS, which allows simulating and designing both state-of-the-art and unconventional systems.

MODELING AND SIMULATION TOOL

A complete reimplement of the ECS modeling and simulation tool allowed adapting the underlying concept according to conclusions drawn from earlier implementations [2] and feedback received from users. This reimplement produced a step change in flexibility and ease-of-use as introduced above. We first detail the conceptual changes that produced these improvements and then present an overview of the scope of the tool. Finally, modeling hypotheses for vapor cycle components are given. Particular attention is paid to the heat exchangers using a steady-state moving boundary method and to turbo compressors for refrigerant.

Modeling and Simulation Methodology

When designing systems, it is not always instrumental to strictly simulate the performance of this system. The reason is, for example, that this is necessary to fulfill system requirements or that certain system components will be devised such that they behave in a specific way. An example is the design of the air distribution system of commercial aircraft. Here, the pressure drop due to wall friction through the air distribution ducts shall be minimized. However, it is not practical to use excessively large duct cross section areas, which is why such distribution systems are usually designed in order to arrive at a well-defined compromise pressure drop. It is incurred via the duct to the cabin zone, which is farthest away from the mixer. All other ducts are then calibrated using orifices to carry a well-defined amount of air to their cabin zones.

When simulating strictly the performance only, all precise orifice parameters had to be established. Such detailed data may not be available during early phases of system design and is even not required. After all, the pressure drop to the cabin zone farthest away from the mixer could be calculated normally and the correct mass flow rates could be prescribed for each duct.

The described approach of idealized and inverse models which is used in several areas of the present tool implies challenges for the steady-state initialization of such models. This is the case especially if they are used on systems, whose thermodynamic cycle involves a loop. This may be the case for the cycle itself (e.g. vapor compression cycle) or due to the system design (e.g. the reverse Joule cycle, which is an open thermodynamic cycle but includes a loop via the rigid inertia-free shaft of the air cycle machine). Then, steady-state initialization may be challenging using local gradient-based algorithms such as damped Newton Methods. The production version of this library uses artificial state variables to break implicit nonlinear algebraic equation systems in key components due to the low risk and high maturity of this approach. An alternative research version of the library using homotopy continuation via a homotopy operator is used to mature this concept in order to introduce it in production work in the future.

The earlier version of this tool used a proprietary approach without artificial state variables. The resulting models simulated faster but required an extra layer of information, which had to be provided by users for each topology separately. The present approach therefore trades in computational expense for ease-of-use, which is reasonable when comparing the price of computational resources with engineering hours.

As a result of the chosen approach for initialization, a fraction of the trajectory of model results does not reflect steady-state results (because artificial transients have not yet been fully damped). In the present simulation tool, this is exploited by classically splitting models into plant and control, which is not always possible when using inverse models with ideal control logic (algebraic control laws). If this separation can be made, then the resulting models are easier to understand for practitioners, as they more closely resemble the systems implemented in reality. Additionally, the component equations become simpler themselves. This is the case because a plain, say, integral control is usually simpler than a complex ideal algebraic control law. An example of the latter can be given for the mixer temperature demanded by trim air valve logic. In this case, non trivial equations have to be used in order to e.g. compensate the demanded temperature with respect to condensation of moist air associated with the pressure drop in ducts. Such equations are not required when using conventional control and the resulting models are easier to understand for practitioners.

Finally, the suggestion of [4] to use inheritance sparingly in equation-based object-oriented modeling was followed in the latest implementation.

Scope of Modeling and Simulation Tool

The modeling and simulation tool roughly spans three core domains. These are Extended Cabin, Air Conditioning, and Ram Air Channel. On top of them, miscellaneous component models of the Engine Bleed Air System, Cabin Air Compressors and the like are provided.

The majority of these models cover off-design performance, which is often not the case in the context of ECS architecture design tools. The authors strongly believe that this is necessary however, because design is intrinsically linked to trade-offs and without properly covering off-design performance such considerations cannot be captured appropriately.

Consequently, all components can be modeled using roughly three different hypotheses. Either, a model simply uses characteristic maps or geometry-based performance estimators. Alternatively, constant efficiency can be used. Characteristic maps are typically created using high fidelity codes and may be scaled using appropriate scaling factors. Geometry-based performance estimators are often based on handbook methods or established discretization schemes and use geometric data to establish component performance.

The Extended Cabin domain covers the cabin itself (control volumes for cabin and flight deck; under floor; heat loads via convection, radiation, and conduction; loads dissipating moisture), air distribution (ducts, fans, pressure regulating valves), mixing (mixer of fresh and recirculating air), and temperature control. The Air Conditioning package covers components of conventional air cycles such as air-to-air heat exchangers, turbo machinery, and water extractors on one hand. On the other, it also includes components to model vapor compression cycle systems (refrigerant-to-air heat exchangers, compressors, expansion valves). Like this unconventional and hybrid systems can be assembled. Finally, the Ram Air Channel provides component models of devices used to capture ambient ram air at the aircraft skin (ram air inlets and outlets in different geometrical shapes). This is typically required to reject excess heat to the ambient or to capture fresh air to be provided to the cabin.

As mentioned in the introduction, the models are kept as flexible as possible with respect to the computational causality. This is useful, because in architecture design of ECS it is natural to establish model causality starting with the functions to fulfill. Casting them into requirements allows the formulation of derived requirements for all other parts of the system. At a later stage in system design, it is more interesting to model the performance of a fixed system however, which is why the causality is then inverted.

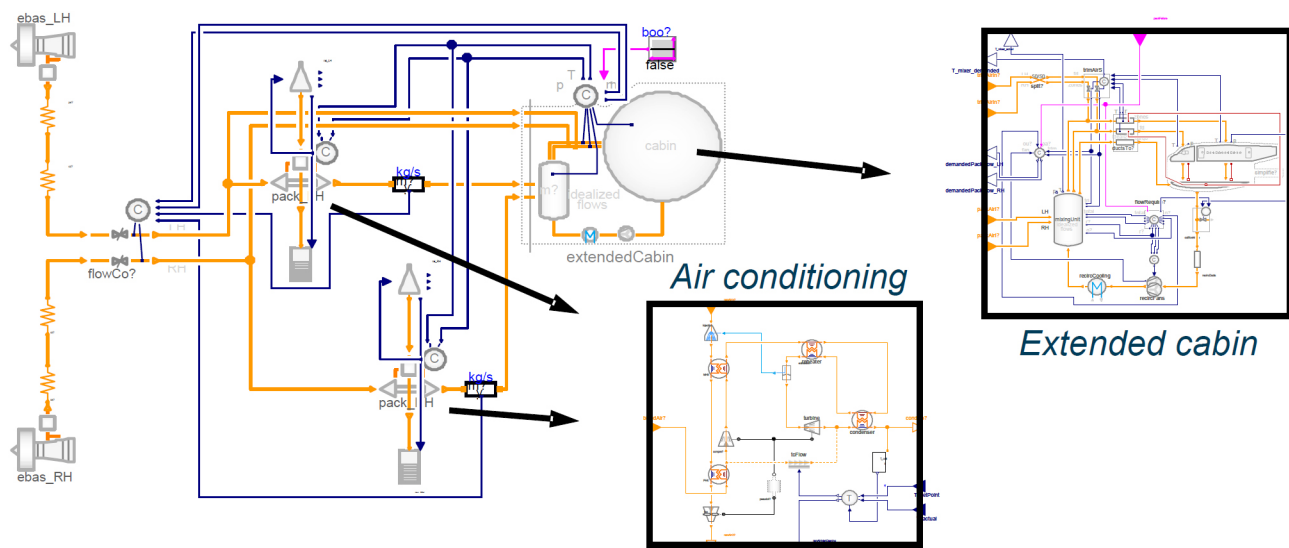


Figure 1. Conventional ECS Architecture.

Selected Vapor Compression Cycle Components

Vapor compression cycles basically consist of heat exchangers - condensers and evaporators - compressors and expansion valves. In this section we introduce the chosen modeling approach for heat-exchangers as well as turbo compressors.

Temperature profiles of heat-exchangers with condensing or evaporating refrigerant flow show a bend at points, where single-phase changes to two-phase flow. Commonly used spatial discretization methods with a fixed grid need a considerably high number of grid points to capture the

temperature profile correctly. In order to minimize the computational effort, we chose a different modeling approach. Heat-exchangers are divided in up to three zones: super-heating, sub-cooling and two phase refrigerant. Steady state mass and energy balance equations are set up for each of these control volumes. Exponential temperature profiles are assumed inside each zone. This approach is very similar to the well known effectiveness-NTU-method, but it is important to understand that there is an individual NTU value for each zone. Zone lengths are implicitly defined by the resulting set of equations. To illustrate this modeling approach temperature distribution of an example counter flow evaporator is sketched in [Figure 2](#).

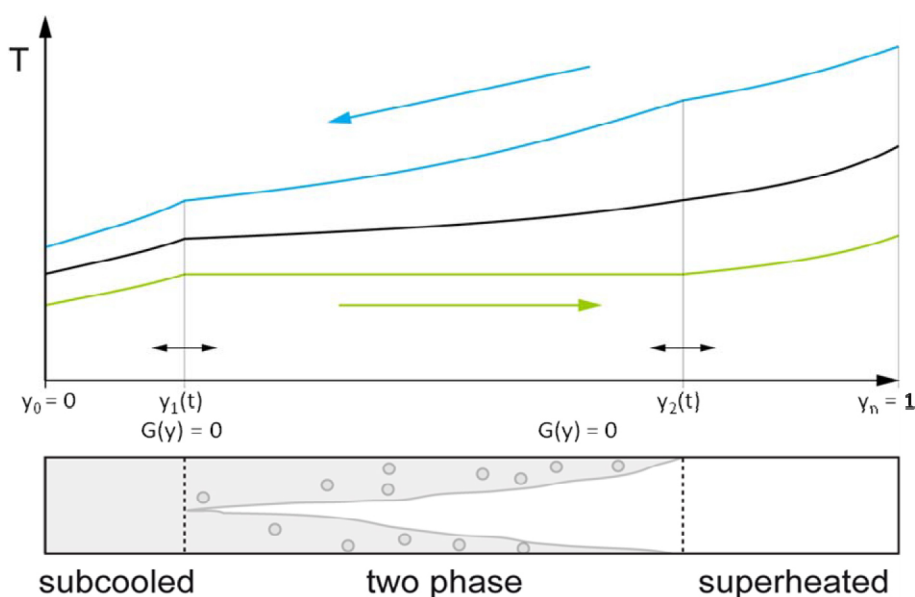


Figure 2. Temperature Distribution of Counter Flow Evaporator Model, refrigerant flow (green) and liquid flow (blue).

Different types of heat-exchanger can be modeled: fin and tube, multi port extruded tube (MPET) and tube and tube heat exchangers. Each type is characterized by a special parameter record class, where all relevant geometry information is stored. Internal parameters are calculated from user given input parameters and passed to transport phenomena models. Inside this replaceable models heat transfer and pressure drop correlations are implemented. The user can choose from several included correlations or implement additional correlations. In particular included heat transfer correlations are Chang and Wang [5] for fin-side flow of MPET heat exchanger, Gnielinski [6] and Dittus-Bölder for single-phase tube-side flow as well as Haaf [7] for fin-side flow of fin and

tube heat exchangers. In order to simulate the turbo compressor a loss based approach is used. Basic parameters of the model are the geometry values to determine the flow conditions in the compressor e.g. inlet and outlet diameter, blade number and thickness, inlet and outlet angle of the fan. Based on Eulers equation for radial turbo compressors the Pfleiderer approach is used to characterize the main loss effects due to friction, shock and fluid losses in the blade channels and diffuser. For the description of the blade losses blade efficiency is defined. Measurement data is used to fit the blade efficiency in dependency of the volume flow rate and compressor speed.