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Methodology for Analyzing Competing Options for Air Management Systems at the Stage of Conceptual Design of Civil Aircraft's Complex of Onboard Systems

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Abstract. Analysis of competing options for the implementation of the system is a key task at the stage of conceptual design of aviation air conditioning systems as these systems have a great impact on the fuel efficiency of the entire aircraft. The decision about choice of competing options regarding not only the appearance of the system, but also a lot of different parameters including technical, technological and so on. In case of conceptual design missing parameters for a complex criterion can be replaced by an alternative risk level estimate. This article shows an example how to compare competing variants of the air management system at the stage of conceptual design and provides a methodology for selecting the key parameters of the comparison criterion. As a result, it is shown that vapor cycle cooling is more promising due to the wide possibilities of reducing the mass of components and increasing the overall cooling efficiency. For the air cycle, most of the possible solutions to increase efficiency have already been implemented now.

1 Introduction

The flights of modern aircrafts occur at high altitudes and speeds that forms high demands to safety and comfort of crew and passengers. One of the ways to achieve safety and comfort records is to improve on-board environmental control system (ECS) [1].

Modern aircraft consists of many subsystems that influence on its flight characteristics. The environmental control system is one of the main on-board systems in terms of this influence. The ECS's installation mass reaches 2% of aircraft take-off mass, the ESC's fuel consumption is up to 4-6% of aircraft's fuel reserve [2,3].

ECS is intended for providing and maintaining a number of rationed air parameters (such as temperature, relative humidity, pressure, speed of air movement, etc.), that provide crew and passengers with comfortable conditions on the ground and in mid-flight; also, it provides required equipment heating modes. This system's work requires on-board compressed-air source [4,5].

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2 Materials

The decisions which, in fact, determine energy efficiency of system should already be developed at the stage of the conceptual design (Gate 2 according to the model Stage-Gate). There are central challenges of this phase [6]:

- development of the concept of the aircraft;
- clarification of technical feasibility;
- impact analysis;
- identification of the main risks of program;
- risk reduction planning;
- protection of technical proposal - establishment of baseline data for design.

All newly developed systems must exceed precursor on its parameters and operational specifications in moral, technical and economic aspects. Also, customer's requirements and obligations of operators must be taken into consideration under the existing aviation legislation in the process of developing. These requirements for cargo plane primarily are characterized by increasing comfort, reduction in the fuel consumption, noise and environmental impact reduction.

In most environmental control systems aviation engines are used as on-board compressed air sources. Bleed air keeps necessary pressure and ventilates the energy lock. Additionally, this air is used as a working fluid in ECS where cycle of refrigeration machine is realized (Joule cycle) [7,8]. Generally, the variability of ECS's options of prospective plane can be represented as a options tree. (Figure 1)

The higher level of solution the greater impact it provides on the aircraft. Such multilayered dependence shows that certain combination of solutions on low levels is able to ensure benefit on high level of the system that can be technically realized for «conventional» ECS's options at present, taking into account primarily levels of technical and economic risks [9]. A complex evaluation criterion is required to compare competing architecture options at all levels of the variants tree. In the general case, a complex criterion should include a set of the most critical technical, technological and economic parameters from the point of view of the development program, a certain combination of which should provide a sufficient basis for making an unambiguous decision in favor of one or another option. At the same time, at the early stages of design, up to 80% of the required information is missing, especially in terms of technological and economic indicators, which leads to the need for a phased refinement and subsequent elimination of options [10,11,12,13].

Considering that all decisions regarding not only the appearance of the system, but also the entire chain of suppliers, the missing parameters for a complex criterion can be replaced by an alternative risk level estimate. In the conditions of the global market and the continuity of technologies, such an assessment will allow us to accurately predict the range of required parameters possible values, which can also give enough grounds for deciding. To assess the level of risk at each design stage, a standard 5x5 risk matrix can be used (Figure 2).

The proposed adaptive structure of complex evaluation criterion is shown in Figure 3.

At the stage of conceptual design, due to a lack of initial data on both the projected system and the aircraft, the criterion for increasing take-off mass is the most appropriate and enough technical criterion for evaluation. At the same time, in calculation the level of risk it should be reflected parameters of the system, that are entering the criterion for increasing the take-off mass, and the parameters of the future aircraft that are "external" with respect to the system parameters [14]. Sufficiency of this criterion on Gate 2 is explained by the fact that the basic tactical and technical characteristics of an aircraft depend on the take-off mass (range, rate of climb, commercial load, etc.) It is known that the system's own installation mass is

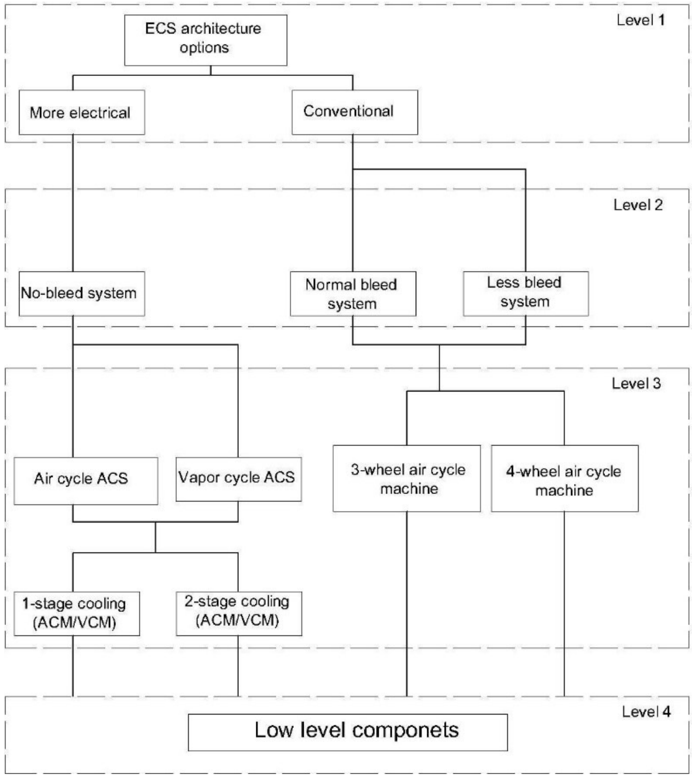

Fig. 1. ECS's options

0 – 5 = Low Risk 6 – 10 = Moderate Risk 11 – 15 = High Risk 16 – 25 = extremely high unacceptable risk		Severity of the potential injury/damage				
		Insignificant damage to Property, Equipment or Minor Injury **1**	Non-Reportable Injury, minor loss of Process or slight damage to Property **2**	Reportable Injury moderate loss of Process or limited damage to Property **3**	Major Injury, Single Fatality critical loss of Process/damage to Property **4**	Multiple Fatalities Catastrophic Loss of Business **5**
Likelihood of the hazard happening	Almost Certain **5**	5	10	15	20	25
	Will probably occur **4**	4	8	12	16	20
	Possible occur **3**	3	6	9	12	15
	Remote possibility **2**	2	4	6	8	10
	Extremely Unlikely **1**	1	2	3	4	5

Fig. 2. Level of risk

not equal to its take-off mass, since it requires energy for its transportation, operation of the units, overcoming the air intake aerodynamic resistance and so on. In the general case, at the stage of conceptual design, the criterion for the increment of take-off mass (fraction of aircraft take-off mass that falls on the ECS) can be written in the following form:

$$\Delta Mto = Mtrans + Mfunct$$

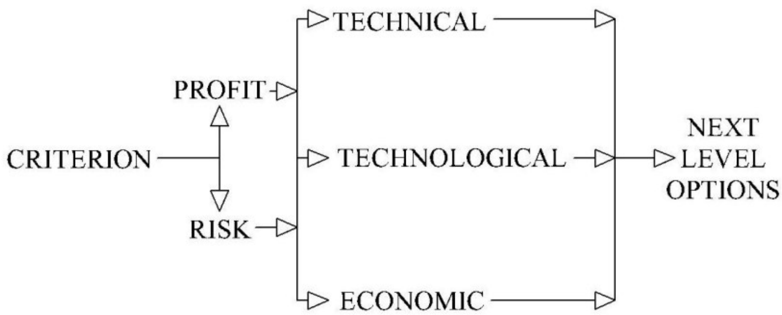

Fig. 3. Structure of complex evaluation criterion

where M_{trans} – fraction of aircraft take-off mass that falls on transportation of ECS:

- mass of fuel spent on transporting the installation mass of ECS;
- additional aircraft structure mass introduced to ensure the installation and functioning of the ECS, as well as the corresponding additional mass of fuel for its transportation.

M_{funct} – part of the aircraft take-off weight, attributable to the mass of fuel spent on ensuring the functioning of the system:

- compensation of energy losses during bleeding of air;
- compensating for energy losses during consuming electrical energy;
- compensation of additional resistance created by air intakes for purging heat exchangers of the ECS, as well as the corresponding additional mass of fuel for its transportation.

The most relevant for perspective aircraft on the technical reliability condition are the ECS with no-bleed architecture (level 1 - more electrical ECS) in accordance with the options tree:

- Air cycle pack, 3-wheel air cycle machine (1 stage cooling);
- Vapor cycle pack, 1 evaporator (1 stage cooling).
- Protection of technical proposal - establishment of baseline data for design.

A key feature of no-bleed architectures is the use of electric drive air compressors as a source for providing air.

The results of a comparative analysis of two ECS options (long-range aircraft of 400450 PAX) are presented in Table 1.

For tables use syntax in Table 1.

The table shows the following parameters:

Expected mass in relation to mass of "conventional" ECS option - as a "conventional" is adopted with bleed air system (the system also selects the engine port from which to bleed) and air cycle pack (3-wheel air cycle machine). In the first approximation, the subsystem of distribution completely corresponds to the compared options.

The compression ratio of the air compressor during cruising flight - the compression ratio is calculated by the condition of providing air pressure in the passenger and crew cabin. According to preliminary estimates, the required pressure behind air compressor for the air cycle circuit should not be lower than the switching threshold of the low-to-high-stage compressor of the engine.

Expected energy consumption in relation to the " conventional " ECS option - the parameter considers both the actual consumption of electric energy (air compressor drive, freon compressor drive, etc. for the considered no-bleed options), and the energy

Table 1. The results of a comparative analysis of the two ECS options

Parameter	Air cycle	Vapor cycle
Expected mass in relation to mass of "conventional" ECS option	+30%	+40%
The compression ratio of the air compressor during cruising flight	10	5
Expected energy consumption in relation to the " conventional " ECS option	-14%	-42%
The estimated level of risk of reliability indicators	3 (Possible occur* Insignificant damage to property, equipment or minor injury)	9 (Possible occur* Reportable injury, moderate loss of process or limited damage to property)
Achievable level of efficiency increment	+5%	+30%

consumption for engine's compressor to pressure air at the point of selection ("conventional ECS").

The estimated level of risk of reliability indicators is assigned in accordance with the matrix and reflects the level of technical risk of providing specified reliability indicators in accordance with the analysis of applied technologies. For air cycle systems, the risk level will be minimized due to the use of such systems on the vast majority of modern aircraft and minimizing novelty at the expense of this.

Achievable level of efficiency increment is a parameter that considers the possibility of improving the efficiency of the option due to its optimization (for example, control logic, components composition, etc.). The value of this parameter will objectively be at vapor cycle due to the wide possibilities to reduce the mass of components and to increase the overall efficiency of the cooling installation. For the air cycle, most of the possible solutions to increase efficiency have already been implemented in the ECS of modern aircraft [15,16,17].

3 Conclusion

No bleed ECS options are the most promising from the point of view of new aircraft designs, however their wide application is still constrained by the necessity of on-board systems complex initial design within the concept of "more electric aircraft".

Based on the results of the analysis of competing options development of vapor cycle pack option is most advisable according to significantly higher energy efficiency of this decision. The level of technical and technological risk together with a larger installation mass will require significant costs for the development, testing, debugging and subsequent implementation, but, at the same time, this option will achieve a significant increase in fuel efficiency at the level of the entire aircraft.

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