Analysis of the work, efficiency, and possibilities of constructive improvement of electrical air conditioning systems

L.A. Grishina[1*], *D.V.* Pronin[1]

[1]Moscow Aviation Institute (National Research University), Volokolamskoe shosse,4, 125993, Moscow, Russia

Abstract. This article discusses the main aspects of electrical air conditioning systems, as well as improving the efficiency of ESAC using the Boeing 787 as an example. In the course of the analysis, a comparative calculation was carried out according to the criterion of takeoff weight increment by the Bulaevsky-Shustrov method and its Western counterpart.

1 Introduction

The purpose of this paper is to study electrical air conditioning systems (ESAC) and engineering solutions aimed at reducing the power consumption requirements of ESAC.

One of the main tasks of manufacturers of modern aircraft is to increase their competitiveness [1-3], namely, to reduce energy costs during the flight, that is, to increase their economic efficiency. In the face of fierce competition, aircraft manufacturers resort to various technical solutions in the design of air conditioning systems (ACS), which are aimed at reducing the impact of their work on the energy efficiency of the aircraft. One such technical solution is the use of electric ACS in the design of modern long-haul passenger aircraft. This system differs in that the air for supply to the passenger compartment is taken not from the compressor stage of the power plant of the aircraft, but from a separate block of autonomous compressors of the air conditioning system.

2 Review of literature

In 2004, the Boeing Corporation introduced a new wide-body airliner that used ESAC as the main one. This system, according to Boeing Corporation, has proven its effectiveness by reducing aircraft fuel consumption compared to the traditional ACS version. Despite the positive results achieved, work to improve this system continues. In 2010, a study was carried out to modernize the ACS air intake system. This scheme was patented by Pradeep G. Parikh [4]. According to the data in this patent, the developers decided to combine two air intakes (Figure 1) into one air intake with flow separation.

* Corresponding author: petrolar88@yandex.ru

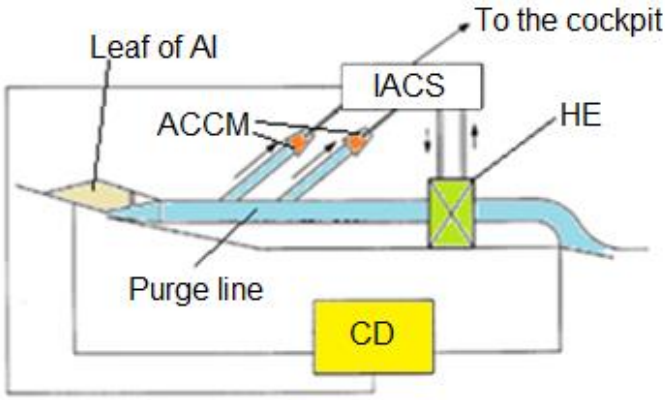

Fig. 1. Proposed scheme.

ACCM - autonomous centrifugal compressor machine, IACS - integrated air conditioning system, HE - Heat exchangers, CD - control device, AI - air intake.

This scheme simplifies the design of the air intake compared to the initial version (Figure 2) and reduces the overall aerodynamic drag. The adjustable air intake flap is controlled by a special device according to the built-in control programs.

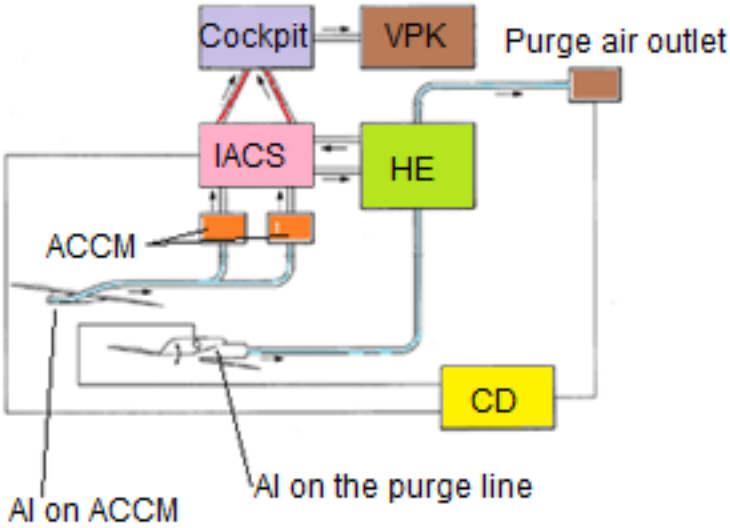

Fig. 2. Initial air flow pattern in ACS.

ACCM - autonomous centrifugal compressor machine, IACS - integrated air conditioning system, HE - Heat exchangers, CD - control device, AI - air intake, OFV – outflow valve.

After testing this variant of air supply to the ACS, the following results were obtained:

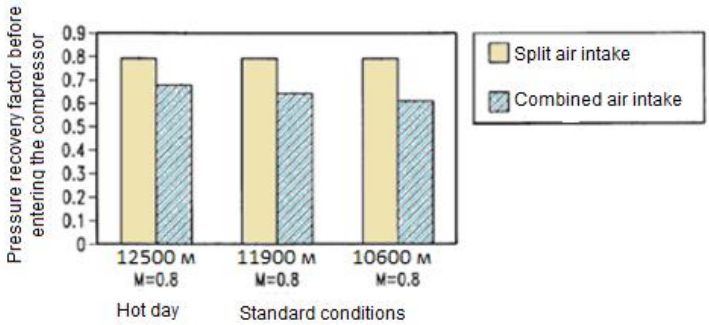

Fig. 3. The coefficient of pressure recovery before entering the compressor, depending on the flight conditions, M – Mach number.

As we can see, the proposed scheme has a lower air recovery coefficient in various flight modes, which, in turn, leads to an increase in the required energy for the compressors of the SCR unit (Figure 4)

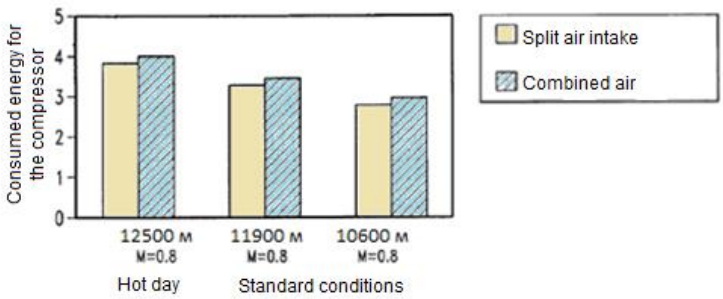

Fig. 4. Required energy for the compressor depending on the flight conditions, M – Mach number.

However, it is worth noting here that the use of a combined air intake has a positive effect on the overall aerodynamics of the aircraft.

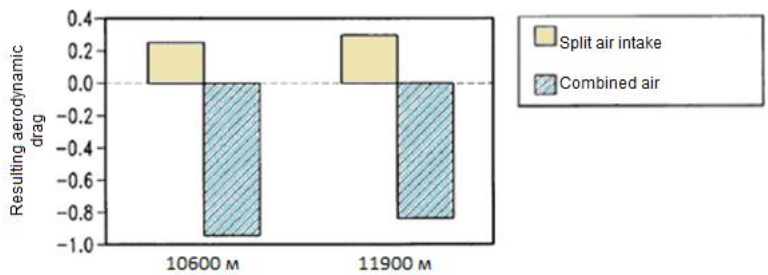

Fig. 5. Resultant aerodynamic drag.

Despite the loss in pressure recovery and the required energy, the lower aerodynamic drag of a single air intake overrides these negative effects. According to the patent, energy overrun results in only a 0.05% increase in fuel consumption, however, the gain in fuel consumption due to aerodynamics alone gives 0.4%, which gives an overall reduction in fuel consumption of 0.35%.

Such a technical solution also provides advantages in terms of system weight, operating costs, and maintenance. In addition, the system is less complicated, since with separate air intakes (Figure 2) an anti-icing system is required for the air duct shell to the compressors of the ACS unit.

In 2015, Chinese specialists conducted a study to improve the fuel efficiency of the Boeing 787 ACS. This study was based on the use of air injected into the pressurized cabin as an additional source of energy in flight [5].

At the international symposium in 2015, dedicated to the problems of heating, ventilation, and air conditioning, the results of this study were presented. The report considered several schemes for converting pressure from a pressurized cabin into an additional source of energy, which, in turn, were compared with the already existing scheme on the aircraft in terms of weight and fuel efficiency [6-11].

Figure 6 shows the original airflow pattern in the Boeing aircraft 787.

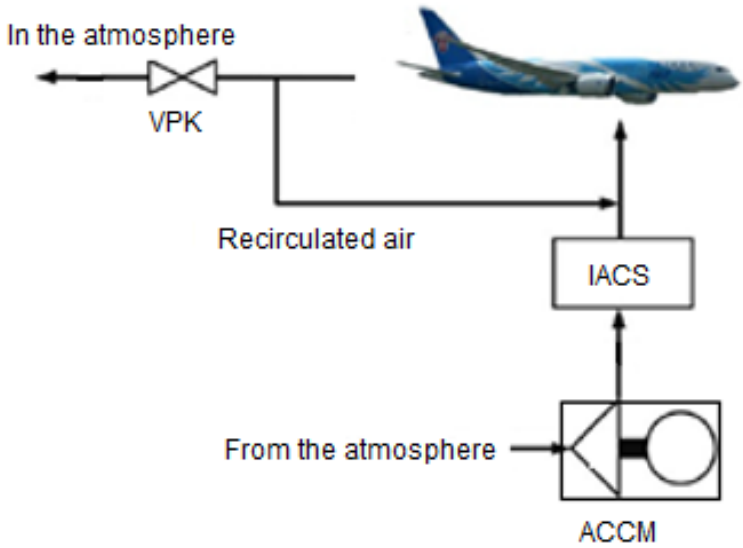

Fig. 6. Original airflow pattern in the Boeing aircraft 787.

ACCM - autonomous centrifugal compressor machine, IACS - integrated air conditioning system.

The difference between scheme 2 is that there is an additional compressor at the inlet, which is driven by a turbine. This turbine works using air leaving the GC under pressure, which varies according to the control program. Figure 7 shows a diagram using a turbine to generate additional energy.

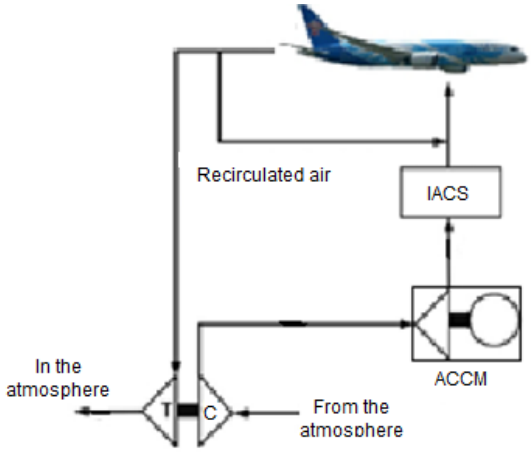

Fig. 7. T – turbine, C – Compressor, ACCM - autonomous centrifugal compressor machine, IACS - integrated air conditioning system.

In this scheme, the air from the GC, instead of the traditional outlet through the outflow valves (OFV), passes through the turbine, which is connected by one shaft to the pre-compressor. That is, before entering the main compressor, the air is additionally compressed and heated. This solution, according to Chinese researchers, reduces the required power of the electric motor, and, consequently, the amount of energy consumed. This design change made it possible to reduce the π_K of the main compressor to 1.13 (approximately 60% of the original compression ratio).

In scheme 3, an ejector has used to pre-compress the air before the main compressor, which made it possible to reduce the compression ratio of the compressor to 2.24 (by 21% of the original value). Air from the recirculation system in this case is partially supplied to the ejector, where it mixes with atmospheric air, which contributes to an increase in pressure entering the ACS.

Figure 8 shows scheme 3 with an ejector.

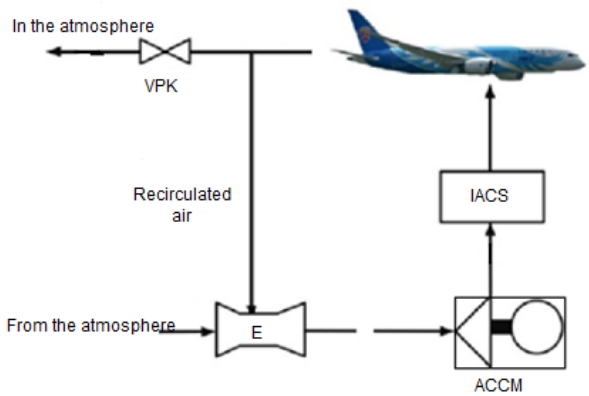

Fig. 8. E – ejector, ACCM - autonomous centrifugal compressor machine, IACS - integrated air conditioning system.

According to the calculations made by Chinese colleagues, none of the proposed schemes led to a decrease in fuel consumption. Table 1 presents the results of a study of fuel losses due to aerodynamic drag and power generation.

Table 1. Results of mass fuel losses.

Parameter	**Scheme 1 (original version)**	**Scheme 2**	**Scheme 3**
Mass of fuel to overcome aerodynamic resistance, kg	-69.1	No	-69.1
Parameter	Scheme 1 (original version)	Scheme 2	Scheme 3
Mass of fuel for power generation, kg	+51.6	+6.9	+80.7
General mass losses, kg	-17.5	+6.9	+11.6

Note. “+” - increase; “-“- decrease

Comparing the method of Chinese colleagues (formula 1) and the method of Bulaevsky-Shustrov (formula 2), which allows evaluating SCR schemes by the criterion of starting mass, it can be seen that the formulas are identical, but differ in the coefficients in the numerator (ξ and $T_{\text{кс}}$) for determining the hourly fuel consumption, required to compensate for power take-off from the motor shaft.

$$q_{m,f,P} = \frac{2{,}94 c_{pg} \xi P_m}{H_u \varepsilon_c (\pi_c^{0.286} - 1)} \quad , \qquad (1)$$

where $q_{m,f,P}$ – hourly fuel consumption selected for work by IACS;

c_{pg} – the heat capacity of the fuel;

ξ – the ratio of the temperature behind the combustion chamber to the temperature at the compressor inlet;

P_m – the power that is taken for work;

H_u – specific heat of combustion of fuel;

ε_c – the efficiency of the combustion chamber; π_c - compression ratio in the engine compressor.

$$G_{mN} = \frac{2{,}94 c_{pg} T_t N_w}{H_u \varepsilon_{cc} (\pi_c^{0.286} - 1)} \quad , \qquad (2)$$

where G_{mN} – hourly fuel consumption selected for the work of the IACS;

c_{pg} – the heat capacity of the fuel;

T_t – the temperature in the turbine;

N_w – the power that is taken for work;

H_u – specific heat of combustion of fuel;

ε_{cc} – the efficiency of the combustion chamber;

π_c - compression ratio in the engine compressor.

Comparison of these coefficients requires further clarification since when the initial values are substituted into formulas (1 and 2), the calculation results have significant discrepancies. The basic formula for calculating the mass of fuel spent on power take-off is the same in both cases:

$$m_{f,P} = \frac{q_{m,f,P}K}{C_e g}\left[exp\left(\frac{C_e \tau_0 g}{K}\right) - 1\right] , \quad (3)$$

where $q_{m,f,P}$ – hourly fuel consumption selected for the work of the IACS;
K – the aerodynamic quality of the aircraft;
C_e – relative fuel consumption;
g – the free fall acceleration;
τ_0 – flight time.

Substituting the values indicated in the calculations of Chinese colleagues, one can notice that there is some discrepancy with the presented data.

The authors obtained the following results, with a decrease in the required power of compressor electric motors by 21% and 60%, respectively. The calculation results are presented in table 2.

Table 2. Results of mass fuel losses.

Parameter	Scheme 1 (original version)	Scheme 2	Scheme 3
Mass of fuel to overcome aerodynamic resistance, kg	-69.1	-69.1	-69.1
Mass of fuel for power generation, kg	+51.6	+20.6	+40.8
General mass losses, kg	-17.5	-48.5	-28.3

Note. “+” - increase; “-“- decrease.

By checking these calculations by the Bulaevsky-Shustrov method, the following results were obtained, which are presented in Table 3.

Table 3. Results of mass fuel losses according to the Bulaevsky-Shustrov formula.

Parameter	Scheme 1 (original version)	Scheme 2	Scheme 3
Mass of fuel for power generation, kg	25449.57	10245.5	20233.77
Fuel consumption for power generation, kg/h	7576.18	3050.03	6023.48

The study showed that the application of the Bulaevsky-Shustrov method for estimating the starting mass criterion for the Boeing 787 aircraft ESAC is possible, but only with the introduction of corrective amendments in the power take-off formulas for the ACS generators, which, in turn, convert this energy into electrical energy.

Based on the analysis performed, it can be concluded that a comparison of competing ESAC variants using the starting mass increment method is possible, but requires further research and clarification on specific coefficients in generally accepted calculation formulas.

2 Conclusion

After analyzing the work of 2010 and 2015, it can be concluded that ESAC is a promising direction in improving the overall efficiency of aircraft. The concept of a fully electric aircraft provides many advantages in improving the fuel efficiency of the aircraft and reducing its mass, and ground handling costs. It is worth noting the important prospect of using the takeoff mass increment method since it can give an idea of fuel economy due to the use of certain design solutions, both in the ACS and other aircraft systems.

References

1. D.Y. Strelets, S.A. Serebryansky, M.V. Shkurin, *Concept of Creation of a Digital Twin in the Uniform Information Environment of Product Life Cycle,* 13th International Conference "Management of large-scale system development" (MLSD), Moscow, Russia, pp. 1-4 (2020). doi: 10.1109/MLSD49919.2020.9247749
2. R. Bekirov, D. Strelets, M. Shkurin, *Approach to the Formation of Requirements for the Design of the Aircraft with Increased Load Capacity and Flight Range*, 15th Int. Con. Management of large-scale system development (MLSD), Moscow, Russian Federation, pp. 1-5 (2022) doi: 10.1109/MLSD55143.2022.9934185
3. S. Serebryansky, M. Shkurin, J. of Eng. Sci. and Tech. Rev. **15(6),** 149 – 154 (2022). DOI 10.25103/jestr.156.18
4. A.K. Kalliopin, R.S. Saveliev, D.I. Smagin, Eng. J. Sci. and Innov. **6** (2017)
5. D.I. Smagin, K.I. Starostin, R.S. Savelyev, Computational nanotechnology **3** (2019)
6. H. Yang, X. Zhang, C. Wang, C. Yang, *Design Analysis of Power Recovery Systems for Cabin Exhaust Air,* 9th Int. Symp. on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd Int. Conf. on Building Energy and Environment (COBEE) (2015)
7. J. Herzog, *Electrification of the environmental control system,* 25th International congress of the aeronautical sciences (2006)
8. 787 Air Conditioning & Pressurization. [Electronic resource] https://prezi.com/p/mzk2spmp2620/787-air-conditioning-pressurization/
9. 787's NO-BLEED Systems: Saving Fuel and Enhancing Operational Efficiencies. [Electronic resource] https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_07/article_02_1.html
10. Patent US 7,849,702 B2
11. Patent US 1 1/599.245