Thermodynamic parameters optimization of an aviation three-shaft turbofan engine with an intercooler and a recuperator under flight condition

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Abstract. The use of heat recovery in turbofan engines to improve their efficiency is not so obvious. Installing a recuperator behind the turbine of the main engine duct to heat the air at the entrance to the combustion chamber, on the one hand, reduces fuel consumption, but on the other hand, leads to a decrease in the temperature at the entrance to the jet nozzle of the main duct, thereby reducing the gas flow rate from the nozzle and, consequently, the specific thrust and thrust of the engine as a whole. The installation of an intercooler for intermediate cooling of the air between compressors allows to reduce the net-work and power of the high-pressure compressor and increase the gas pressure behind the turbine, and, consequently, the speed, specific thrust, and thrust of the engine. However, the amount of possible gain in the efficiency of a turbofan engine due to heat recovery will depend on how well the parameters of the working process of the engine and heat exchanger are selected. And this can be done only by optimizing these parameters in terms of evaluating the efficiency of the engine in the aircraft system. The article presents the results of optimizing the parameters of the working process of three-shaft turbofan engines with an intercooler and a recuperator in the system of a passenger aircraft of the Boeing 737 MAX 7 according to such criteria as the total weight of the power plant and the fuel required for the flight, and the specific fuel consumption of the aircraft per ton-kilometer of the transported commercial load.

Introduction
The use of complex thermodynamic cycles scheme in aircraft engines (Fig.1) provides several advantages, such as a decrease in specific fuel consumption, a decrease in the cooling airflow rate required to cool a high-pressure turbine by reducing the temperature of the cooling air at the outlet of the high-pressure compressor, and also reducing NOx emissions by reducing the flame temperature in the combustion chambers [1-4]. However, the difficulties in the technical implementation of such developments are associated with the complication of the design, the increase in the frontal dimensions and weight of the engine due to the installation of a heat exchanger. Hence, during the design of gas turbine engines with complex thermodynamic cycles, it is necessary to take into account not only the increase in fuel efficiency but also the deterioration of mass characteristics, since these factors have the opposite effect on the efficiency of the power plant in the aircraft system [5-8].
Currently, special attention is dedicated to the problems of increasing the efficiency of aircraft engines due to heat recovery [9-11]. Chengyu Zhang presents a simulation model of the helicopter with a recuperator to evaluate the ability of a recuperated helicopter under given two flight missions [12].

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Kwan, P.W. et al [13] and Xu L. et al [14] presented a detailed analysis of the characteristics of a plate heat exchanger and tube heat exchanger for a turbofan with an intercooler. Xin Z. [15] provides a conceptual design of a two-pass cross-section intercooler for an aircraft engine. The most preferred heat exchanger for aviation applications is plate recuperators [16-21]. The main advantages of the plate heat exchanger are relatively easy to manufacture and quite promising in terms of the possibility of obtaining overall good mass indicators when using them in modern aviation gas turbine engines and the further implementation of high-temperature cycles.

The work presents the results of analyzing the possibilities of improving the efficiency of turbofan engines by using complex thermodynamic cycles (the Brighton cycle together with heat recovery behind the turbine and intermediate cooling during compression) based on optimizing the thermodynamic parameters of three-shaft turbofan engine with an intercooler and a recuperator.

**Problem statement of optimizing the parameters of the working process of three-shaft turbofan engine with an intercooler and a recuperator**

The mathematical problem formulation for optimizing the parameters of the working process of a three-shaft turbofan engine with an intercooler and a recuperator according to a set of criteria for evaluating the engine in the aircraft system is formulated as follows:

$$\Omega^* = \arg \{ \min_x \max_y \delta y_i (X, p) | a_j < x_j < b_j; g(X, p) \leq 0 \}$$

(1)

Where:

- \(X = (T_4^*, r_c^*, m, r_{fan}^*, \theta_{inter}, \theta_{recu} ..., x_j)\) is the optimized workflow parameters \(j = 1, k\); \(T_4^*\) – the turbine inlet temperature, \(r_c^*\) – compressor pressure ratio, \(m\) – bypass ratio, \(r_{fan}^*\) – the pressure ratio of fan, \(\theta_{inter}\) – the intercooler effectiveness, \(\theta_{recu}\) – recuperator effectiveness of the.
- \(Y = \{C_{sp}, M_{engine+fuel}, SFC ... Y\}\) is the set of optimization criteria, \(i = 1, n\); \(C_{sp}\) – the specific fuel consumption of the aircraft on a ton per kilometer, \(M_{engine+fuel}\) – the total weight of the power plant and required fuel, \(SFC\) – the specific fuel consumption of the engine.
- \(a_j, b_j\) is the set of limitations on optimized variables.
- \(g(X, p) = \{h_{cout}, h_{lin}, r_t, D_4\}\) – the set of functional limitations.
- \(p = \{\sigma_{in}, \sigma_{cc}, \eta_{cc}, \eta_{t}, \phi_{in}\}\) – the set of deterministic initial design data.
- \(\delta y_i (X, p) = \rho_i \frac{Y(X) - Y(X_{opt})}{Y(X_{opt})}\) – relative deviation of the optimization criteria from the optimal value.
- \(\rho_i\) – criterion significance \(\rho_i = 0 \ldots 1\).

For a three-shaft turbofan engine with a recuperator and an intercooler, the number of optimized variables is six: \(r_c^*, T_4^*, m, r_{fan}^*, \theta_{inter}, \theta_{recu}\), the region of locally optimal parameters by any criterion...
is a hyperspace. In this case, the minimax optimality principle is used to find the most rational parameters solution from the Pareto set according to the set of consideration criteria.

In this paper, the following criteria are selected for evaluating the engine in the aircraft system: flight-technical (fuel consumption per ton-kilometer ($C_{sp}$) and the total weight of the power plant and fuel $M_{engine+fuel}$[22, 23]. The design weight of a compact heat exchanger was determined by the model given work in [24].

**Initial data and results of optimization of a three-shaft turbofan engine with an intercooler and a recuperator in the aircraft system**

The selected aircraft as the prototype is close to the characteristics of the Boeing 737 MAX 7 passenger aircraft. The scheme of the investigated three-shaft engine with a separate flow from the ducts and with a recuperator and an intercooler is shown in Fig. 1.

In this study, the heat exchanger effectiveness for intercooler and recuperator ($\theta_{inter}$, $\theta_{recu}$) was set from 0 to 0.9. The gas temperature in front of the turbine in cruising mode was assumed to be equal to 1400, 1600, 1800 and 2000 K. The engine thrust for the aircraft was determined based on the power plant thrust required, taking into account its aerodynamic characteristics, based on flight cycle simulation. The hydraulic losses in the heat exchanger channels for intercooler and recuperator are constant ($\sigma_{inter} = 0.97$ and $\sigma_{recu} = 0.95$).

The results of optimizing the parameters of the working process of turbofan engine with a recuperator by the author are presented in [11].

Figures 2 and 3 show the results of optimization of thermodynamic parameters of a three-shaft turbofan engine with a recuperator and an intercooler considering all 6 optimized parameters. The results show that with an increase in the gas temperature in front of the turbine, the optimal values of the bypass ratio, the compressor pressure ratio and the heat exchanger effectiveness of the recuperator and intercooler increase. Furthermore, the efficiency of the turbofan engine increases by 25 .. 30% according to the criteria $M_{engine+fuel}$ and $C_{sp}$ with an increase in the gas temperature in front of the turbine from 1400 K to 2000 K.

![Figure 2](image-url) **Figure 2.** Regional of optimal parameters of three-shaft turbofan engines with a recuperator and intercooler according to the criteria $M_{engine+fuel} \rightarrow \min$ considering optimizing all six parameters ($T_{4,crui} = 1600 K$, $H = 11 \text{ km}$, $M = 0.8$, $M_{pl} = 20 \text{ ton}$, $L_{flight} = 7000 \text{ km}$)

- $\bullet M_{engine+fuel}$ when $T_{4}^* = 1400 \text{ K}$; $\blacksquare M_{engine+fuel}$ when $T_{4}^* = 1600 \text{ K}$; $\triangle M_{engine+fuel}$ when $T_{4}^* = 1800 \text{ K}$; $\times M_{engine+fuel}$ when $T_{4}^* = 2000 \text{ K}$;
- Regional of optimal parameters when $T_{4}^* = 1400 \text{ K};$
- Regional of optimal parameters when $T_{4}^* = 1600 \text{ K};$
- Regional of optimal parameters when $T_{4}^* = 1800 \text{ K};$
- Regional of optimal parameters when $T_{4}^* = 2000 \text{ K}.$
Figure 3. Regional of optimal parameters of three-shaft turbofan engines with a recuperator and intercooler according to the criteria $C_{sp} \rightarrow \min$ considering optimizing all six parameters ($T_{4,\text{cruise}} = 1600$ K, $H = 11$ km, $M = 0.8$, $M_{pl} = 20$ ton, $L_{flight} = 7000$ km).

- $C_{sp}$ when $T_{4}^* = 1400$ K;
- $C_{sp}$ when $T_{4}^* = 1600$ K;
- $C_{sp}$ when $T_{4}^* = 1800$ K;
- $C_{sp}$ when $T_{4}^* = 2000$ K;

Regional of optimal parameters when $T_{4}^* = 1400$ K;
Regional of optimal parameters when $T_{4}^* = 1600$ K;
Regional of optimal parameters when $T_{4}^* = 1800$ K;
Regional of optimal parameters when $T_{4}^* = 2000$ K;

Figures 4 and 5 show the effect of the heat exchanger effectiveness of intercooler and recuperator on the optimal values of the compressor pressure ratio in the cycle and the bypass ratio of a turbofan engine with a recuperator and intercooler according to the criteria $M_{\text{engine+fuel}}$ and SFC.

Figure 4. Regional of optimal parameters of three-shaft turbofan engines with a recuperator and an intercooler according to criteria $SFC \rightarrow \min$ ($T_{4,\text{cruise}} = 1600$ K, $H = 11$ km, $M = 0.8$, $M_{pl} = 20$ ton, $L_{flight} = 7000$ km).

- $SFC$ when $\theta_{\text{inter}} = 0.0, \theta_{\text{recu}} = 0.0$;
- $SFC$ when $\theta_{\text{inter}} = 0.9, \theta_{\text{recu}} = 0.5$;

Regional of optimal parameters when $\theta_{\text{inter}} = 0.9, \theta_{\text{recu}} = 0.7$;
Regional of optimal parameters when $\theta_{\text{inter}} = 0.9, \theta_{\text{recu}} = 0.9$;

Regional of optimal parameters when $\theta_{\text{inter}} = 0.9, \theta_{\text{recu}} = 0.5$;
Regional of optimal parameters when $\theta_{\text{inter}} = 0.9, \theta_{\text{recu}} = 0.7$;
Regional of optimal parameters when $\theta_{\text{inter}} = 0.9, \theta_{\text{recu}} = 0.9$;
Figure 5. Regional of optimal parameters of three-shaft turbofan engines with a recuperator and an intercooler according to criteria $M_{\text{engine+fuel}} \rightarrow \min$

$T_{4,*}^\text{cruise} = 1600 \text{ K}, H = 11 \text{ km}, M = 0.8, M_{\text{pl}} = 20 \text{ ton}, L_{\text{flight}} = 7000 \text{ km}$

- $M_{\text{engine+fuel}}$ when $\theta_{\text{inter}} = 0.0, \theta_{\text{recu}} = 0.0$;
- $M_{\text{engine+fuel}}$ when $\theta_{\text{inter}} = 0.5, \theta_{\text{recu}} = 0.5$;
- $M_{\text{engine+fuel}}$ when $\theta_{\text{inter}} = 0.5, \theta_{\text{recu}} = 0.7$;
- $M_{\text{engine+fuel}}$ when $\theta_{\text{inter}} = 0.5, \theta_{\text{recu}} = 0.9$.

Regional of optimal parameters when $\theta_{\text{inter}} = 0.5, \theta_{\text{recu}} = 0.5$.
Regional of optimal parameters when $\theta_{\text{inter}} = 0.5, \theta_{\text{recu}} = 0.7$.
Regional of optimal parameters when $\theta_{\text{inter}} = 0.5, \theta_{\text{recu}} = 0.9$.

The results show that with an increase in the heat exchanger effectiveness of intercooler and recuperator, the optimal values of the compressor pressure ratio decrease by 3…5 times, according to criteria $SFC \rightarrow \min$ and $M_{\text{engine+fuel}} \rightarrow \min$. The optimal value of bypass ratio also decreases with the increase in the heat exchanger effectiveness of intercooler and recuperator by about 25…30%.

Figures 6, 7 and 8 show the effect of the gas temperature in front of the turbine on the optimal values of the criteria $M_{\text{engine+fuel}}, C_{sp}$ and $SFC$ at different values of the heat exchanger effectiveness of intercooler and recuperator. It can be seen that with an increase in the gas temperature in front of the turbine, the efficiency of the turbofan engine increases. It also increases with the increase in heat exchanger effectiveness of intercooler and recuperator.

Figure 6. Effect of the gas temperature in front of the turbine $T_{4,*}^\text{cruise}$ and heat exchanger effectiveness of the intercooler $\theta_{\text{inter}}$ and recuperator $\theta_{\text{recu}}$ on the optimal values of the criteria $SFC$ ($H = 11 \text{ km}, M = 0.8, M_{\text{pl}} = 20 \text{ ton}, L_{\text{flight}} = 7000 \text{ km}$)
Figure 7. Effect of the gas temperature in front of the turbine $T_4^*$ and heat exchanger effectiveness of the intercooler $\theta_{\text{inter}}$ and recuperator $\theta_{\text{recu}}$ on the optimal values of the criteria $M_{\text{engine+fuel}}$ ($H = 11 \text{ km}$, $M = 0.8$, $M_{pL} = 20 \text{ ton}$, $L_{\text{flight}} = 7000 \text{ km}$)

Figure 8. Effect of the gas temperature in front of the turbine $T_4^*$ and heat exchanger effectiveness of the intercooler $\theta_{\text{inter}}$ and recuperator $\theta_{\text{recu}}$ on the optimal values of the criteria $C_{sp}$ ($H = 11 \text{ km}$, $M = 0.8$, $M_{pL} = 20 \text{ ton}$, $L_{\text{flight}} = 7000 \text{ km}$)

Conclusion
According to the study, a mathematical model and a method for multi-criteria optimization and selection of rational parameters of the working process of a three-shaft turbofan engine with a recuperator and an intercooler were developed. Based on numerical modeling, the regularities of optimizing the operating parameters of turbofan engine with a recuperator and intercooler are established according to the criteria for evaluating the engine in the aircraft system: the total mass of the power plant and the fuel required for the flight, and the specific fuel consumption of the aircraft per ton-kilometer, as well as the specific fuel consumption of the engine.
From the analysis of the presented results, it follows that the optimal values of the compressor pressure ratio significantly decrease about 3...5 times with an increase in the recovery rate from 0 to 0.9, according to the criteria $M_{\text{engine+fuel}}$, $C_{\text{sp}}$, and SFC. The optimal value of bypass ratio also decreases with the increase in the recovery rate, but significantly less, by about 25 ... 30%. Noted that with an increase in the gas temperature in front of the turbine, the efficiency of a turbofan engine with a recuperator and an intercooler increases by 15 ... 20%. It also increases with the increase in the recovery rate.

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