Development of a mathematical model of the compact heat exchanger used for optimizing thermodynamic parameters of the aviation gas turbine engine

H.H. Omar[1], **V.S. Kuz'michev**[1], **A.Y. Tkachenko**[1], **A.V. Thomas Jayachandran**[1]

[1]Samara National Research University, Moskovskoe Shosse 34A, Samara, Russia, 443086

Abstract. Nowadays, the task of using automation for improving the technical and economic efficiency of the engine by reducing the specific fuel consumption and reducing the specific weight is one of the main trends in the development of the aviation industry. A promising approach for decrement of specific fuel consumption and obtaining high thermal efficiency of the gas turbine engine (30% and above) is based on the concept of the recuperative cycle of the gas turbine engine. The article presents the computer-aided calculation of a heat exchanger for analysing the heat exchanger surface and developing the mathematical model of heat exchanger in terms of weight goodness, flow passage goodness, and optimum weight and flow passage. Design calculations had been carried out for an aircraft engine with a heat exchanger made up with deferent heat transfer surfaces. To appraise the reliability of the obtained models, the results of design calculations on the developed models have been compared with the data of other authors and with the data on the created regenerator. The obtained model focus on mathematical design calculation for optimizing the main thermodynamic parameters of a gas turbine engine coupled with a heat exchanger at the stage of conceptual design of aviation gas turbine engine with heat recovery of exhaust gas.

1. Intoduction

Aviation gas turbine engines have reached a high degree of perfection. Nevertheless, the task of improving the technical and economic efficiency of the engine by reducing the specific fuel consumption and reducing the specific weight is still one of the main trends in the development of the aviation industry. A promising approach for reducing specific fuel consumption and obtaining high thermal efficiency of the gas turbine engine (30% and above) is based on the concept of the regenerative cycle of gas turbine engines [1-3]. However, the predicament of technical implementation of such developments is relevant to the intricacy of the design, increasing the size and weight of the engine due to the installation of the heat exchanger. Thus, the creating a gas turbine engine with the heat the exchanger is mandatory for taking consideration not only the increment in fuel efficiency but also the deterioration of weight characteristics since both factors have the opposite influence on the efficiency of the power unit as a whole. Through the viewpoint of the weight goodness and acceptable performance indicators demand further improvement of the methods for calculating compact heat exchangers, analyzing the conditions for rational matching the parameters of the heat exchanger and the engine, researching new highly efficient types of heat exchange surfaces, optimizing the operating parameters of the engine and heat exchangers [7-9]. The main requirements for heat exchangers include are the minimum weight and volume, structural integrity, low hydraulic pressure loss and high thermal efficiency and high reliability and durability.

Increase the heat exchanger effectiveness θ leads to decrement the specific fuel consumption (SFC) of the engines with a heat exchanger, however, with an increase in the heat exchanger effectiveness, the weight of the heat exchanger W_{hex} increased. Moreover, the weight of the heat exchanger has more intensively increased associated with increasing heat exchanger effectiveness. In evaluating the efficiency of the engine in an aircraft system, it is necessary to take account of both the decrease specific fuel consumption and the increase in the weight of the engine W_{engine}. For this purpose, a criterion such as the total weight of power plant ($W_{engine+fule}$) is used, which includes the weight of the engine with heat exchangers, and the weight of fuel is necessary for flying at a given range. Reducing the specific fuel consumption and an increase in the weight of the heat exchanger with an increase the heat exchanger effectiveness leads to the formation of a minimum of the total weight of the power plant. Consequently, selecting the parameters of the working process of the engine with the heat exchanger, it is necessary to simultaneously optimize both the parameters of the working process (π_c^*, m, T_g) and the heat exchanger effectiveness (θ).

The most preferred characteristic of aviation gas turbine heat exchangers is the plate-type recuperators (compact heat exchanger) [4,11]. According to the results of previous researches, McDonald, C.F. et.al. [4-6], Utrianen E. Sunden B. A. [8] and Kuz'michev V.S. et.al. [12], the primary surface of the heat exchanger (see fig.1) has the advantage of relatively larger effectiveness. Hence, it is more possible to achieve minimum volume and weight on the high heat exchanger effectiveness. For the further research in our study take into consideration the prime surface for design calculation of compact heat exchanger.

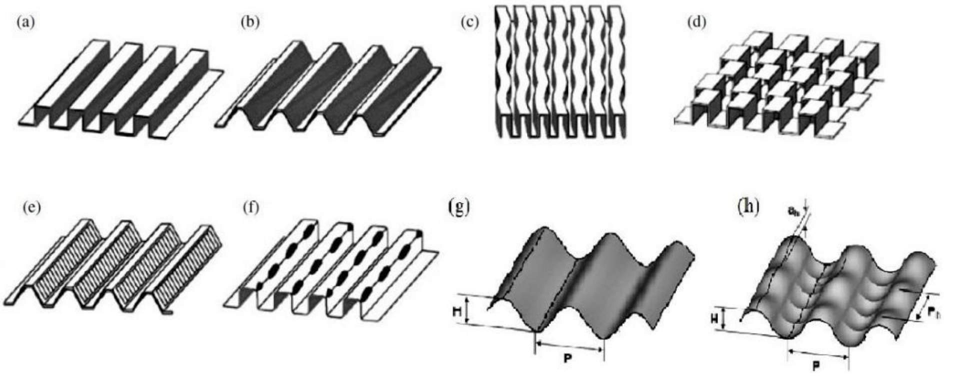

Figure 1. (a) Plain rectangular (b) plain trapezoidal (c) wavy fin (d) offset strip fin (e) louvred (f) perforated (g) Prime surface smooth channel (h) prime surface with heat transfer intensification [12].

2. Development of a model for estimating the weight of the compact heat exchanger

In this step of the work, the first model of heat exchanger (weight goodness) has been developed based on the design calculation algorithms of the compact heat exchanger, which developed in the ASTRA program tools [10]. Design calculation carried out under the following parameter conditions shown in table 1.

The following assumptions are the same for heat surfaces:

- The plate thickness, air and gas fin thickness equal 0.12 mm and the thickness of welding alloy for a pate-fin surface is equal 0.02 mm
- Flow schemes passage section of heat carriers Z=2
- Thermal conductivity and density of the material of the fin and walls $\lambda_p = 20.8, W/m.K$, $\rho_p = 7900 \ , kg/m^3$, respectively

The compact heat exchanger carried out for various degrees of heat exchanger effectiveness θ and gas velocity V_g. The results of the design calculations and the initial design data are given in table 2. Based on the investigated results, presented the dependence of the specific weight of the heat exchanger $\gamma_{\text{hex}} = W_{hex} / G_a$ on the heat exchanger effectiveness θ and gas velocity, as well as the dependence of the relative weight of the heat exchanger $\bar{\gamma}$ on heat exchanger effectiveness θ (Fig. 2,3).

Table 1. Initial parameter conditions for design calculation of compact heat exchanger.

Airflow rate G_a	43 kg/s
Heat exchanger effectiveness θ	0.7
Inlet heat exchanger air temperature	660 K
Inlet heat exchanger gas temperature	1000 K
Inlet heat exchanger air pressure	1497000 Pa
Inlet heat exchanger gas pressure	111000 Pa
Hydraulic diameter of gas side	1.5 mm
Hydraulic diameter of air side	0.75 mm

Table 2. Design calculation results of the specific weight heat exchangers.

№	Plate heat exchangers nomination	Main performance characteristics of plate heat exchangers					
		Initial design data			Design calculation results		
		airflow rate, G_a, kg/s	heat exchanger effectiveness θ	Gas velocity V_g, m/s	Heat exchanger weight W_{hex}, kg	Specific weight γ_{hex}, $kg/kg/s$	relative weight $\bar{\gamma}$
1	HE- A1	43	0.5	30	260	6.04	1
2	HE-A2	43	0.6	30	477	11.09	1.83
3	HE-A3	43	0.7	30	880	20.46	3.38
4	HE-A4	43	0.8	30	1750	40.69	6.73
5	HE-A5	43	0.9	30	4550	105.81	17.5
6	HE-B1	43	0.5	150	100	2.32	1
7	HE-B2	43	0.6	150	195	4.53	1.95
8	HE-B3	43	0.7	150	400	9.3	4
9	HE-B4	43	0.8	150	858	19.95	8.58
10	HE-B5	43	0.9	150	1992	46.32	19.92

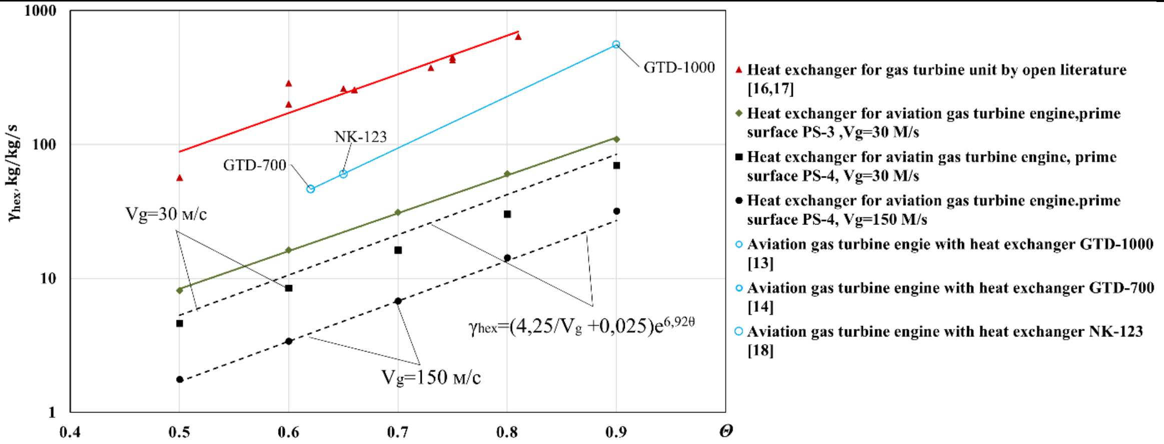

Figure 2. The influence of the specific weight of the various types of heat exchangers on the heat exchanger effectiveness (logarithmic scale).

The investigation design results have been evidenced through investigated data in the available open literature, the data on plate heat exchangers of aircraft gas turbine engines[13-15], data on plate heat exchangers of stationary gas turbine plants [16,17]. As well as data published in the paper from MAI [18], were presented in fig. 8 and 9. It can be seen from the figure 8 and 9, the influence of the specific weight of the heat exchanger according to the developed model and from various sources almost coincides, which proves the adequacy of the mathematical model.

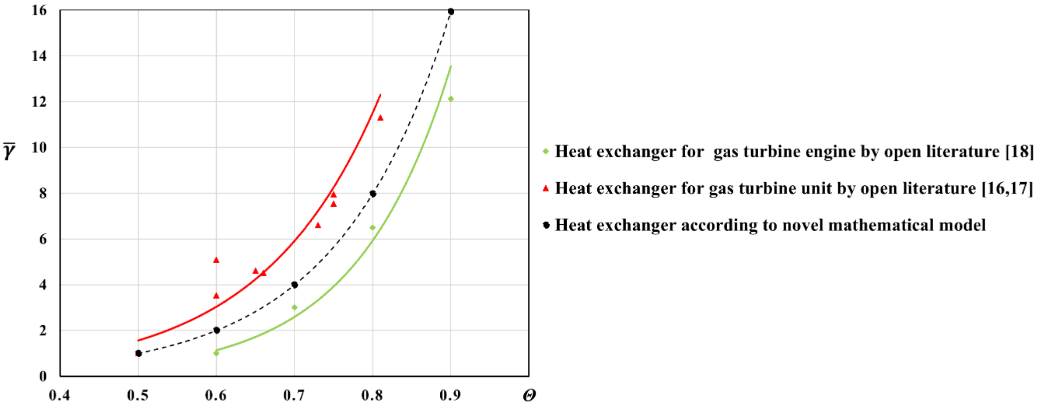

Figure 3. The influence of the heat exchanger effectiveness on the relative weight of heat exchangers.

Depending on the given heat exchanger effectiveness and gas velocity through the heat exchanger, the specific weight of the heat exchanger is calculated by:

$$\gamma_{\text{hex}} = (4{,}25\ /V_{\text{g}} + 0{,}025\ )e^{6.8\theta}, \text{kg/kg}\quad / s$$

For a given airflow rate through the heat exchanger and the calculated specific weight, the weight of the heat exchanger is determined by:

$$W_{\text{hex}} = G_a[(4{,}25\ /V_{\text{g}} + 0{,}025\ )e^{6.8\theta}], \text{kg}$$

Moreover, the second and third model (flow passage goodness and optimum weight and flow passage) were developed and the investigation results shown in the fig.8.

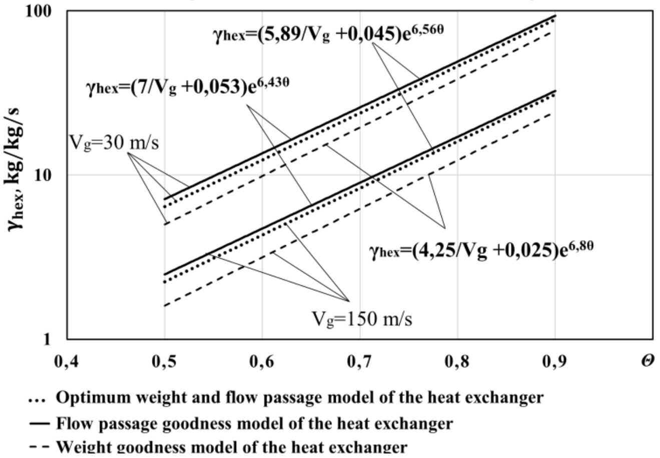

Figure 4. The influence of the specific weight of various models of heat exchanger on the heat exchanger effectiveness.

3. Conclusion

Three mathematical models had been developed and presented in the article, the first model is compact heat exchanger with the prime surface (PS-4) for both air and gas side channels (weight goodness). The second model is compact heat exchanger with prime surface (PS-2) for both air and gas side channels (flow passage goodness) and the third one model is the combined compact heat exchanger with prime surface (PS-2) for the gas side channel and prim surface (PS-4) for airside channels (optimum weight and flow passage). These models can be used for optimizing the parameters of the working process and the heat exchanger effectiveness at the stage of conceptual design of aviation gas turbine engine with heat recovery of exhaust gas. Herewith, two way-cross scheme of the relative motion of the heat carriers in the heat exchanger were chosen as the most rational flow schemes passage of heat carriers. The dependence of the specific weight of the heat exchanger on the heat exchanger effectiveness at different gas velocity is determined for the selected surface type on the basis of a detailed calculation algorithm, which led to investigating a correlation-regression model. A comparative analysis had been made for the influence of the heat exchanger effectiveness on the specific weight of the heat exchanger to assess the reliability of the obtained model, with the data of other open literature and with the data of the existing heat exchanger.

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