Intensification of heat transfer in the cooling systems of radio electronic equipment under free and forced convection

A.A. Lopatin^1, Ali Kamil Sebur^2, Israa S.Ahmed^2, R.A. Gabdullina^1, A.R. Biktagirova^1

^1Federal State Budgetary Educational Institution of Higher Education «Kazan National Research Technical University named after A.N. Tupolev–KAI», Department of Jet Engines and Power Plants, 420111, Kazan, st. K. Marx, 10.

^2Electromechanical Engineering Department, University of Technology, Baghdad, Iraq

aalopatin@kai.ru, arbiktagirova@kai.ru, rozzy94@mail.ru

50278@uotechnology.edu.iq, 50112@uotechnology.edu.iq.

Abstract. This paper considers the issues of heat transfer intensification in the air cooling system of heat-loaded elements of radio-electronic equipment based on split fins. The results of the study of heat transfer in free and forced convection cooling systems for heat-loaded elements of electronic equipment are presented. The thermal efficiency of systems based on smooth and partially split ribs is compared; the efficiency of split ribs is 16-20%. The dependences of thermal resistance on thermal load are determined. The results of a comparison of mathematical and physical modeling are provided. The influence of the method of supplying heat to split ribs is estimated. Optimization of the work area is presented.

Keywords: heat transfer, heat transfer intensification, cooling systems, partially split ribs, heat flow.

1. Introductions

Modern electronic and power equipment, a part of aviation equipment, is characterized by high heat generation, the absolute values of which can exceed 300-800 W [1]. Such values result from, first of all, by the rapid development of radio electronics and the nanoindustry, contributing to an increase in productivity and simultaneous miniaturization of microchips and other elements of modern electrical equipment.

One of the primary reasons for the failure of the expensive elements of radio-electronic equipment in aviation equipment is the failure to comply with thermal operating conditions. In addition to the problem of heat removal, issues related to the optimization of the weight and size characteristics of cooling and thermal stabilization systems also come to the fore. Evidently, the existing problems with the removal of high-density heat fluxes cannot be addressed using a universal cooling method, since
each heat-loaded element carries its own individual operating characteristics and parameters, due to specific design features and operating conditions of the equipment, power supply, the requirements for ensuring environmental and fire safety, etc.

Depending on the design and shape of the components that require cooling, various solutions are used for organizing permanent heat removal. With regard to power transistors and diodes of medium power, it is possible to use pin fin heat sink with a solid or dissected base. The cooling of such surfaces is usually carried out under conditions of natural convection by the surrounding air. These systems are disadvantaged because of their low thermal efficiency (heat transfer coefficient $\alpha \leq 10 \text{ W/m}^2\text{°C}$).

In the current thematic scientific literature, detailed studies on this subject are presented [2-4], simultaneously, however, discussions are quite acute regarding the possible ways of intensifying heat transfer. The significant interest in the issues related to the intensification of heat transfer at surfaces of various shapes and sizes as applied to the cooling systems of electronic equipment is evidenced by the presence of a large number of publications in modern scientific journals, both in Russia and abroad. The issues of heat transfer intensification in technical systems are also described in a significant number of works [5-11]. One of the most effective methods for increasing heat transfer in air cooling systems is split or partially split finning. [12,13]. The use of ribs as a method of intensifying heat transfer leads to an increase in the value of the heat transfer coefficient by tens of times. This method of intensification implies a wide variety of different types of finning: longitudinal, transverse, rolling, spiral and many others [14, 15].

Due to the practical impossibility of extensively considering in one work the entire range of problems associated with the intensification of heat transfer in conditions of free and forced convection, the authors decided to focus on the practical significant topics - the cooling system of a continuous X-ray flaw detector. With a power of up to 190 W for glass x-ray tubes, the maximum possible operating conditions is a temperature of 80 °C.

2. Methods
To study the effectiveness of the proposed method of heat transfer intensification, a comparative analysis of sections with smooth and sections with split ribs was carried out (Figure 1,2). The ribs are made of M1 brand copper and are arranged concentrically. The influence of the tightness conditions during the alternate lowering of the casing pipe on the working section, as well as the optimal opening angle of the “petals” of the ribs were determined experimentally, the thickness of the boundary layer and the criterion equations are also analytically determined. The influence of the method of heat input, the determination of the optimal number of cuts of the edge of the rib and the temperature distribution along the surface of the rib are calculated numerically.

To analyze the possible optimization parameters for split finning, a number of numerical studies were conducted to determine the most effective method for supplying heat and identifying the number of sections of the edge of the rib, and the geometry of the working section.

In order to determine the most effective way for supplying heat to the split finning, modeling was carried out under the condition of heating the entire lateral edge of the rib (100 mm), as well as heat transfer through a sector 30, 50 and 70 mm long. The temperature of the upper part of the rib of the working section with a maximum length of 100 mm is slightly higher than the temperatures with the other three methods of heat input, however, the apparent difference is insignificant and falls into the deviation error range of 5%.
3. Experimental Research

The experimental bench included a heater simulating isothermal heating, a working section located on the surface of the heater, and instrumentation. To study forced convection, an additional blower was installed. The working section consisted of copper fins located along an axial pattern. A sketch of the working area is shown in Figure 3.

In the process of research, a comparison was made of the heat transfer in the area with smooth and split ribs. On each edge of the section with a split finning, three dissections are plotted. To study the effectiveness of the proposed method of heat transfer intensification, a comparative analysis of sections with smooth and sections of split ribs was conducted. The ribs are made of M1 brand copper and are concentrically arranged. The influence of the tightness conditions during the alternate lowering of the casing pipe on the working section, as well as the optimal opening angle of the “petals” of the ribs were determined experimentally, the thickness of the boundary layer and the criterion equations are analytically determined. “Petal” refers to a segment of a cut rib. The influence of the method of heat input, the determination of the optimal number of cuts of the edge of the rib and the temperature distribution along the surface of the rib are calculated numerically.
4. Results

Figure 4 shows the dependence of heat transfer in the case of the forced movement of the coolant in cooling systems created on the basis of partially split (index “p”) and flat (“p”) ribs. It can be observed that at moderate Reynolds numbers (Re < 5000), the difference in heat transfer between the two systems is insignificant. However, at Re > 10000, a considerably sharp increase in Nur begins and at Re ≈ 22000, the intensification reaches 1.4 times (Nur / Nup ≈ 1.4 is the ratio of the Nusselt number in the section with split finning to the Nusselt number with flat edges), which is in accordance with the results, presented in Gortyshov Yu.F. [15]. Thus, it can be noted that the working section with partially split ribs features a higher thermal efficiency than a system with flat ribs. Figure 5 indicates the dependence of the differential pressure on the working areas with flat ribs and partially split fins. It is observed that in the entire range of Reynolds numbers there exists a slight excess of hydraulic resistance at the working section with partially split fins.

![Figure 4. Dependence of the Nusselt number on the Reynolds number: ○, Δ - Smooth and split edges, respectively](image1)

![Figure 5. Pressure drop P (hydraulic resistance) in areas with smooth (○) and split (Δ) ribs](image2)

Figures 6 and 7 Indicate the results of heat transfer studies for smooth and split ribs at different heights of lifting the casing, as well as at different angles of the opening of the ribs.
Figure 6. The study of convective heat transfer surfaces. Casing lifting height: - there is no casing, • - hp = 90mm, ▲ - hp = 80mm, ○ - hp = 70mm, ● - hp = 60mm, ◆ - hp = 50mm, + - hp = 40mm, ● - hp = 30mm, ■ - hp = 10mm, ■ - hp = 20mm, ○ - smooth rib, calculation according to known dependencies: • - Mikheev M. A. formula, ◆ - Isachenko V.P. formula

Zero height of the casing corresponds with the base of the working area. As a comparison of the experimental results with the data from studies by renowned authors, Fig. 3 indicates the calculation lines by M.A. Mikheev, formula (1), Written E.N. [16] and V.P. Isachenko, formula (2), Lopatin A.A. [12] for free convection:

\[
Nu = 0.46 \times Ra^{0.25} \tag{1}
\]

\[
Nu = 0.63 \times Ra^{0.25} \tag{2}
\]

The maximum values of heat transfer are attained when the height of the casing is increased by 40 mm and the opening angle of the ribs is 30°. The presence of these maxima is explained by the formation of the self-traction effect in the cavity of the constraining casing and the opening of the boundary layers. With a decrease in the height of raising the casing, the amount of working air entering the casing region decreases and the air surrounding the ribs heats up. With an increase in the lifting height of the casing pipe, the area of ribs inside the pipe decreases, which impedes the intensity of the process. When the opening angle of the ribs is less than 30°, the boundary layers close together, which significantly worsens the heat transfer process. At the opening angles of the ribs by 45° and 60°, the diameter of the circle of the base of the working section decreases, thereby negatively affecting the overall intensification process.
The results of calculating the temperature distribution over the surface of the split fin are indicated in Figure 9. The results of optimizing the geometric characteristics of the cooling system are shown in Figure 10.

5. Discussion

As a result of a joint consideration of the thermal and hydraulic efficiency of air cooling systems, it can be noted that the achieved heat exchange intensification using partially split ribs can be explained by the combined influence of two indicated factors: firstly, the presence of dissections of the heat-exchange surface does not allow the formation of a complete boundary layer along the length of the rib and secondly, due to the constant stalling of the flow from the initial and final edge of the rib, some additional turbulence occurs of flow.
The primary parameter characterizing the quality of cooling systems is thermal resistance - the ratio of the temperature difference on the cooled surface to the amount of heat flowing through it (°C/W). However, as previously noted, due to a significant increase in thermal efficiency at Re> 20,000 (Figure 5), partially split ribs are more preferable for use in forced convection cooling systems for continuous X-ray flaw detectors.

The operating temperature range of cooling systems with external air blowing is indicated in Fig. 8. It can be indicated that a system based on flat and split edges at tc = 80 °C can divert ≈500 W, which is not sufficient for ensuring the stable operation of the device. The maximum possible operating conditions should be understood by tc. Therefore, systems built using partially split ribs can be use adopted d for flaw detectors of medium and low power (Q ≤ 600 W). The low heat flux removed by the air cooling system, created on the basis of partially split fins, can be explained by some coupled factors that have a decisive influence on the heat transfer process as a whole. Therefore, with all of the above-mentioned advantages of partially split fins, it should be noted that in the absence of an increase in the heat transfer area, additional turbulization caused by the dissection of the heat exchange surfaces, and, consequently, the mixing of the flow, leads primarily an increase, though insignificant, in the hydraulic resistance. Moreover, the increase in heat transfer is not leading and, accordingly, does not have a decisive influence on the process as a whole.

An analysis of the results of numerical modeling of the temperature distribution in the working area facilitates determining the areas of fins with maximum and minimum heat transfer, which subsequently became the basis for further optimization.

The resulting model of split ribs allows one to remove the necessary heat fluxes, power up to 190 watts, and also provides a reduction in the mass of the working area by 16.5%.

6. Conclusion
As a result of the work, studies of heat transfer intensification in natural and forced convection using split ribs were carried out and presented. The effectiveness of using split finning is indicated; during the experiment, the most optimal geometric parameters of the working section were identified. Criteria are obtained for calculating the heat transfer of systems with axial split finning. It can also be assumed that the intensity of heat transfer processes will depend not only on the mode, but also on the geometric parameters of the partially split finning, including the depth of the cut, step and shape of the “petals”, etc. To confirm the above assumptions, it is necessary to conduct a series of refinement experiments. As a result of physical and numerical simulations, data were obtained indicating the absence of the influence of the length of the edge of the rib through which heat is supplied to the heat transfer, as well as illustrating the possibility of optimizing mass and size characteristics, which leads to a saving of 16.5% in mass.

The aim of this study is the verification of experimental data in numerical simulation programs and the topological optimization of the resulting model. Creating rib geometry by modeling based on topological optimization allows you to purposefully adapt the component and the cooling system as a whole. Solutions that cannot be manufactured industrially or can only be created with disproportionate effort can also be produced as separate parts using additive manufacturing processes. However, it is also necessary to consider the structural nuances associated with the production process.

References
[1] Lopatin A.A., Schelchkov A.V., "Intensification of heat transfer in cooling systems of continuous x-ray apparatus.", In the mat. RNKT-5. M.: Publishing House of MPEI, 2008, v.
Industrial and environmental engineering.

[2] Yarkaev M.Z., Al-Janabi A.Kh.A., Gilmanov A.Kh., Gortyshov Yu.F., Popov I.A., Schelchkov A.V., "A comparative study of heat exchangers with intensification of heat transfer", Bulletin of Kazan State Technical University. A.N. Tupolev. - 2013. - No. 2-2. - pp. 73-79.

[3] Popov I.A. "Hydrodynamics and heat transfer of external and internal free-convection vertical flows with intensification." Intensification of heat transfer: monograph / Ed. ed. Yu.F. Gortishova. - Kazan: Center for Innovative Technologies, 2007. - 326 p.

[4] Gortyshov Yu.F., Popov I.A., Usenkov R.A. "Heat transfer of free-convection flows in the presence of surface intensifiers", News of Higher Education Institutions. Aircraft technology. - 2003. - No. 3.- ss. 29-32.

[5] Vasiliev V.Ya., "Rational intensification of convective heat transfer by dissection of long smooth channels", Bulletin of the Moscow Aviation Institute. - 2010. - T.17. - No. 3. - pp. 143-152.

[6] Popov I.A. "Hydrodynamics and heat transfer of external and internal free convective vertical flows with intensification.", Intensification of heat transfer: monograph, Ed. ed. Yu.F. Gortyshova. - Kazan: Center for Innovative Technologies. - 2007. - 326 s.

[7] Dreitser G.A., Lobanov I.E., "Ultimate intensification of heat transfer in pipes due to artificial turbulentization of the flow for gaseous coolants with variable thermophysical properties", Moscow Aviation Institute Bulletin. - 2005. - T.12. - No. 3. - ss. 18-25.

[8] Gortyshov Yu.F., Popov I.A., Usenkov R.A., "Heat transfer of free-convection flows in the presence of surface intensifiers", News of Higher Education Institutions. Aircraft technology. - 2003. - No. 3.- ss. 29-32.

[9] Baldwin, C. S., Bhavani, S. H., Jaeger, R. C., "To ward Optimized Enhanced Sur faces for Passive Immersion Cooled Heat Sinks", IEEE Trans. Comp. Hy brids, Manufact. Technol., 23 (2000), pp. 70-79.

[10] Gortyshov Yu.F., Popov I.A., Olimpiev V.V., Schelchkov A.V., Kaskov S.I. "Intensification of heat transfer. Thermohydraulic efficiency of promising methods of heat transfer intensification in the channels of heat exchange equipment", Center for Innovative Technologies Publishing House. 2009. Kazan. 530.

[11] Vasiliev V. Ya.,"Efficiency of the process of rational intensification of convective heat transfer in channels with discrete turbulators", Herald of the Moscow Aviation Institute. 2010.Vol. 17. No. 3. P. 153-162.

[12] Lopatin A.A. "Heat transfer and resistance in cooling systems of electric power equipment with split finning", Bulletin of Kazan State Technical University named after A.N. Tupolev. - 2013. - No. 2-1. - ss. 187-190.

[13] Lopatin A.A., Nikolaeva D.V., "Investigation of the capabilities of split fins in cooling systems of electronic equipment", Problems and prospects for the development of aviation, land transport and energy ANTE-2015: International Scientific and Technical Conference, October 19-21, 2015. Collection of reports. Kazan: Brig Publishing House. - 2015.-- pp. 566-592.

[14] Fraas A., Otisik M., " Calculation and design of heat exchangers", M.: Atomizdat, 1971, 356 p.

[15] Gortyshov Yu.F., Olimpiev V.V.," Heat exchangers with intensified heat transfer ", Kazan: Kazan Publishing House. state tech. University, 1999.176 s.

[16] Written E.N., " New effective developed heat exchange surfaces for solving problems of energy and resource conservation", Prom. heat engineering. - 2007. - T.29. - No. 5. - pp. 7-16.