Optimization of porous microchannel heat exchanger

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Abstract. The technical progress in information and communication sphere leads to a sharp increase in the use of radio electronic devices. Functioning of radio electronics is accompanied by release of thermal energy, which must be diverted from the heat-stressed element. Moreover, using of electronics at negative temperatures, on the contrary, requires supply of a certain amount of heat to start the system. There arises the task of creating a system that allows both to supply and to divert the necessary amount of thermal energy.

The development of complex thermostabilization systems for radio electronic equipment is due to increasing the efficiency of each of its elements separately. For more efficient operation of a heat exchanger, which directly affects the temperature of the heat-stressed element, it is necessary to calculate the mode characteristics and to take into account the effect of its design parameters. The results of optimizing the microchannel heat exchanger are presented in the article. The target optimization functions are the mass, pressure drop and temperature. The parameters of optimization are the layout of porous fins, their geometric dimensions and coolant flow. For the given conditions, the optimum variant of porous microchannel heat exchanger is selected.

1. Introduction
The problem of maintaining necessary temperature of heat-stressed elements of radio electronic equipment under conditions of intense heat generation leads to creation of various devices and complex systems. Typically, such systems consist of a heat exchanger adjacent to a heat source, a heat-transfer agent device, and an external cooling unit. The classic example is the cooling system of a personal computer processor, consisting of heat pipes, a radiator and a fan [1, 2]. In the case of increased release of thermal energy, it is possible to use thermoelectric materials, multi-circuit systems with phase transition elements [3]. Often this leads to an increase in the number of elements for any of these systems and increases their mass-dimensional characteristics. In addition, this makes it difficult to predict functioning of such systems, especially under conditions of rapidly changing thermal loads. Modern trends towards miniaturization of dimensions of heat-stressed elements themselves lead to the problem of removing high heat flux from a small area.

One of the variants of the proposed technical solution is the use of porous fins that make it possible to form a developed heat exchange surface on the surface with intense heat release. The use of continuous porous media leads to increased pressure drop and, as a consequence, the selection of a pump with a large head. To reduce the pressure, distributed coolant supply to the porous fins is used. The dimensions of a heat exchanger, the materials used for its manufacture have a direct effect on the structural elements, in particular the thickness of the porous fins, their mutual arrangement and quantity. For practical development of heat stabilization systems, the data on the effect of these characteristics on the heat exchange and hydraulic characteristics of the heat exchanger are required.
2. Problem statement
The porous microchannel heat exchanger shown in figure 1 consists of the base 1, the cover 2, the inlet fitting 3 and outlet fitting 4 of the heat-transfer agent (the orifices are indicated). To distribute the heat flow from the heat-stressed element of a small area, the base with the prismatic element 5 shown in figure 1 (b) is provided. The size of the site for the removal of thermal energy is four times larger than the area of the heat-stressed element (4 cm² and 16 cm², respectively). On the indicated site inside the heat exchanger, porous fins 6 are located, through which the coolant passes. One of the structural variants of the inner unit is a continuous porous solid, occupying the entire internal space. In this case, the hydraulic resistance is high in comparison with the proposed alternative, where the coolant is uniformly supplied through several channels.

![Figure 1. Porous microchannel heat exchanger.](image)

To evaluate the thermohydraulic characteristics and to choose the optimal variant, various designs of porous fins are considered. 8 variants are defined, divided into 3 groups. The optimization parameters are the angle $\gamma$, the thickness of the fin $b$, the distance between the fins $c$ (figure 1 (c)). Parameter values are shown in table 1. The thermophysical characteristics of the heat exchanger and boundary conditions: porosity of the fins $\Pi = 0.4$; the particles dimension $d_p = 0.5 \cdot 10^{-3}$ m; the fins material is aluminum or copper; the heat-transfer agent is water (at $t_0 = 20^\circ C$, $\mu_f = 1,003 \cdot 10^{-3}$ Pa-s, $\rho = 998,2$ kg/m³, $\lambda_f = 0.6$ W/(m-K), $c_p = 4182$ J/(kg-K)). To estimate the performance characteristics of each of the heat exchanger variants, the flow range is $G = 0,003..0,05$ kg/s.

| Variant | $\gamma$ | $b$, mm | $c$, mm | $n$ |
|---------|---------|---------|---------|-----|
| 11      | 87      | 2       | 1.0575253750 | 8   |
| 12      | 87      | 4       | 0.9841283450 | 6   |
| 13      | 87      | 3       | 1.8806851333 | 6   |
| 21      | 85      | 2.5     | 1.0950138500 | 6   |
| 22      | 85      | 6       | 1.5273983950 | 4   |
| 31      | 90      | 5       | 1.6666666667 | 6   |
| 32      | 90      | 3       | 2.0000000000 | 8   |
| 33      | 90      | 4.5     | 2.1666666667 | 6   |
3. Solution

3.1. Preliminary determination of coefficients and quantities

When solving the problem, the model for laminar motion of the coolant and the two-temperature model of heat transfer in a porous medium have been adopted. To solve this problem, it is necessary to determine the following parameters.

Viscosity coefficient [4]:

\[ \alpha = \frac{150(1-\Pi)}{\Pi^3d_p^2}. \]  

Inertial coefficient [4]:

\[ \beta = \sqrt{\alpha}. \]  

Contact surface area [5]:

\[ A_{fs} = \frac{6(1-\Pi)}{d_p}. \]  

Heat transfer coefficient between porous matrix and coolant [5]:

\[ h_{fs} = \frac{\dot{\lambda}_f}{d_p} \left[ 2 + 1.1 \text{Pr}^{1/3} \left( \frac{\rho_f}{\mu_f} \frac{u_0d_p}{\dot{\lambda}_f} \right)^{0.6} \right], \]  

where \( \text{Pr} = \frac{\mu_f c_{pf}}{\dot{\lambda}_f}. \)

Previously tested approach has been used to determine the velocity of the coolant \( u_0 \) and its thermophysical properties \( \mu_f, c_{pf}, \dot{\lambda}_f \) and the heat transfer coefficient \( h_{fs} \) [6].

3.2. Modeling the operation of the porous microchannel heat exchanger

To determine the objective functions, a three-dimensional model of the heat exchanger was constructed for each of the porous fins structural variants. Then each model was imported into the engineering analysis system *Ansys Fluent* and were adapted for calculation. Adaptation consisted in constructing the flow volumes of the supply and return collectors, as well as in increasing the length of the inlet and outlet fittings to ensure that the solution did not cause backflows. The grid generator allowed to break the model into finite volumes.

The number of elements of the grid was changed according to the different variants and was in the range from 704,069 to 4,549,702. The ranges of the grid quality parameters are presented in table 2. The grid for several elements is shown in figure 2.

| Table 2. Calculation grid parameters. |
|-----------------|-----------------|-----------------|-----------------|
| Value           | Element Quality | Skewness        | Orthogonal      |
| Minimum         | 0.10600 - 1.000 | 9.678·10⁻⁶ - 7.051·10⁻⁵ | 8.888·10⁻⁶ - 1.000 |
| Maximum         | 0.99966 - 1.000 | 0.8972 - 0.9688  | 1.000           |
| Average         | 0.74300 - 0.837 | 0.224 - 0.276   | 0.826 - 0.863   |
To solve the problem, the following assumptions and boundary conditions were adopted. The heat flux \( q = 100 \text{ W/cm}^2 \) acted upon the base of the prismatic element. At the inlet to the heat exchanger, the mass flow rate of the coolant with a temperature of 20 °C was set. All other walls were thermally insulated. In addition, two flow models were accepted for the internal volume (through which the coolant passes): laminar for the porous fins and turbulent for the inlet and outlet manifolds. When performing calculations, to obtain more accurate solution, the heat balance and mass flow balance of the coolant were monitored. To do this, in the first case, the faces of the heat-stressed element, the inlet and outlet of the coolant were examined, and in the second case, only the ones of the inlet and outlet of the coolant. To determine the pressure drop in the heat exchanger, the mean values over the area at the inlet and outlet faces were considered. Moreover, the maximum temperature of the coolant in its entire volume was estimated to monitor the phase transition change. The maximum temperature of the heat-stressed element was also determined under various operating conditions of the heat exchanger. To analyze the results obtained, graphs were constructed for one group. They are shown in figures 3-4.

![Figure 2. Calculation grid.](image)

**Figure 2.** Calculation grid.

To choose the optimum variant of the porous microchannel heat exchanger, the pressure drop and temperature, the maximum temperature of the heat-stressed element and its mass were estimated. To simplify the evaluation, the diagram shown in figure 5 is constructed.

![Figure 3. Dependence of pressure drop on the coolant consumption.](image)

**Figure 3.** Dependence of pressure drop on the coolant consumption.

![Figure 4. Dependence of the maximum temperature on the coolant consumption.](image)

**Figure 4.** Dependence of the maximum temperature on the coolant consumption.
3.3. Summary
The analysis of the obtained results allows to determine the values of the flow and pressure drop for critical temperature regimes of the heat-stressed elements. For example, in order to prevent the substrate from exceeding the temperature of 380 K, the water flow should be 0.029 kg/s, and the pressure drop will be 1.2 kPa (variant 11). Considering the complex characteristic (figure 6), it is possible to choose the optimal variant of the heat exchanger, which has a large temperature difference at small pressure and mass differential.

4. Conclusion
The carried out optimization of the porous microchannel heat exchange apparatus made it possible to determine the most effective variant of the construction of the heat exchange - element porous fins (variant 21). The values of the parameters turned out to be the following: $\gamma = 85^\circ$C, $b = 2.5$ mm, $c = 1.095$ mm, $n = 6$. The material for making the porous element is aluminum.

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