Based on the Matrix of Silicon Nanocrystals a Modeling Study of Thermo-hydraulic Properties of Micro-channel Heat Transfer Elements

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Abstract

The construction of a heat exchange element based on a matrix of silicon whiskers for thermal stabilization systems of miniature heat sources with specific power up to 100 W/cm2 operating over a wide range of ambient temperatures is proposed. Based on the developed mathematical model of convective heat transfer in a microchannel compact heat exchanger with a developed heat exchange surface, numerical simulation of the hydrodynamics and heat transfer processes for various configurations of microchannel insertions was carried out. Fields of pressures, flow velocities, coolant temperatures and matrix from silicon single crystals have been obtained in a wide range of coolant flow rates, criteria dependencies for the Nusselt number and pressure losses of various geometric configurations of heat exchangers have been determined. Critical operation modes are investigated; optimization directions are proposed. According to the developed technology, prototypes for testing have been manufactured.

Key Words: Monocrystalline Silicon, Convective Heat Transfer, The Criteria Dependence, Intensification of Heat Exchange, Critical Modes of Operation.

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Introduction

Active development of industries such as energy, electricity tronics leads to an increase in the energy intensity of individual elements of energy and electronic equipment and an increase in heat generation against the background of increased requirements for compactness and miniaturization of thermal protection systems [1-3]. Nanocrystalline materials are polycrystalline materials comprising of grains. In nanometer range they can possibly display remarkable physical, mechanical and synthetic properties, which could, on a basic level, lead to new applications and novel advancements. [4-8] To ensure the stable operation of the specified equipment, it is necessary to maintain working thermal conditions, which leads to the need to create thermal stabilization systems operating in conditions of both high and low ambient temperatures. So, for example, for terrestrial satellite systems control systems it is required to maintain high thermal stability (± 0.1 °C), which may require the use of various kinds of highly efficient heat exchange elements. Miniaturization of devices and increased loads require intensification of heat transfer. Various types of porous and microchannel recuperative heat exchangers are widely used. A wide range of structural, thermophysical, hydraulic, chemical, optical and other properties of porous and microchannel materials, ease of manufacture of structural elements from them, high heat transfer intensity - all this makes it possible to use these heat exchange elements under high thermal loads and temperatures, where other types of cooling structures are ineffective.

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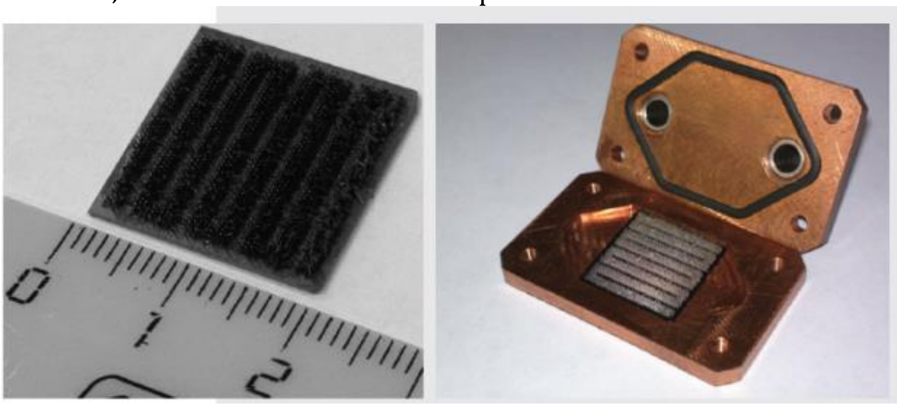
For example, in thermal protection systems for liquid propellant rocket engines, supersonic fire-jet cutters, plasmatrons, as well as power supplies, microcircuits, modern processors, base stations, satellite and space communications, porous heat exchangers with interchannel have been developed and successfully tested conveyor cooler. One of the promising methods for supplying / removing heat from an energized surface is the use of microchannel heat exchangers based on a matrix of silicon whiskers. This allows one to significantly increase the heat transfer coefficient from the heat-generating surface to the heat carrier, and the specific heat removal can be up to 100 W / cm^2. It should be noted that the heat transfer process is directly influenced not only by the convective component, but also by the thermophysical properties of the heat-removing element itself, as well as the thermal resistance between the "hot" surface and the cooler. So, when the coefficient of internal pore heat transfer is equal to $h_v = 10^9$ ... 10^{11} W / (m^3. K), the effective thermal conductivity of the copper matrix will be 160 W / (m. K), and the specific thermal resistance between the heated surface and the heat exchanger is of the order of 10^{-3} to 10^{-2} (m .K) / W, which, as a whole, negates the efficiency of porous cooling. In turn, the technology for producing silicon single crystals makes it possible in some cases to grow a heat exchange element with a regular structure on a fuel surface, which eliminates thermal resistance at the contact point. Therefore, maintaining a given operating temperature of energy-stressed devices, accurate prediction of their operating modes is an urgent task.

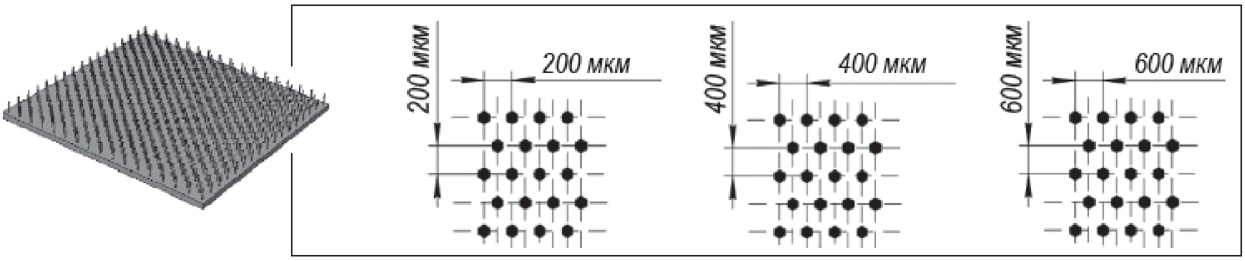
Materials and Research Methods

Based on the technology [9], a mock-up of the basic version of the heat-removing element from whisker silicon single crystals grown on a silicon substrate was developed and created (Fig. 1a). Silicon whiskers are grown on silicon single-crystal substrates in a furnace with a horizontal arrangement of a tubular quartz reactor in an open chloride-hydrogen system environment. After crystal growth, the supply of silicon tetrachloride to the reaction zone ceases, and the reactor with the grown samples of whiskers is cooled to room temperature. Morphological studies are performed by scanning probe microscopy. The proposed technology allows the growth of silicon whiskers with various configurations of their arrangement (continuous row, snake, etc.). The heat exchanger consists of a copper base, in which there is a heat exchange element made of a matrix of silicon single crystals and a top cover with inlet and outlet fittings cooler. The base and cover are tightened with screws. A rubber gasket is provided to prevent leakage of the cooler. The cooler is supplied to the heat exchanger (Fig. 1b) through the cooler supply nipple, passes through the area of the silicon filament monocrystal matrix, is heated from them, cooling the heat-stressed element on which the heat exchanger is installed, and is discharged through the cooler outlet. The silicon substrate has dimensions 20 × 20 mm (Fig. 2a), the thickness of the substrate on which spikes are grown 0.2 mm, the height of the spikes 1 mm, the diameter of the spikes 0.1 mm Heatsink elements (spikes) are located in a checkerboard order, the distance between their centers along the x and y axis is 200, 400, 600 μkm, respectively (Fig. 2b). In this embodiment, the heat-removing elements form a monolithic structure together with the substrate, which eliminates thermal resistance. Currently, there are practically no results of mathematical and numerical modeling of heat and mass transfer processes in microchannel structures of this kind. Application of mathematical models and classical criterion equations of heat and mass transfer for macromodels including flow around tube bundles in heat exchangers for evaluating processes on a micro scale gives unsatisfactory results. Using an ideal porous medium model for predicting the performance of rock channel elements is also imperfect, which is a serious discrepancy between the results of numerical and experimental modeling This is due to the fact that it is necessary to study the features of the processes of hydrodynamics and heat transfer in microchannels, when it is necessary to take into account near-wall flows near walls and spikes, as well as developed flows in free space. A significant temperature gradient between the spike and the cooler also makes adjustments to the accuracy of the simulation of hydrodynamic processes, including non-stationary operating modes. The incorrectness of existing models leads to a loss of accuracy in the assessment heat and mass transfer processes in the developed elements of thermal protection, which can lead to its destruction during critical operating conditions. The modeling of convective heat transfer in such media is based on the phenomenological Darcy – Brinkman – Forchheimer equations [10–11]. To obtain an analytical solution, an elementary volume is allocated for a single spike, volume averaging is performed, and then a one-sided integral transformation is applied together Laplace and the finite integral Fourier transform. To confirm the correctness and adequacy of the proposed mathematical model, to clarify the hydrodynamic situation, numerical simulation was performed in the ANSYS environment. The system of equations for the nonisothermal (with heat transfer) flow of an incompressible fluid in Cartesian rectangular coordinates will consist of the equations of continuity (1), motion (2) and energy (3).



a - matrix of whisker silicon single crystals b - general view of the heat exchanger

Fig. 1. Heat exchanger with a matrix of whiskers single-crystal fishing for silicon.



a - 3D model b - the arrangement of the spikes on the substrate.

Fig. 2. Silicon substrate

$$\nabla \cup = 0 \qquad (1)$$

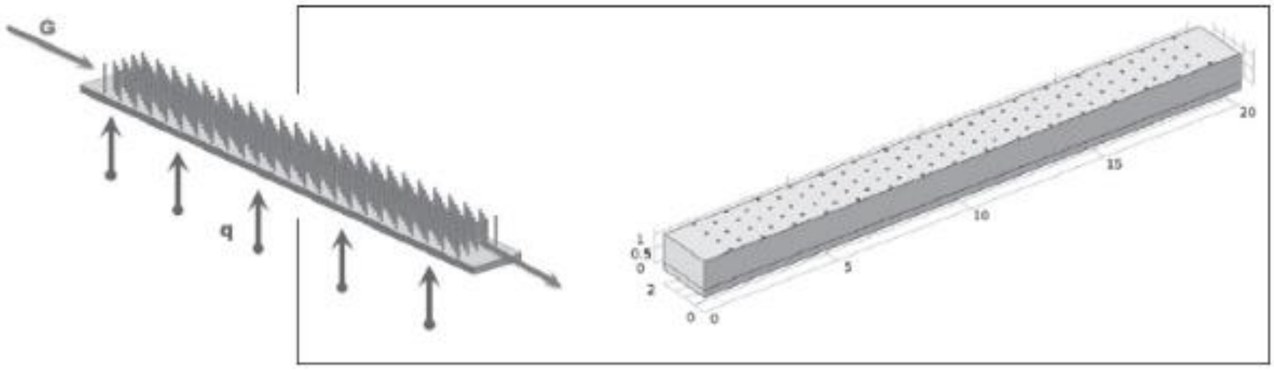
$$\frac{\partial \cup}{\partial t} + (\cup.\nabla) \cup = J - \frac{1}{\rho} \nabla p + v\Delta \cup \qquad (2)$$

$$\frac{\partial T}{\partial t} + (\cup.\nabla)T = a\Delta T + \frac{q_v}{\rho c_p} \qquad (3)$$

where U - is the flow rate of the cooler;
p - is the pressure;
τ - is the time;
ρ - is the fluid density;
J - is the resulting vector of mass forces,
μ - is the coefficient of dynamic (molecular) viscosity;
v - is the kinematic viscosity of the medium ($v = \mu / \rho$),
a - is the thermal diffusivity ($a = \lambda / \rho c_p$).
the goal of speeding up the computational process was to use.

The model substrate element of silicon filamentary single crystals shown in Fig. 3a is used. The geometric dimensions of the model were 2 × 20 mm. The remaining geometric dimensions and the arrangement of the spikes remained unchanged. The computational domain together with the generated discrete partition is shown in Figure 3b. The choice of the turbulence model when using the ANSYS package should take into account that the model should be tested for a similar class of problems, it should be invariant to the use of geometric and thermophysical parameters characterizing the selected type of heat exchange elements with a regular matrix and use available experimental data on hydrothermal fields, as well as meet the criterion of stability and convergence of the computing process. As a mathematical model of the hydrodynamics of the cooler flow, a two-layer SST model was chosen, which provides good convergence with sufficient speed, taking into account the structure of the turbulent flow in the core and the boundary layer near the surface of the spikes. The advantage of this model is that this model takes into account both vortex formation (k – ω model) and ripple intensity (k - ε model). This choice is correlated with studies of the SST model presented in [12–13]. When analyzing the presented software image for the ANSYS package, the following assumptions were used:

- The coolant was a Newtonian incompressible fluid bone.
- Thermophysical properties of the thread and the filamentary matrix single crystals of silicon were calculated at an average temperature process temperature;
- the initial hydrodynamic section at the inlet of the heat there was no exchange element
- The flow of the coolant is stationary and three-dimensional character;
- there are no internal heat releases;
- heat flow is supplied through the bottom wall, side and the top wall are thermally insulated.



a - a portion of the substrate with studs

b - 3D model of the computational domain

Fig. 3. Model element

For mathematical modeling Ansys Fluent v. 17, intended for the numerical solution of the equations of fluid motion and heat transfer in the computational domain of interest, which allowed us to reduce the complexity and reduce the duration of the calculations. Ansys Usage Algorithm Fluent to solve this problem is as follows. At the first stage, the constructed 3D model of the object under study is imported into the Fluent solver; on the second - decomposition of the computational domain and post-swarming of a grid, its quality is estimated; at the third stage, it is necessary to determine the boundary conditions, select the calculation parameters, material properties, selection of additional models for turbulence modeling; on the fourth, the solution of the problem is carried out. The influence of supply and discharge collectors was not taken into account. To carry out the calculations, a volumetric model of the object was generated, after which the calculated region was decomposed in the form of flat triangular elements for the substrate and in the form of tetrahedra for the flow region using boundary separation. The generated grid for the calculation areas had the following parameters:

for the area with a spacing of studs of 200 × 200 microns: mesh type - tetragonal; cell sizes:
min 3,793176 × 10−17 m, max 2,098848 × 10−11 m; number of cells - 17736744 pcs.;

for the area with a pitch of spikes of 400 × 400 microns, the type of mesh is tetragonal; cell sizes:
min 4,980473 × 10−17 m, max 3.267845 × 10−11 m; number of cells - 16999847 pcs.;

for the area with a pitch of spikes of 600 × 600 microns: mesh type - tetragonal; cell sizes:
min 3,569304 × 10−17 m, max 3,999074 × 10−11 m; number of cells - 16534874 pcs.

In the calculations, the geometric dimensions of the matrix were varied, namely, the center-to-center distance of the spikes was 200 × 200, 400 × 400, and 600 × 600 μkm. The flow range, inlet temperature, and heat input were the same for all substrate designs.

Results and Discussion

To conduct a computational experiment, the following initial data were selected. Water was chosen as the heat carrier. The mass flow rate of the cooler ranged from 0.0006 kg / s to 0.0100 kg / s. On the heating surface, boundary conditions of the second kind are specified, the specific heat flux from the heat-generating surface q = 100 Bm / cm^2. There is no heat flow through the side and top walls. Silicon thermal conductivity λ_s = 130 Bm / m · K; thermal conductivity of water λ_f = 130 Bm / m · K. At the inlet to the heat exchanger, boundary conditions of the first kind are set, and the temperature of the cooler was 20 ° C. As an example of calculation, Figures 4–

5 show the visualization of ANSYS calculations for a matrix of silicon whiskers with a step of 600 × 600 µkm.

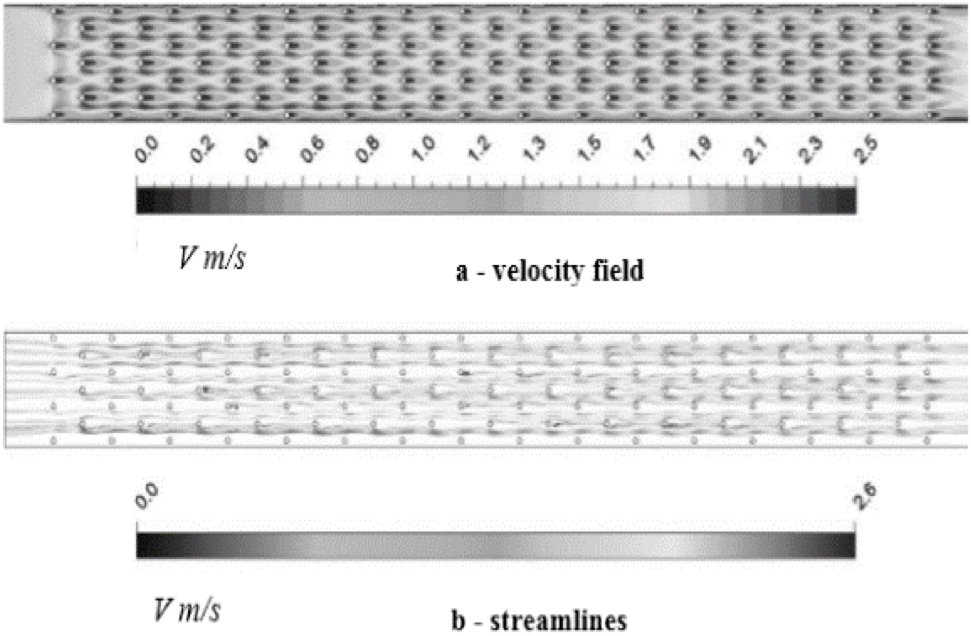


Fig. 4. The hydrodynamic flow pattern for a 600x600 µkm matrix

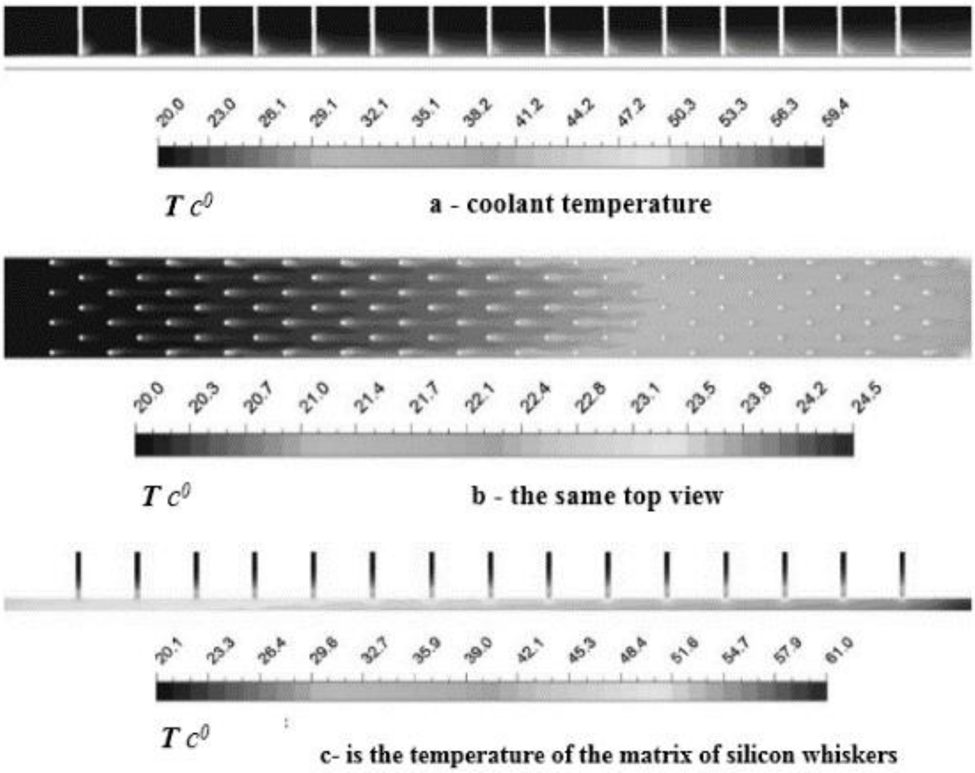


Fig. 5. Temperature distribution of the microchannel element (600 x 600 µkm)

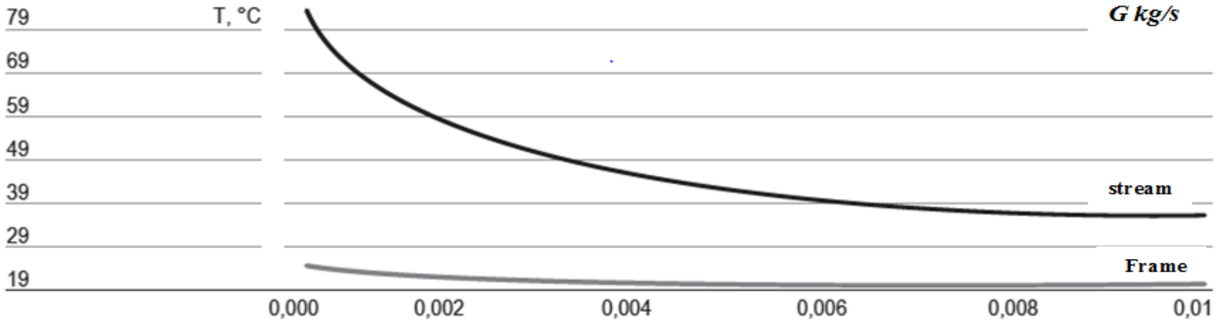


Fig. 6. The dependence of the temperature of the stream and the frame on the flow rate of the cooler (600 x 600) microns

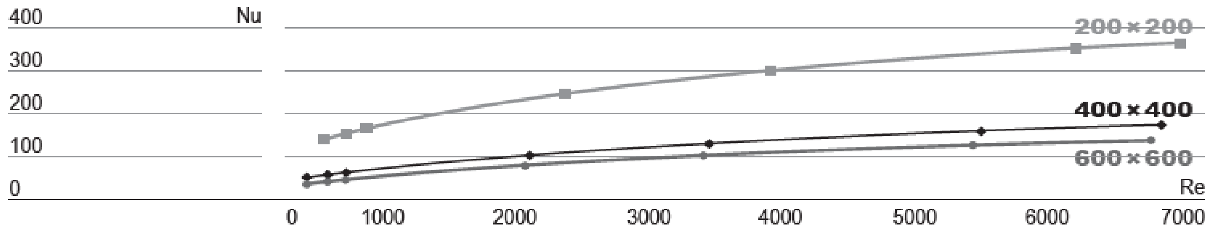


Fig. 7. A comparative graph of the dependence of the number Nu on the number Re

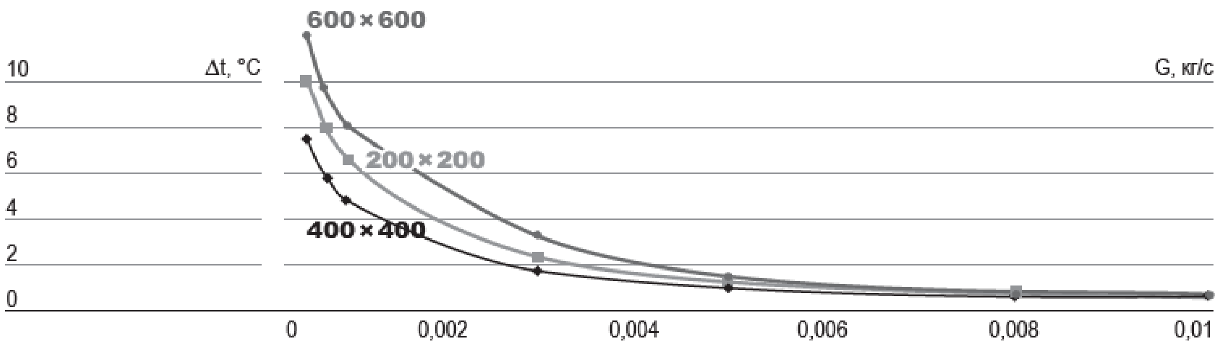


Fig. 8. A comparative graph of the temperature difference at the inlet and outlet of the matrix from the flow rate of the cooler

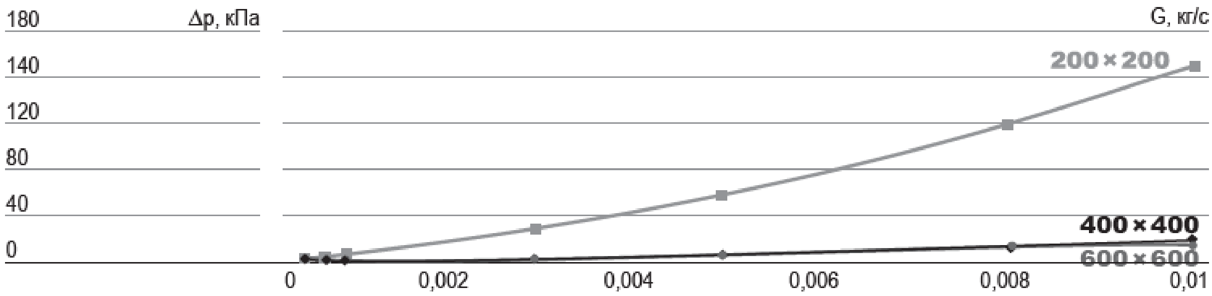


Fig. 9. Comparative graph of the differential pressure from the flow of the cooler

Figure 6 shows the temperature dependences of the matrix and cooler in the studied range of flow rates. Figures 7–9 show the dependences of the thermohydraulic characteristics depending on the flow rate of the coolant. The processing of the results of computational experiments is presented in the classical criterial form for the Nusselt numbers and pressure losses for the applied spectrum of the structure of the matrices used. Results processing results for:

- substrates with a center distance of studs of 200 × 200 μkm

$Nu = 12.035 \cdot Re^{0.3876}$, $\Delta p = 154.295 \cdot G^{1.4888}$

- substrates with a center distance of studs of 400 × 400 μkm

$Nu = 3.173 \cdot Re^{0.4515}$, $\Delta p = 24.841 \cdot G^{1.5422}$

- substrates with a center distance of studs of 600 × 600 μkm

$Nu = 1.9698 \cdot Re^{0.4833}$, $\Delta p = 28.645 \cdot G^{1.6057}$

Where

$$Nu = \alpha_f \frac{d}{\lambda_f}\ ; Re = \vartheta d/v$$

An analysis of the results of a computational experiment is Hall, that the flow of the coolant is symmetrical in relation to the walls and core of the flow. At flow rates of 0.0006–0.0030 kg / s, the flow of the coolant is laminar in nature. There are no flow swirls, as a whole, so and near local elements (spikes). At a coolant flow rate of more than 0.0030 kg / s, a pronounced transitional flow regime from laminar to turbulent with a local occurrence of separated flows is observed behind the spikes, which indicates the occurrence of stagnant zones, the value of which reaches the distance between the spikes only at high flow characteristics. There is a significant difference between temperature matrix frame of whisker silicon single crystals and cooler temperature. This indicates the correctness of applying the two-temperature approach to the construction of a mathematical model. From the data received it follows that with an increase in the flow rate of the cooler there is no increase in heat removal, because heating of the coolant occurs only in its lower part. A decrease in the pitch of the spikes also does not contribute to an increase in the cooling efficiency, and also significantly increases the pressure loss of the cooler through a matrix of whisker silicon single crystals.

Rational spike height of ≈ 0.6 mm and an intercenter distance between the spikes of 600 × 600 μkm were found, which allow the substrate to be cooled as much as possible with an insignificant increase in pressure loss on the coolant pumping. In the initial heat section X ≈ 0.2l (l is the length of the heat exchanger) the spike height can be reduced to a value from 0.2 to 0.3 mm, which will have a positive effect on hydraulic resistance, without reduction thermal indicators. The developed mathematical model allows one to evaluate the localization of the critical isotherm by the temperature field of the coolant and to draw a conclusion about a possible phase transition taking into account the given absolute pressure isotherm.

Conclusions

A computational experiment based on the ANSYS package made it possible to clarify the local hydrodynamic structure of the coolant flow and show that the influence of the frequency of the staggered arrangement of the spikes in the ranges of 0.2 × 0.2; 0.4 × 0.4 and 0.6 × 0.6 mm does not significantly affect the mixing of the coolant during its flow through the heat exchange element. The use of the ideal displacement model for the description of heat transfer in a heat exchange element with a regular matrix of threadlike silicon single crystals is confirmed. Analytical and numerical solutions show a significant temperature difference between the frame and the cooler, as well as a significant non-linear distribution temperature by the height of the spikes. When modeling microchannel heat exchange elements with a matrix of filiform silicon single crystals, these facts must be taken into account to exclude local overheating. The simulation results can be considered as the basis for an engineering calculation methodology and tools for choosing the design parameters of the designed heat transfer systems and identifying rational modes of their functioning.

References

Dzyubenko BV, Kuzma-Kichta YA, Leont'ev AI, Fedik II, Kholpanov LP. *Intensification of heat and mass transfer at the macro, micro – and nanoscale.* Moscow, FGUP «TsNIIATOMINFORM», 2008: 532.

Konovalov DA, Drozdov IG, Shmatov DP, Dakhin SV, Kozhukhov NN. Development and modeling of microchannel cooling systems. *Voronezh,* VSTU publ., 2013: 222.

Konovalov DA, Lazarenko IN, Drozdov IG, Shmatov DP. Modern approaches to the development and creation of elements of system of thermal protection of electronic components. *Voronezh,* VSTU publ., 2014; 10(1): 97–104.

Roco MC, Williams RS, Alivisatos P. *Nanotechnology research directions.* Dordrecht: Kluwer 2000.

Kear BH, Mago WE. Nanostructured Films and Coatings (NATO Science Series) ed GM Chow, IA Ovid'ko and T Tsakalakos 2000.

Gleiter H. Nanostructured materials: basic concepts and microstructure. *Acta materialia* 2000; 48(1): 1-29.

Komarneni S, Vaja RA, Lu GQ, Matsushita JI, Parker JC. Nanophase and nanocomposite materials IV. *MRS symposium proceedings* 2003: 703.

Komarneni S, Parker JC, Vaia RA, Lu GQ, Matsushita JI. Nanophase and Nanocomposite Materials IV held in Boston, Massachusetts 2001. Materials Research Society Warrendale PA 2002.

Berndt CC, Fischer T, Ovid'ko IA, Skandan G, Tsakalakos T. Nanomaterials for structural applications. *MRS symposium proceedings* 2003: 740.

Nebol'sin VA, Ievleva EV, Shmakova SS. On the relationship of the electronic structure and catalytic properties of metal catalysts for the growth of silicon whiskers. *Voronezh,* VSTU publ., 2012; 8(7.2): 37–42.

Bear J. Bachmat Y. *Introduction to Modeling of Transport Phenomena in Porous Media.* Dordrecht, Kluwer Academic Publishers 1991, 553.

Chen GM, Tso CP. A two-equation model for thermally developing forced convection in porous medium with viscous dissipation. *International journal of heat and mass transfer* 2011; 54(25-26): 5406-5414.

Belov IA, Isaev SA. *Modeling of turbulent flows.* Sankt-Peterburg, BGTU pub 2001: 106.

Garbaruk AV, Strelets M.Kh, Shur ML. Modeling turbulence in complex flows calculations: proc. manual. *Sankt-Peterburg.* Politechnic pub. 2012: 88.

Aftab MN, Zahra SQ, Bashir I, Ashiq MN, Iqbal F. Lanthanum zirconate nanoparticles, used in blades of gas turbine engines, can disturb behavior, leukocyte count and antioxidant metabolites of vital organs of albino mice. *NeuroQuantology* 2019; 17(4): 60-68. https://doi.org/10.14704/nq.2019.17.4.2106

Pandarakalam JP. Scientific evidences for discarnate existence and a search for the sacred. *NeuroQuantology* 2019; 17(4): 45-59.