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Study of fluid flow in a microchannel with an array of pins taking into account heat transfer

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Numerical methods are used to study the effect of changing the internal configuration of microchannels on heat and mass transfer. The numerical models were validated by comparing them with the results of laboratory experiments using microfluidic chips. Graphs are presented for the dependence of the average temperature and volumetric flow rate on the pressure drop across the channel cross-section, velocity distributions, and temperature fields within the channels. The study demonstrated that the identified effects of changing the arrangement of columns within the microchannel and the fluid injection mode on the hydrodynamic and thermophysical parameters of the system can be used in the design of microheat sinks..

Keywords: microheat sink, silicon microchannel, heat and mass transfer, microfluidics.

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Microscopic cooling systems, such as microchannel heat sinks, are becoming increasingly important in modern heat exchange technologies. These devices provide highly efficient heat dissipation and maintain stable temperature levels in microelectromechanical systems, integrated circuits, and other microdevices subject to short-term high thermal loads. Their applications include electronics cooling [1], thermal management in aerospace engineering, and biological and chemical research [2].

The results of theoretical and experimental studies aimed at enhancing heat and mass transfer at the macro-, micro-, and nanolevel in single- and two-phase media have been presented in [3]. An important aspect in the development of efficient microheat sinks is the selection of optimum internal geometry of microchannels. Since most studies are focused on microchannels with characteristic dimensions of hundreds of micrometers, a thorough understanding of the features of heat and mass transfer in microfluidic heat sinks with characteristic hydraulic diameters of tens of micrometers is needed in order to determine the optimum conditions for efficient heat transfer as functions of the microchannel configuration. This is what lends significance and novelty to the present study.

The influence of changes in the internal configuration of microchannels with a rectangular cross section on the characteristics of heat and mass transfer are examined numerically. The flow of cold fluid in a microchannel with a distributed array of columns (pins) under the influence of a constant pressure drop is considered. The bottom wall of the channel (plate that secures the columns) and the columns are maintained at a constant temperature. The upper wall of the channel (another plate that secures the columns) is not heated. Column diameter d is $110\,\mu$m, the height of the microchannel and the columns is $25\,\mu$m, and the length and width of a microchannel element are 2.5 mm. The columns are arranged uniformly (see the insets in Fig. 1). Distances Δ between the columns (see the insets in Fig. 1) vary from 40 to $50\,\mu$m.

The Ansys Fluent software system for finite element analysis was used to model numerically the fluid flow in the microchannel with obstacles with account for heat transfer. The thermophysical properties of water (working fluid) and silicon (microchannel material) were set in modeling. The data were verified by comparison with the analytical solution for a flat microchannel without obstacles in the isothermal case and with account for heat transfer at the channel walls. In addition, a series of hydrodynamic experiments were carried out to validate the obtained numerical data. The corresponding models were designed for these experiments, and microfluidic chips were fabricated by soft lithography from the RT 601 A/B (ELASTOSIL) optically transparent polydimethylsiloxane material (Fig. 1). The experimental setup for microfluidic research (see Fig. 1) was assembled and tested. Fluid flows in the chip were induced by pressure controller VSO-BT *1*. The volumetric flow rate was measured by Elveflow sensor *2*. The microfluidic chip was placed on the stage of Olympus IX-71 optical microscope *3* coupled with Photron FASTCAM SA5 high-speed video camera *4*. The setup used and the experimental procedure were discussed in more detail in our earlier studies [4,5].

A series of experiments were carried out for two structures (Fig. 1) at a constant pressure drop of 4–10 kPa (its magnitude was varied in 1 kPa steps). Measurements were performed with the model fully saturated with fluid after pumping several pore volumes. At each pressure drop, the volumetric flow rate was recorded after a steady level had been established; water was the working fluid. To visualize the flow, polymer particles with a diameter of $1\,\mu$m were added to the fluid. The methods for velocity

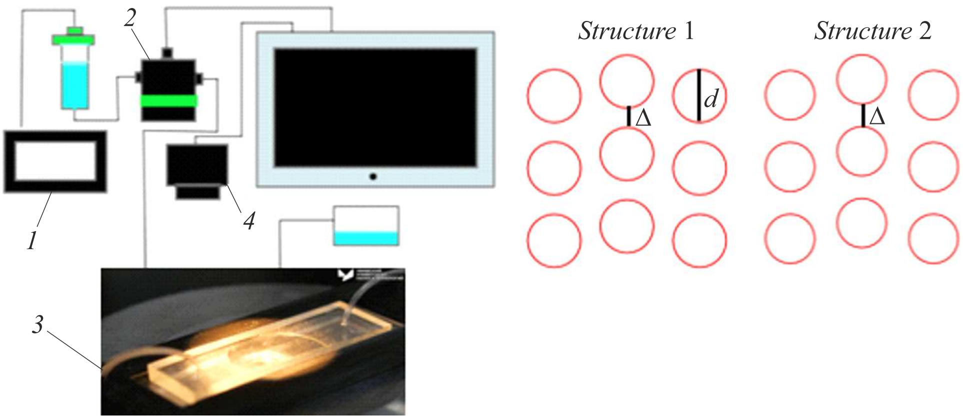

Figure 1. Schematic diagram of the experimental setup with microfluidic chips. The insets show different arrangements of columns in the microchannel.

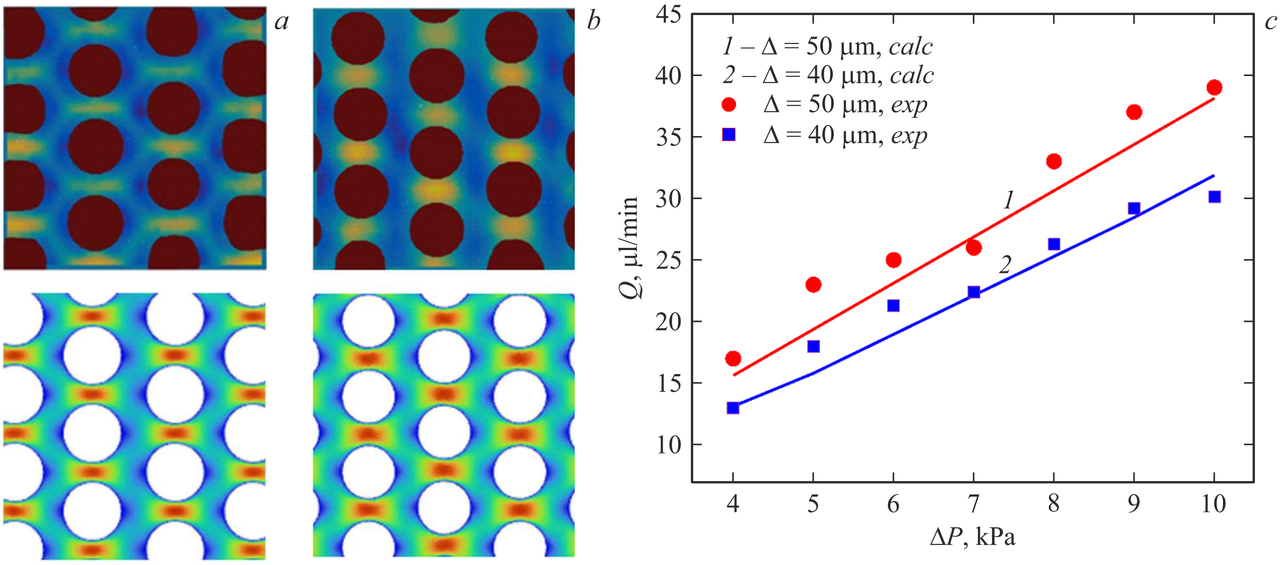

Figure 2. Comparison of experimental (*exp*) and numerical (*calc*) data for fluid flow in microchannels with different internal configurations: velocity modulus fields (*a* — $\Delta = 40\,\mu$m; *b* — $\Delta = 50\,\mu$m) and volumetric flow rate fields for $\Delta = 40$ and $50\,\mu$m (*c*).

determination through analysis of the dynamics of tracer particles were used to plot velocity fields in the PIVlab package at the same volumetric flow rate of $1\,\mu$l/min.

Figures 2, *a*, *b* present a qualitative comparison of velocity fields for the structures with $\Delta = 40$ and $50\,\mu$m obtained experimentally (top row) and numerically (bottom row). The fluid flows from left to right. The experimentally (points) and numerically (lines) obtained volumetric flow rates were also compared for both chip configurations (Fig. 2, *c*). It can be seen from Fig. 2 that the results match closely.

A multiparameter analysis of fluid flow in the microchannel with a distributed array of cylindrical pins was performed in the present study with account for heat transfer. At constant temperatures $T = 323$ K of the lower wall of the channel and pins and $T = 300$ K of the supplied fluid, the change in distribution of the temperature field and the velocity of fluid was examined within the range of pressure differences ΔP from 1.25 to 125 kPa. Figure 3 shows the temperature (*a*) and velocity (*b*) fields in the middle plane of the microchannel for a uniform arrangement of columns spaced $40\,\mu$m apart and pressure drops of 1.25 and 125 kPa.

With a pressure drop smaller than 20 kPa, the fluid is heated to the maximum temperature at the very start of the structure before the contact with columns. As ΔP increases, the region of complete heating of the fluid shrinks in size, but the power needed to pump the cooling fluid increases. The trace with virtually zero velocity behind the columns at the exit of the microchannel also has different lengths at different pressure drop magnitudes. The results for the microchannel configuration with a column spacing of $50\,\mu$m are similar. We have already examined the hydrodynamic flow characteristics in similar structures using a

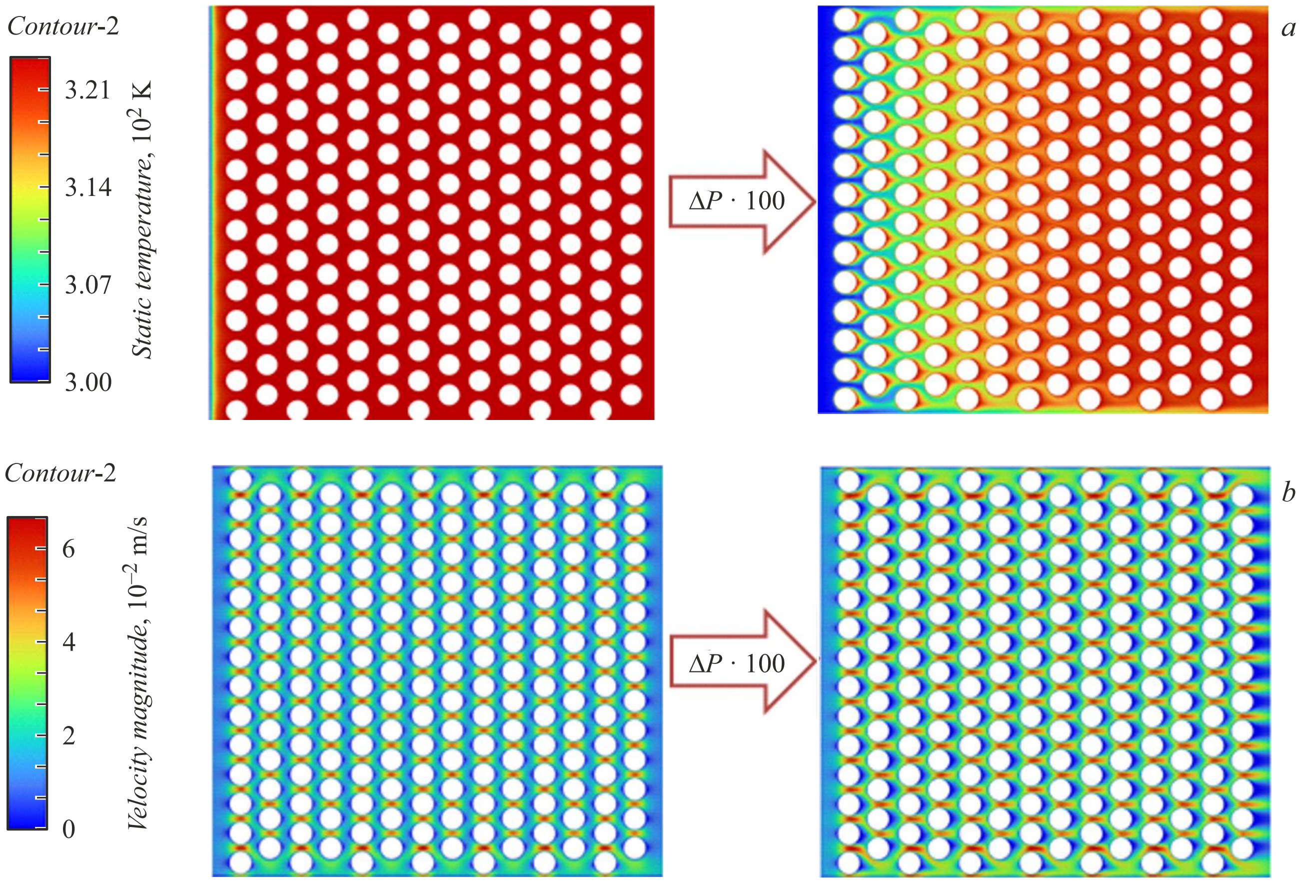

Figure 3. Changes in distribution of the temperature field (*a*) and the velocity modulus (*b*) in the structure with distances between pins $\Delta = 40\,\mu$m in the middle plane of the microchannel corresponding to a 100-fold change in pressure drop (from 1.25 to 125 kPa).

numerical approach based on the boundary element method accelerated by the fast multipole method implemented on heterogeneous architectures [4,6], but heat transfer was neglected in this study, and the range of pressure drop magnitudes was narrower. The velocity distribution for smaller pressure differences (Fig. 2) is qualitatively similar to the results obtained earlier without heat transfer [4,6].

The dependence of the average temperature on pressure drop magnitude was plotted for two structures (Fig. 4, *a*). The obtained data make it clear that with a small pressure drop, the fluid in the channel with a larger distance between pins is heated to a higher temperature; however, as the pressure difference increases, the nature of the distribution changes. In addition, the volume of fluid pumped through the structure is an important aspect in choosing the optimum geometry of a microfluidic heat sink. The dependence of the volumetric flow rate of fluid on pressure drop magnitude was plotted (Fig. 4, *b*) in order to assess the change in throughput capacity of sections of the considered microchannels. It is evident that the structures have almost the same throughput at small pressure differences. With an increase in ΔP, the hydrodynamic resistance of the microchannel with $\Delta = 40\,\mu$m increases significantly. It should be noted that the relation between flow rate and pressure drop values is nonlinear. Thus, the obtained integral curves suggest that it is possible to adjust the conditions for optimum fluid heating with account for the internal configuration of the microchannel.

A numerical and experimental study of fluid flow in a microchannel with an array of pins was performed with heat transfer taken into account. Special attention was paid to the influence of the internal microchannel configuration (specifically, the arrangement of pins) on the heat and mass transfer characteristics. Three-dimensional modeling in Ansys Fluent and a series of experiments with microfluidic chips allowed us to obtain reliable data validated by comparing the numerical results with experimental ones. It was found that changes in the distance between columns (40 and 50 μm) and the pressure drop magnitude (from 1.25 to 125 kPa) have a significant influence on the distribution of fluid velocity and temperature.

The revealed specifics of the influence of changes in the arrangement of columns inside the microchannel and the fluid injection mode on the hydrodynamic and thermophysical parameters of the system may aid the design of microheat sinks. In the future, the study is planned to be expanded to include non-stationary modes; a constant heat flow; variable parameters, such as wall roughness; and

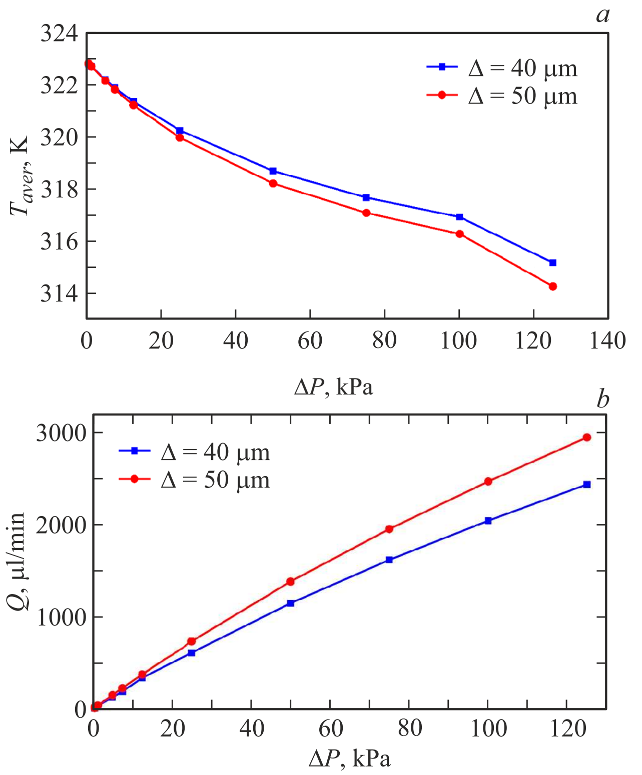

Figure 4. Dependence of the average temperature (*a*) and the volumetric fluid flow rate (*b*) in the microchannel on the pressure drop.

additional pin arrangements. This should help deepen our understanding of heat transfer processes in microchannels and optimize the designs of microheat sinks.

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Conflict of interest

The authors declare that they have no conflict of interest.

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