Optimal design of subcooled triangular microchannel heat sink exchangers with variable heat loads for high performance cooling

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Abstract. Deionized water at a temperature of 25 °C was used as the cooling fluid and aluminium as the heat sink material in the geometric optimization and parameter modelling of subcooled flow boiling in horizontal equilateral triangular microchannel heat sinks. The thermal resistances of the microchannels were minimized subject to fixed volume constraints of the heat sinks and microchannels. A computational fluid dynamics (CFD) ANSYS code used for both the simulations and the optimizations was validated by the available experimental data in the literature and the agreement was good. Fixed heat fluxes between 100 and 500 W/cm$^2$ and velocities between 0.1 and 7.0 m/s were used in the study. Despite the relatively high heat fluxes in this study, the base temperatures of the optimal microchannel heat sinks were within the acceptable operating range for modern electronics. The pumping power requirements for the optimal microchannels are low, indicating that they can be used in the cooling of electronic devices.

1. Introduction
Subcooled flow boiling occurs in the microchannel when the temperature of the bulk fluid remains below the saturation temperature and the inner wall temperature of the microchannel is above saturation for nucleation of bubbles. Thermal management of electronic systems is important for their efficient operations hence cooling of electronic and power devices can be achieved by supplying the coolant to the microchannels in subcooled conditions [1-3].

In the optimization procedure, a fixed volume constraint was applied to the microchannel heat sinks to obtain global optima with respect to the channel hydraulic diameter and axial flow length for the single-phase and subcooled (two-phase) regimes. Computation of CHF data was done for optimal microchannel heat sinks using a non-equilibrium boiling model [4] of wall heat flux partitioning (RPI) model in the CFD code. The aim was to show the upper operating limits of the selected optimal microchannel heat sinks.

2. Methodology

2.1. Description of the physical model
Figure 1(a) shows a heat sink with many microchannels; $H_{ch}$, $W_{ch}$ and $L$ are the height, width and axial length of the microchannel. The microchannels were arranged symmetrically in the heat sink and this advantage was taken to select any unit cell microchannel heat sink as shown in Figure 1(b) so as to save computational time.
Figure 1. Microchannel heat sink and computational domain.

3. Model validation
The wall heat flux partitioning (RPI) model was compared with the work of Qu and Mudawar [5] for validation of the CFD code. The numerical results were compared with the experimental data for outlet subcooling at boiling incipience for various inlet velocities with inlet temperature of 30 °C. The comparison of numerical results with experimental data is shown in Figure 2.
**Figure 2.** Comparison of numerical results with experimental data of outlet subcooling at boiling incipience [5].

**4. Optimization results and discussion**

4.1 **Optimal geometric and flow parameters**

Approximate values of geometric parameters of the unit cell microchannel heat sink used for the optimization are given in Table 1.

| Height of sink | Width of sink | Height of channel | Width of channel | Length of sink/channel |
|---------------|--------------|------------------|-----------------|-----------------------|
| $H_s$         | $W_s$        | $H_{ch}$         | $W_{ch}$        | $L_s$                 |
| 588.96        | 588.96       | 468.78           | 541.30          | 9750                  |

In this study, numerical analyses and optimizations were done to obtain microchannel heat sinks that performed optimally at high heat fluxes not commonly reported for similar geometries in the open literature. Similar explanation for rectangular microchannel and the geometric parameters can be found in Ariyo and Bello-Ochende [6].

Optimal geometric and flow parameters for subcooled boiling are shown in Figure 3 for heat fluxes between 100 W/cm$^2$ and 500 W/cm$^2$. Thermal resistances at 400 and 500 W/cm$^2$ were obtained at high velocities because of high base temperatures recorded at low velocities. It can be observed from Figure 3 that as Reynolds number increases, thermal resistance decreases which is consistent with the trend in the open literature. The number of points on each of the curves is the same as the number of optimal microchannel heat sinks. The corresponding base temperatures are shown in Figure 4. Base temperatures increase as heat flux increases which is expected. The pumping power requirements for the microchannel heat sinks are shown in Figure 5. The relatively high pumping power requirements at 400 and 500 W/cm$^2$ were as a result of high pressure drops because of high velocities used in the simulation and optimization study.

**Figure 3.** Thermal resistances of optimal microchannel heat sinks.
4.2. Critical heat flux study

Figure 6 shows the boiling curves for the selected optimal microchannel heat sinks at different velocities. Optimal microchannel heat sinks at velocities between 2.0-2.5 and 3.0-3.5 m/s and 100 W/cm² were used for the study. Non-equilibrium subcooled model was used for the simulations up to critical heat flux. Wall superheat was calculated as the difference between the wall temperature at the exit and saturation temperature at 101325 N/m². The critical heat flux corresponding to optimal velocity in 3.0-3.5 m/s is 900 W/cm². Critical heat flux increases as velocity increases as shown in the figure. Critical heat fluxes for other velocities can be obtained at the last stable values on their curves before the excursion of high temperatures.
Figure 6. Critical heat fluxes of microchannel heat sinks with optimal performance at 100 W/cm$^2$.

5. Conclusions
The maximum temperatures obtained from the optimization study for optimal microchannel heat sinks are well below the maximum operating temperature of 85-90 °C (358.15-363.15K) for modern electronic chips [7] despite the high heat fluxes, which is an indication that optimal microchannel heat sinks in subcooled flow boiling are an efficient option in the cooling of microelectronic devices.

The velocities and pumping power requirements for the optimal microchannel heat sinks in subcooled flow boiling are considered adequate for practical applications as shown in Figure 5. The best performances for the microchannel heat sinks are shown in Figures 3-5. Simulations were done up to critical heat flux for the selected microchannel heat sinks to distinguish between optimal performance and maximum limit of operation as shown in Figure 6. This study could be extended to other microchannel configurations.

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