A comparative analysis of innovative microchannel heat sinks for electronic cooling☆

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ARTICLE INFO
Available online 10 May 2016
Keywords:
Double-layer microchannel
Multi-layer microchannel
Thermal resistance
Pumping power

ABSTRACT
In this work, a comparative analysis of innovative microchannel heat sinks such as two-layered and multi-layered microchannel heat sinks (MCHS), or thin films within flexible complex seals and cooling augmentation using microchannels with rotatable separating plates, is presented. A compilation of the numbers of layers, main characteristics, setups, advantages and disadvantages, thermal resistance, pumping power in double-layer (DL-MCHS) and multi-layer MCHS (ML-MCHS) is presented. In addition, the thermal resistance is analyzed in order to present a comparison between the single-layer MCHS (SL-MCHS) and multi-layer microchannels. The results of comparison indicates that double-layer and multi-layer MCHS have lower thermal resistance and require smaller pumping power and they resolve the high streamwise temperature rise problem of SL-MCHS.

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1. Introduction
The heat removal issue has become increasingly important in electronics applications. In this work, innovative microchannels are investigated. Microchannels were first introduced by Tuckerman and Pease [1]. Microchannel heat sinks maximize the surface area, minimize the thermal resistance, and thus increase the heat transfer from the component into the surroundings while offering a compact cooling system.

The large majority of microchannels studies in the literature are based on single-layer microchannels. The disadvantage of SL-MCHS is the relatively high streamwise temperature rise which can have an adverse influence on the equipment. This high streamwise temperature rise is caused by heat released by the equipment and carried out by a relatively small amount of coolant, which results in a high streamwise temperature. Hence, the undesirable high temperature rise causes larger thermal stress, for example, in chips and electronic packages due to the coefficient of thermal expansion mismatch among different materials thus undermining device reliability. In addition, the adverse effects of many electrical parameters are caused by a sharp temperature rise. One way to reduce the undesired temperature rise in single-layered microchannels is to increase the pumping power, which can generate more noise and require bulkier packaging. This is certainly undesirable.

However, the two-layered microchannel, first established by Vafai and Zhu [2,4], as well as multi-layered microchannels also first established by Vafai and Zhu [3], reduce the undesired temperature gradient in the streamwise direction. The design concept is based on a two-fold microchannel structure, one atop another. For such an arrangement, streamwise temperature rise for the coolant and the substrate in each layer are remunerated through conduction between the two layers. Since the temperature gradient is much smaller than the SL-MCHS, the required pressure drop can be substantially smaller than SL-MCHS, which can require a significantly smaller pumping power.

Following the works of Vafai and Zhu [2–4], extensive investigations have been conducted regarding the two- and multi-layer microchannel heat sinks in order to optimize the configurations and improve the thermal performance for various applications. In this work, studies on ML-MCHS are investigated and synthesized. These are comprehensively summarized in Table 2. In this work, ML-MCHS main characteristics, icon diagram, advantages and disadvantages, thermal resistance and pumping power are characterized. Also the comparisons of thermal resistance and pumping power between the SL-MCHS and ML-MCHS are investigated.

2. Analysis

2.1. Thermal resistance

The overall thermal resistance, which is defined as:

$$Q = \frac{\Delta T}{R_{th}} = qA_{sub}$$  \hspace{1cm} (1)

$$R_{th} = \frac{\Delta T}{qA_{sub}}$$  \hspace{1cm} (2)
The SL-MCHS is obtained by calculating the average value among all the SL-MCHS cases. The maximum and the minimum average values are used to find the average value. The final average unit overall thermal resistance for the SL-MCHS is obtained by calculating the average value among all the average values we have calculated.

The average value of the overall thermal resistance can be calculated simply by either:

\[
R_{ave} = \frac{R_{\text{max}} + R_{\text{min}}}{2}
\]

or

\[
R_{ave} = \frac{R_1 + R_2 + \ldots + R_n}{n}
\]

2.2. Pumping power

The pumping power is defined as

\[
\Omega = Q \Delta p = u_\text{in} A_c \Delta p N
\]

where \( Q \) is the volumetric flow rate, \( \Delta p \) the pressure drop, \( A_c \) the channel cross-sectional area and \( N \) is the number of channels.

In order to unify the pumping power, the unit length pumping power is calculated.

\[
\Omega_{\text{unit}} = \frac{\Omega}{L}
\]

where \( L \) is the total length of microchannel heat sinks.

The same way with thermal resistance is utilized in order to make a comparison.

The average value of the pumping power can be calculated simply by either:

\[
\Omega_{\text{ave}} = \frac{\Omega_{\text{max}} + \Omega_{\text{min}}}{2}
\]

or

\[
\Omega_{\text{ave}} = \frac{\Omega_1 + \Omega_2 + \ldots + \Omega_n}{n}
\]

3. Results and discussion

Table 1 shows the pertinent unit overall thermal resistance and pumping power in single-layer microchannel heat sinks in the literature and their average value.

Table 2 presents the synthesis of a wide range of the innovative design heat sink equipment for cooling applications. Also, included is an innovative design for the control of exit flow and thermal conditions using two-layered thin films by flexible complex seals and cooling augmentation using microchannels with rotatable separating plates, which were introduced by Khaled and Vafai [7,20]. Their main characteristics, icon diagram, advantages and disadvantages, thermal resistance and pumping power attributes are all illustrated.

The comparison between the SL-MCHS and ML-MCHS is presented in Table 3. In general, ML-MCHS improves the thermal performance of heat sinks by reducing the overall thermal resistance, and decreases the required pumping power. It should be noted that ML-MCHS reduces the thermal resistance, anywhere from 6.3% up to 97.9% and also the pumping power, anywhere from 26.1% up to 99.9%. It should be noticed that the few blanks in these three tables are because the values have not been provided in the corresponding references. In addition, regarding reference [17], nanopillars were added within the structure, resulting an increase in the thermal resistance. Also with respect to reference [21], due to different operating conditions, the pumping power increases.
Table 1
Thermal resistance and pumping power of single-layer microchannel.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Number of layers</th>
<th>Main characteristics</th>
<th>Icon diagram</th>
<th>Advantages and disadvantages</th>
<th>Thermal resistance $R$ ($\degree C \cdot m^2/W$)</th>
<th>Pumping power $\Omega$ (W/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Tuckerman, David B., and R. F. W. Pease. “High-performance heat sinking for VLSI.” <em>Electron Device Letters, IEEE</em> 2.5 (1981): 126–129.</td>
<td>1</td>
<td>1. Water in silicon and single layer  2. $A_{sub} = 1 cm \times 1 cm$; $Wch = 50 \mu m$; $Wfin = 50 \mu m$; $L = 302 \mu m$</td>
<td>![Image of icon diagram]</td>
<td>Advantages: High convective heat transfer and low thermal resistance Disadvantages: High streamwise temperature rise, which causes thermal stress that will undermine device reliability and even brings about electrical-thermal unstabilities and thermal breakdown.</td>
<td>0.09</td>
<td>1.84</td>
</tr>
</tbody>
</table>

References

<table>
<thead>
<tr>
<th>Reference</th>
<th>Thermal resistance $R$ ($\degree C \cdot m^2/W$)</th>
<th>Average value of thermal resistance</th>
<th>Total average value of thermal resistance</th>
<th>Pumping power $\Omega$ (W/cm)</th>
<th>Average value of pumping power $\Omega$ (W/cm)</th>
<th>Total average value of pumping power $\Omega$ (W/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[38] Harms, Todd M., Michael J. Kazmierczak, and Frank M. Gerner. “Developing convective heat transfer in deep rectangular microchannels.” <em>International Journal of Heat and Fluid Flow</em> 20.2 (1999): 149–157.</td>
<td>0.84</td>
<td>0.79</td>
<td>0.69</td>
<td>0.61</td>
<td>0.52</td>
<td>0.45</td>
</tr>
<tr>
<td>[40] Kishimoto, Tohru, and Takaaki Ohnishi. “VLSI packaging technique using liquid-cooled channels.” <em>Components, Hybrids, and Manufacturing Technology, IEEE Transactions on</em> 9.4 (1986): 328–335.</td>
<td>0.176–0.316</td>
<td>0.246</td>
<td></td>
<td>0.038</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td>[41] Phillips, Richard J., Leon R. Glickman, and Ralph Larson. “Forced-convection, liquid-cooled, microchannel heat sinks.” <em>U.S. Patent No. 4,894,709.</em> 16 Jan. 1990.</td>
<td>0.236</td>
<td>0.33</td>
<td></td>
<td>0.10</td>
<td>0.10</td>
<td>0.64</td>
</tr>
</tbody>
</table>

(Continued on next page)
Table 1 (continued)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
<th>Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[42] Mahalingam, Mali.</td>
<td>&quot;Thermal management in semiconductor device packaging.&quot; Proceedings of the IEEE 73.9 (1985): 1396-1404.</td>
<td></td>
<td>0.5 0.75 (water as coolant) 0.36</td>
</tr>
<tr>
<td>[43] Samalam, Vijay K.</td>
<td>&quot;Convective heat transfer in microchannels.&quot; Journal of Electronic Materials 18.5 (1989): 611-617.</td>
<td></td>
<td>0.07-0.25 (low aspect ratio) 0.055-0.065 (high aspect ratio) 0.11</td>
</tr>
<tr>
<td>[44] Copeland, Darol, Masoud Behnia, and Wataru Nakayama.</td>
<td>&quot;Manifold microchannel heat sinks: isothermal analysis.&quot; Components, Packaging, and Manufacturing Technology, Part A. IEEE Transactions on 20.2 (1997): 96-102.</td>
<td></td>
<td>0.42 0.25 0.48 0.27 0.42 0.25 0.47 0.27 0.35</td>
</tr>
<tr>
<td>[45] Ryu, J. H., D. H. Choi, and S. J. Kim.</td>
<td>&quot;Three-dimensional numerical optimization of a manifold microchannel heat sink.&quot; International Journal of Heat and Mass Transfer 46.9 (2003): 1553-1562.</td>
<td></td>
<td>0.06-0.9 0.031-0.039 0.26 2.56 2.56</td>
</tr>
<tr>
<td>[47] Chein, Reiyu, and Janghwa Chen.</td>
<td>&quot;Numerical study of the inlet/outlet arrangement effect on microchannel heat sink performance.&quot; International Journal of Thermal Sciences 48.8 (2009): 1627-1638.</td>
<td></td>
<td>0.826-1.228 1.027 0.09 0.05 0.029 0.08 0.045 0.026 0.083 0.047 0.028 0.106 0.056 0.031 0.103 0.056 0.031 0.056</td>
</tr>
<tr>
<td>[49] Li, Ji, and G. P. Peterson.</td>
<td>&quot;Geometric optimization of a micro heat sink with liquid flow.&quot; Components and Packaging Technologies, IEEE Transactions on 29.1 (2006): 143-154.</td>
<td></td>
<td>0.156 0.223 0.19 0.05 0.05</td>
</tr>
<tr>
<td>Reference</td>
<td>Paper Title and Authors</td>
<td>Equation(s)</td>
<td>Values</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------------</td>
<td>-------------</td>
<td>--------</td>
</tr>
<tr>
<td>[53] Chen, Reiyu, and Jason Chuang.</td>
<td>Experimental microchannel heat sink performance studies using nanofluids.</td>
<td>$0.16-1.71$</td>
<td>$1.435$</td>
</tr>
<tr>
<td>[54] Kawano, Koichiro, et al.</td>
<td>Development of microchannel heat exchanger.</td>
<td>$0.116$</td>
<td>$0.105$</td>
</tr>
<tr>
<td>[55] Chein, Reiyu, and Jason Chuang.</td>
<td>Experimental microchannel heat sink performance studies using nanofluids.</td>
<td>$0.1$</td>
<td>$0.1$</td>
</tr>
<tr>
<td>[56] Zhang, Lian, et al.</td>
<td>Measurements and modeling of two-phase flow in microchannels with nearly constant heat flux boundary conditions.</td>
<td>$1.216$</td>
<td>$1.216$</td>
</tr>
</tbody>
</table>

Table 1 (continued)
Table 2
A comparative analysis of innovative microchannel heat sinks for electronic cooling.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Number of layers</th>
<th>Main characteristics</th>
<th>Icon diagram</th>
<th>Advantages and disadvantages</th>
<th>Thermal Resistance (°C m²/W)</th>
<th>Pumping power (W/cm²)</th>
</tr>
</thead>
</table>
Table 2 (continued)


9

1. Microfluidic microchannel: two layers of microchannels, and two layers of manifold, and one fluid connection layer. All these made of silicon.
2. Counter-flow and parallel-flow carried on the same structure.
3. Allow different flow rate flowing through the upper and bottom layer.
4. \( \Delta h_{\text{u}} = 0.11 \text{ mm}, \Delta h_{\text{b}} = 0.056 \text{ mm} \).
5. \( h_{\text{u}} = 0.053 \text{ mm}, h_{\text{b}} = 0.061 \text{ mm} \).
6. \( h_{\text{u}} = 0.023 \text{ mm}, h_{\text{b}} = 0.05 \text{ mm}, h_{\text{j}} = 0.05 \text{ mm} \).
7. Adverse effect:
   1. Significantly reduce the streamwise temperature rise on the base surface.
   2. Substantially reduce the required pressure drop and pumping power.
   3. High heat flux capability.
   4. Significantly reduce the flow rate.
   5. Improve the temperature uniformity with counter-flow layout.
   6. Reduce the peak temperature with parallel-flow arrangement.
   7. Reduce the total and on-chip thermal resistance to adjusting the flow proportion for counter-flow layout.
   8. Reduce the on-chip resistance by increasing flow passing the bottom layer for a fixed flow-rate of parallel flow.

0.09


2

1. Double-layer microchannel with counter flow.
2. \( H_{\text{u}} = 3.65 \text{ mm}, H_{\text{b}} = 3.66 \text{ mm} \).
3. \( \rho_{\text{u}} = 8.12 \text{ kg/m}^3, \rho_{\text{b}} = 15.74 \text{ kg/m}^3 \).
4. \( \rho_{\text{j}} = 713.09 \text{ kg/m}^3, \rho_{\text{s}} = 2692.89 \text{ kg/m}^3 \).

Adverse effect:
1. Significantly reduce the streamwise temperature rise on the base surface.
2. Substantially reduce the required pressure drop and pumping power.
3. High heat flux capability.
4. Significantly reduce the flow rate.
5. Reduce the thermal resistance.

1.064


1.5

2. \( L = 0.3 \text{ m, } W = 0.17 \text{ m, } T = 0.2 \text{ m} \).
3. \( h_{\text{co}} = 0.5 \text{ m, } h_{\text{cu}} = 0.3 \text{ m} \).
4. \( h_{\text{u}} = 0.015 \text{ m, } h_{\text{j}} = 0.056 \text{ m} \).
5. \( h_{\text{b}} = 0.053 \text{ m, } h_{\text{b}} = 0.061 \text{ m} \).
6. \( h_{\text{cu}} = 0.023 \text{ m, } h_{\text{cu}} = 0.05 \text{ m}, h_{\text{j}} = 0.05 \text{ m} \).

Adverse effect:
1. Significantly reduce the streamwise temperature rise on the base surface.
2. Substantially reduce the required pressure drop and pumping power.
3. High heat flux capability.
4. Significantly reduce the flow rate.
5. Distribute the coolant uniformly to microchannels with the help of multilayer.
6. Improve the temperature uniformity with counter-flow layout.
7. Reduce the peak temperature with parallel-flow arrangement.
8. Reduce the total and on-chip thermal resistance to adjusting the flow proportion for counter-flow layout.
9. Reduce the on-chip resistance by increasing flow passing the bottom layer for a fixed flow-rate of parallel flow.
10. Minimize localizing heating effects with the optimized heat source locations.

0.3


2

1. Microfluidic microchannel: two layers of microchannels, and two layers of manifold, and one fluid connection layer. All these made of silicon.
2. Counter-flow and parallel-flow carried on the same structure.
3. Allow different flow rate flowing through the upper and bottom layer.
4. \( \Delta h_{\text{u}} = 0.11 \text{ mm}, \Delta h_{\text{b}} = 0.056 \text{ mm} \).
5. \( h_{\text{u}} = 0.053 \text{ mm}, h_{\text{b}} = 0.061 \text{ mm} \).
6. \( h_{\text{u}} = 0.023 \text{ mm}, h_{\text{b}} = 0.05 \text{ mm}, h_{\text{j}} = 0.05 \text{ mm} \).

Adverse effect:
1. Significantly reduce the streamwise temperature rise on the base surface.
2. Substantially reduce the required pressure drop and pumping power.
3. High heat flux capability.
4. Significantly reduce the flow rate.

0.09


1.5

1. Water in silicon
2. \( A_{\text{j}} = 1 \text{ cm}^2, L = 365 \text{ mm}, h_{\text{u}} = 5 \text{ mm}, q = 200 \text{ W/cm}^2 \).

Adverse effect:
1. Significantly reduce the streamwise temperature rise on the base surface.
2. Substantially reduce the required pressure drop and pumping power.
3. High heat flux capability.
4. Significantly reduce the flow rate.

0.002


2

1. An in-silicon stacked two-layer microchannel with enhanced mixing passive microstructure.
2. The delta wing and V-shape rib can provide the best thermal performance.
3. \( h_{\text{i}} = 0.03 \text{ mm}, W_{\text{i}} = 0.1 \text{ m} \).
4. \( h_{\text{u}} = 100 \text{ mm}, h_{\text{j}} = 50 \text{ mm} \).
5. \( v_{\text{i}} = 30 \text{ mm}, v_{\text{u}} = 10,20,30 \text{ mm} \).
6. \( h_{\text{j}} = 14.8 \text{ mm} \).

Adverse effect:
1. Significantly reduce the streamwise temperature rise on the base surface.
2. Substantially reduce the required pressure drop and pumping power.
3. High heat flux capability.
4. Significantly reduce the flow rate.
5. Enhance the thermal performance and reduce the necessary pumping power with the placement of passive microstructures.
6. Simple structure, easy manufacturing by micro machining method, low cost and higher reliability for passive microstructures.
7. Enhance heat transfer by increasing the secondary flow motion.
8. Improve mixing mechanism of cold and hot fluid in the present configuration.

0.1


3

1. Silicon nanowires based multilayer water-cooled heat sink.
2. Small diameter (3-5 μm) and large lengths (-100 mm).
3. \( \text{v}_{\text{in}} = 1 \text{ mm/s}, \text{v}_{\text{in}} = 10 \text{ mm/s}, \text{v}_{\text{in}} = 50 \text{ mm/s}, \text{v}_{\text{in}} = 100 \text{ mm/s} \).
4. \( h_{\text{u}} = 2 \text{ mm}, h_{\text{j}} = 20 \text{ mm}, h_{\text{j}} = 15910 \text{ mm}, \text{v}_{\text{in}} = 3 \text{ mm/s} \).

Adverse effect:
1. Enhance the overall thermal performance of electronic components by a noteworthy amount.
2. Significantly increase heat dissipation rate of electronic devices with nano pillars.
3. High surface area of these silicon pillars which gives enhanced convective heat transfer rate, and hence requires less coolant flow rate, resulting in less pumping power.
4. Simpler, low cost, easy to fabricate and smaller overall packaging area.

0.08

(continued on next page)
Table 2 (continued)

<table>
<thead>
<tr>
<th>Page</th>
<th>Reference</th>
<th>Additional Notes</th>
</tr>
</thead>
</table>
1. Water in silicon microchannel with vertical interconnections.  
2. Three different sizes of interconnection have been placed.  
3. \( W_{ch} = 57 mm; H_{ch} = 150 mm; \)  
4. Laminar flow, \( Re = 450 \)  
5. Advantages:  
   - Significantly reduce the streamwise temperature rise on the base surface.  
   - Substantially reduce the required pressure drop and pumping power.  
   - High heat flux capability.  
   - Significantly reduce the fanpower.  
6. Disadvantages:  
   - Enhance heat removal capacity of the heat sink with the cross-flow between the channels obstructing boundary layer.  
   - Improve the heat performance compared with the heat sink without interconnection.  
   - The vertical channels act as a thermal resistance to the heat flow in the subchannels.  
   - 0.15 0.15 |
1. Water in brass heat sink.  
2. Staggered honeycomb microchannels.  
3. Off-set fins and multi-layer channels structure construction with a cost-effective way.  
4. Double fluid flow inlets and outlets  
5. 15 honeycomb layers in each heat sink (40×20×1.6 mm )  
6. D=2.494 mm; \( W_{ch} = 0.2 mm \)  
7. Advantages:  
   - Significantly reduce the streamwise temperature rise on the base surface.  
   - Substantially reduce the required pressure drop and pumping power.  
   - High heat flux capability.  
   - Significantly reduce the fanpower.  
8. Disadvantages:  
   - Obtain more uniform substrate temperature distribution in comparison of the single and double ones.  
   - Reduce the flow rate as a result of the hydrodynamic heat loss of separator and combinational flow in double pipes.  
   - Shock in the development of thermal boundary layer.  
   - Easy to fabrication.  
   - Benefit the long distance electronic products cooling application under small flow rate.  
   - 2.28 0.18 |
1. (a) Rectangular microchannel and (b) double layered (CL) microchannels isolated by rotatable plates.  
2. Anti-reflective flexible seals supports the separating plate.  
3. Only the rotational motion about a pivot is allowed.  
4. Advantages:  
   - Significantly reduce the streamwise temperature rise on the base surface.  
   - Substantially reduce the required pressure drop and pumping power.  
   - High heat flux capability.  
   - Significantly reduce the fanpower.  
5. Higher effectiveness and the heat transfer rate per unit pumping power for the flexible-microchannel-exchanger than that for the rigid one.  
6. Provide more cooling effects per unit pumping power for the flexible microchannels devices by improving flow Reynolds numbers baffles number and aspect ratio.  
   - 0.068 (Re=45) 0.308 (Re=100) 11.40 |
1. Water in silicon and double layer microchannel heat sink.  
2. \( H_{ch}=100 \mu m; H_{sep}=30 \mu m; \)  
3. \( N=200; Re=0.4 mm; \)  
4. \( \eta = 800 \mu m; \eta = 1100; \)  
5. Advantages:  
   - Significantly reduce the overall thermal resistance.  
   - Increase the uniformity of the temperature under the chip.  
   - Improve the temperature uniformity with counter flow layout.  
   - Reduce the peak temperature with parallel flow arrangement.  
   - 0.057 0.057 |
1. Water in silicon double layer microchannel heat sink.  
2. \( H_{ch}=35mm=35mm; N=200; \)  
3. \( H_{ch}=4.7mm; \)  
4. \( \eta = 0.055 mm; \)  
5. Advantages:  
   - Significantly reduce the streamwise temperature rise on the base surface.  
   - Substantially reduce the required pressure drop and pumping power.  
   - High heat flux capability.  
   - Significantly reduce the fanpower.  
6. Better heat dissipation by changing the (long/parallel counter flow) according to the provided pumping power.  
   - 0.15 0.1 |
1. Four different types of substrate materials (copper, aluminum, silicon, and steel) and three different coolants (water, ethylene glycol, and glycerol).  
2. \( \alpha = 0.1 \)  
3. \( \beta = 0.5 \)  
4. \( \gamma = 0.5 \)  
5. Advantages:  
   - Significantly reduce the streamwise temperature rise on the base surface.  
   - Substantially reduce the required pressure drop and pumping power.  
   - High heat flux capability.  
   - Significantly reduce the fanpower.  
5. Substantially enhance cooling performance due to the lowest temperature rise for Cooper.  
6. Obtain the lowest total thermal resistance by properly optimizing the geometric parameters.  
   - 0.115 0.1 |
1. \( 1.0 \) ml of 5% (C) water nanofluid silicon double layer microchannel heat sink.  
2. \( \alpha = 0.1 \)  
3. \( \beta = 0.5 \)  
4. \( \gamma = 0.5 \)  
5. Advantages:  
   - Significantly reduce the streamwise temperature rise on the base surface.  
   - Substantially reduce the required pressure drop and pumping power.  
   - High heat flux capability.  
   - Significantly reduce the fanpower.  
5. Enhance the thermal performance (22%) with the AG203 5% water nanofluid.  
6. Obtain the lowest total thermal resistance by properly optimizing the geometric parameters.  
7. Disadvantages:  
   - Decline of the effectiveness under high pumping power.  
   - 0.098(2+1) 0.038(3+9) 0.9 |
Table 2 (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>25°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>50%</td>
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<tr>
<td>Airspeed</td>
<td>1 m/s</td>
</tr>
</tbody>
</table>

Note: All measurements were taken under standard atmospheric conditions and with a precision of ±0.1%.

Table 2 (continued)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Experiment Setup</th>
<th>Advantages</th>
<th>( D )</th>
<th>( h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water in Silicon double-layered microchannel heat sink with truncated top channels</td>
<td>( T_{in} = 300 \text{K} ); ( N = 100 ); ( \Delta p = 0.1 \text{MPa} ); ( L = 20 \text{mm} ); ( W = 10 \text{mm} ); ( H = 15 \text{mm} ); ( R_{in} = 0.05 \text{mm} ); ( R_{out} = 0.05 \text{mm} ); ( \alpha = 0.5 ); ( \beta = 1 ); ( \rho = 1050 \text{kg/m}^3 ); ( c_p = 4184 \text{J/kg} \cdot \text{K} ); ( \Delta T = 0.15 \text{K} ); ( \dot{Q} = 200 \text{W} ); ( \dot{m} = 0.06 \text{kg/s} ); ( H_{out} = 0.15 \text{K} ); ( L = 0.3 \text{m} ).</td>
<td>1. Significantly reduce the streamline temperature rise on the base surface. 2. Substantially reduce the required pressure drop and pumping power. 3. High heat flux capability. 4. Significantly reduce the flowrate. 5. Prevent the downstream coolant with higher temperature in the top channel from heating the upstream coolant with lower temperature in the bottom channel. 6. Further reduce the overall thermal resistance. 7. Further decrease maximum temperature difference on the bottom wall.</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>Water in Silicon double-layered microchannel heat sink</td>
<td>( T_{in} = 300 \text{K} ); ( N = 10 ); ( \Delta p = 0.1 \text{MPa} ); ( L = 20 \text{mm} ); ( W = 10 \text{mm} ); ( H = 15 \text{mm} ); ( R_{in} = 0.05 \text{mm} ); ( R_{out} = 0.05 \text{mm} ); ( \alpha = 0.5 ); ( \beta = 1 ); ( \rho = 1050 \text{kg/m}^3 ); ( c_p = 4184 \text{J/kg} \cdot \text{K} ); ( \Delta T = 0.15 \text{K} ); ( \dot{Q} = 200 \text{W} ); ( \dot{m} = 0.06 \text{kg/s} ); ( H_{out} = 0.15 \text{K} ); ( L = 0.3 \text{m} ).</td>
<td>1. Significantly reduce the streamline temperature rise on the base surface. 2. Substantially reduce the required pressure drop and pumping power. 3. High heat flux capability. 4. Significantly reduce the flowrate. 5. Prevent the downstream coolant with higher temperature in the top channel from heating the upstream coolant with lower temperature in the bottom channel. 6. Further reduce the overall thermal resistance. 7. Further decrease maximum temperature difference on the bottom wall.</td>
<td>0.13</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>Water in Silicon double-layered microchannel heat sink with truncated top channels</td>
<td>( T_{in} = 300 \text{K} ); ( N = 100 ); ( \Delta p = 0.1 \text{MPa} ); ( L = 20 \text{mm} ); ( W = 10 \text{mm} ); ( H = 15 \text{mm} ); ( R_{in} = 0.05 \text{mm} ); ( R_{out} = 0.05 \text{mm} ); ( \alpha = 0.5 ); ( \beta = 1 ); ( \rho = 1050 \text{kg/m}^3 ); ( c_p = 4184 \text{J/kg} \cdot \text{K} ); ( \Delta T = 0.15 \text{K} ); ( \dot{Q} = 200 \text{W} ); ( \dot{m} = 0.06 \text{kg/s} ); ( H_{out} = 0.15 \text{K} ); ( L = 0.3 \text{m} ).</td>
<td>1. Significantly reduce the streamline temperature rise on the base surface. 2. Substantially reduce the required pressure drop and pumping power. 3. High heat flux capability. 4. Significantly reduce the flowrate. 5. Prevent the downstream coolant with higher temperature in the top channel from heating the upstream coolant with lower temperature in the bottom channel. 6. Further reduce the overall thermal resistance. 7. Further decrease maximum temperature difference on the bottom wall.</td>
<td>0.182 (D=0.05)</td>
<td>0.393 (h=1)</td>
</tr>
</tbody>
</table>
Table 3
Comparison between single-layer microchannels and multi-layer microchannels.

<table>
<thead>
<tr>
<th>References</th>
<th>ML-MCHS thermal resistance (°C·m²/W)</th>
<th>SL-MCHS thermal resistance (°C·m²/W)</th>
<th>Percentage of thermal resistance changed</th>
<th>ML-MCHS thermal pumping power (W/cm)</th>
<th>SL-MCHS average pumping power (W/cm)</th>
<th>Percentage of pumping power changed</th>
</tr>
</thead>
<tbody>
<tr>
<td>[5] Cheng, S. H., T. T. Ou, and T. N. Wong. &quot;Optimisation of single and double layer counter flow microchannel heat sinks.&quot; Applied Thermal Engineering 22.14 (2002): 1569–1585.</td>
<td>0.058 (Laminar) 0.066 (Turbulent)</td>
<td></td>
<td>-81.9% 1.05</td>
<td>0.06 (Laminar) 0.066 (Turbulent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[6] Wei, Xiaojin, and Yogendra Joshi. &quot;Optimization study of stacked micro-channel heat sinks for micro-electronic cooling.&quot; Components and Packaging Technologies, IEEE Transactions on 26.1 (2003): 55–61.</td>
<td>0.14 (3-layers)</td>
<td></td>
<td>-56% 0.01</td>
<td>0.06 (Laminar) 0.066 (Turbulent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[9] S. Lu, K. Vafai / International Communications in Heat and Mass Transfer 76 (2016) 271–284</td>
<td>0.17</td>
<td></td>
<td>-47% 0.148</td>
<td>1.76</td>
<td>0.06 (Laminar) 0.066 (Turbulent)</td>
<td>-92%</td>
</tr>
<tr>
<td>[10] Wei, Xiaojin, and Yogendra Joshi. &quot;Stacked microchannel heat sinks for liquid cooling of microelectronic components.&quot; Journal of Electronic Packaging 126.1 (2004): 60–66.</td>
<td>0.05</td>
<td></td>
<td>-84% 0.77</td>
<td>0.058</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[13] Le, N. P. Skandakumar, and A. Ortega. &quot;Experiments and modeling of multilayer copper microchannel heat sinks in single-phase flow.&quot; Thermal and Thermomechanical Phenomena in Electronic Systems, 2006. ITERM'06. The Tenth Intersociety Conference on. IEEE, 2006.</td>
<td>0.3</td>
<td></td>
<td>-6% 0.01</td>
<td>0.058</td>
<td></td>
<td></td>
</tr>
</tbody>
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(continued on next page)
<table>
<thead>
<tr>
<th>Ref</th>
<th>Author(s)</th>
<th>Title</th>
<th>Journal, Volume, Issue, Year</th>
<th>0.12</th>
<th>–63%</th>
<th>0.0056</th>
<th>–100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>[23]</td>
<td>Hung, Tu-Chieh, Wei-Mon Yan, and Wes-Ping Li.</td>
<td>&quot;Analysis of heat transfer characteristics of double-layered microchannel heat sink.&quot; International Journal of Heat and Mass Transfer 55.11 (2012): 3090–3099</td>
<td>0.098( Q = 0.1)</td>
<td>–69.4%</td>
<td>0.1</td>
<td>–94.3%</td>
<td></td>
</tr>
<tr>
<td>[24]</td>
<td>Hung, Tu-Chieh, and Wei-Mon Yan.</td>
<td>&quot;Enhancement of thermal performance in double-layered microchannel heat sink with nanofluids.&quot; International Journal of Heat and Mass Transfer 55.11 (2012): 3255–3259.</td>
<td>0.055( Q = 0.9)</td>
<td>–82.8%</td>
<td>0.9</td>
<td>–48.9%</td>
<td></td>
</tr>
<tr>
<td>[27]</td>
<td>Wong, Kok-Cheng, and Fashli Nazhirin Ahmad Muezzin.</td>
<td>&quot;Heat transfer of a parallel flow two-layered microchannel heat sink.&quot; International Communications in Heat and Mass Transfer 49 (2013): 136–140.</td>
<td>0.07</td>
<td>–78%</td>
<td>0.08</td>
<td>1.76</td>
<td></td>
</tr>
<tr>
<td>[28]</td>
<td>Lu, Bin, W. J. Meng, and Fanghua Mei.</td>
<td>&quot;Experimental investigation of Cu-based, double-layered, microchannel heat exchangers.&quot;</td>
<td>Journal of Micromechanics and Nanomanufacturing 23.3 (2013): 035017.</td>
<td>0.289</td>
<td>–10%</td>
<td>0.08</td>
<td>1.76</td>
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</tbody>
</table>
4. Conclusions

Compared to the single-layer microchannel heat sinks, the innovative DL-MCHS and ML-MCHS heat sink designs overcome the drawbacks, and possess attributes that are superior to that of SL-MCHS. ML-MCHS designs reduce the problem of high streamwise temperature rise and they reduce the thermal resistance and pumping power to a large degree. Furthermore, the proposed two-layered thin film is supported by flexible complex seals, unlike other controlling systems, and does not require additional mechanical control or external cooling devices. In addition, the DL-flexible microchannel devices are found to provide more cooling effects per unit pumping power than the rigid ones at flow Reynolds numbers below specific values, and at stiffness number and an aspect ratio above certain values.

References


