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

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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.

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

$$Q = \frac{\Delta T}{R_{th}} = qA_{sub} \tag{1}$$

$$R_{th} = \frac{\Delta T}{qA_{sub}} \tag{2}$$

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Nomenclature

A_{sub}	the area of the substrate (cm^2)
H_{ch}	channel height (μm)
H_{ba}	base thickness (μm)
L	microchannel length (μm)
W	microchannel width (μm)
W_{ch}	channel width (μm)
W_{fin}	fin width (μm)
N	channel number
ΔP	pressure drop (Pa)
q	applied heat flux (W/m^2)
Re	Reynolds number
h	heat transfer coefficient (W/m^2K)
R_{th}	overall thermal resistance (°C/W)
k	thermal conductivity ($W/(m \cdot K)$)
T_{in}	inlet temperature (°C)
u_{in}	inlet velocity (m/s)
Q	flow rate (ml/min)
l	truncation length of the top channel (μm)
x, y, z	coordinates (μm)
D	diameter (μm)
D_h	hydraulic diameter (μm)

Greek letters

α	aspect ratio ($=H_{ch}/W_{ch}$)
β	channel-to-fin width ratio
λ_l	dimensionless truncation length
Ω	pumping power (W/cm)

Subscripts

1	lower layer channel
2	upper layer channel
3	third layer
4	fourth layer
5	fifth layer
f	fluid phase
s	solid phase
np	nanopillar
rib	the horizontal base in the microchannel

$$R_{th} = \frac{T_J - T_{in}}{qA_{sub}} \tag{3}$$

where T_J is the junction temperature, T_{in} the inlet temperature of coolant, q the heat flux, Q the heat transfer and A_{sub} the base area of the heat sink.

In order to unify the overall thermal resistance, the unit overall thermal resistance is employed when comparing SL-MCHS and ML-MCHS cases.

$$R_{unit} = R_{th}A_{sub} \tag{4}$$

A wide range of pertinent SL-MCHS cases in the literature are selected and the unit overall thermal resistances are presented in Table 1 in order to establish a reasonable comparison. After arriving at the thermal resistance from the literature, the corresponding average thermal resistance for the SL-MCHS in the literature is calculated. 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:

$$R_{ave} = \frac{R_{max} + R_{min}}{2} \tag{5}$$

or

$$R_{ave} = \frac{R_1 + R_2 + \ldots + R_n}{n} \tag{6}$$

2.2. Pumping power

The pumping power is defined as

$$\Omega = Q_V \Delta p = u_{in} A_C \Delta p N \tag{7}$$

where Q_V is the volumetric flow rate, Δp 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.

$$\Omega_{unit} = \frac{\Omega}{L} \tag{8}$$

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:

$$\Omega_{ave} = \frac{\Omega_{max} + \Omega_{min}}{2} \tag{9}$$

or

$$\Omega_{ave} = \frac{\Omega_1 + \Omega_2 + \ldots + \Omega_n}{n} \tag{10}$$

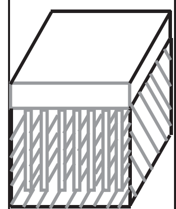
3. Results and discussion

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.

Reference	Number of layers	Main characteristics	Icon diagram	Advantages and disadvantages	Thermal resistance R (°C • m²/W)	Pumping power Ω (W/cm)
[1] Tuckerman, David B., and R. F. W. Pease. "High–performance heat sinking for VLSI." Electron Device Letters, IEEE 2.5 (1981): 126–129.	1	1. Water in silicon and single layer 2. Asub = 1cm x 1cm; Wch = 50μm; Wfin = 50μm; L = 302μm		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 unstableness and thermal breakdown.	0.09	1.84

References	Thermal resistance R (°C•m²/W)	Average value of thermal resistance	Total average value of thermal resistance	Pumping power Ω (W/cm)	Average value of pumping power Ω (W/cm)	Total average value of pumping power Ω (W/cm)
[1] Tuckerman, David B., and R. F. W. Pease. "High–performance heat sinking for VLSI." *Electron Device Letters, IEEE* 2.5 (1981): 126–129.	0.09	0.09		1.84	1.84	
[35] Weisberg, Arel, Haim H. Bau, and J. N. Zemel. "Analysis of microchannels for integrated cooling." *International Journal of Heat and Mass Transfer* 35.10 (1992): 2465–2474.	0.1	0.1		0.095 0.34 0.54 1.31	0.57	
[36] Missaggia, L. J., et al. "Microchannel heat sinks for two–dimensional high–power–density diode laser arrays." *Quantum Electronics, IEEE Journal of* 25.9 (1989): 1988–1992.	0.035–0.0430	0.2		1.33	1.33	
[37] Knight, Roy W., et al. "Heat sink optimization with application to microchannels. "*Components, Hybrids, and Manufacturing Technology, IEEE Transactions on* 15.5 (1992): 832–842.	0.056 0.052	0.054		12.2 10.0	11.12	
[38] Harms, Todd M., Michael J. Kazmierczak, and Frank M. Gerner. "Developing convective heat transfer in deep rectangular microchannels." *International Journal of Heat and Fluid Flow* 20.2 (1999): 149–157.	0.84 0.79 0.69 0.61 0.52 0.45 0.39 0.34 0.3 0.27 0.61 0.54 0.5 0.43 0.39 0.36 0.33 0.3 0.275 0.256 0.238 0.219 0.213 0.2	0.43		0.006 0.011 0.021 0.044 0.097 0.21 0.42 0.84 1.71 3.82 0.003 0.006 0.01 0.018 0.03 0.05 0.084 0.161 0.31 0.56 1.13 2.32 4.18 7.98	0.96	
[39] Fedorov, Andrei G., and Raymond Viskanta. "Three-dimensional conjugate heat transfer in the microchannel heat sink for electronic packaging." *International Journal of Heat and Mass Transfer* 43.3 (2000): 399-415.	0.1-0.35	0.225				
[40] Kishimoto, Tohru, and Takaaki Ohsaki. "VLSI packaging technique using liquid-cooled channels." *Components, Hybrids, and Manufacturing Technology, IEEE Transactions on* 9.4 (1986): 328-335.	0.176-0.316	0.246		0.038	0.038	
[41] Phillips, Richard J., Leon R. Glicksman, and Ralph Larson. "Forced-convection, liquid-cooled, microchannel heat sinks." U.S. Patent No. 4,894,709. 16 Jan. 1990.	0.236 0.128 0.087	0.33		0.10 0.64 4.79	3.69	

(*Continued on next page*)

Table 1 (*continued*)

[42] Mahalingam, Mali. "Thermal management in semiconductor device packaging." *Proceedings of the IEEE* 73.9 (1985): 1396–1404.	0.5 0.75 (water as coolant)	0.36				1.76
[43] Samalam, Vijay K. "Convective heat transfer in microchannels." *Journal of Electronic Materials* 18.5 (1989): 611–617.	0.07–0.25 (low aspect ratio) 0.055–0.065 (high aspect ratio)	0.11				
[44] Copeland, David, Masud Behnia, andWataru Nakayama. "Manifold microchannel heat sinks: isothermal analysis." *Components, Packaging, and Manufacturing Technology, Part A, IEEE Transactions on* 20.2 (1997): 96–102.	0.42 0.25 0.48 0.27 0.42 0.25 0.47 0.27	0.35	0.32			
[45] Ryu, J. H., D. H. Choi, and S. J. Kim. "Three–dimensional numerical optimization of a manifold microchannel heat sink." International Journal of Heat and Mass Transfer 46.9 (2003): 1553–1562.	0.06–0.9 0.031–0.039	0.26		2.56	2.56	
[46] Escher, W., et al. "Experimental investigation of an ultrathin manifold microchannel heat sink for liquid–cooled chips." *Journal of Heat Transfer* 132.8 (2010): 081402.	0.09	0.09		0.24	0.24	
[47] Chein, Reiyu, and Janghwa Chen. "Numerical study of the inlet/outlet arrangement effect on microchannel heat sink performance." *International Journal of Thermal Sciences* 48.8 (2009): 1627–1638.	0.826–1.228	1.027		0.09 0.05 0.029 0.08 0.045 0.026 0.083 0.047 0.028 0.08 0.045 0.026 0.106 0.056 0.033 0.103 0.056 0.033	0.056	
[48] Kim, S. J., and D. Kim. "Forced convection in microstructures for electronic equipment cooling." *Journal of Heat Transfer* 121.3 (1999): 639–645.	0.075 0.070	0.073		2.27 2.56	2.42	
[49] Li, Ji, and G. P. Peterson. "Geometric optimization of a micro heat sink with liquid flow." *Components and Packaging Technologies, IEEE Transactions on* 29.1 (2006): 145–154.	0.156 0.223	0.19		0.05	0.05	
[50] Qu, Weilin, and Issam Mudawar. "Analysis of three–dimensional heat transfer in micro–channel heat sinks." *International Journal of heat and mass transfer* 45.19 (2002): 3973–3985.	0.14–0.04	0.27				1.76
[51] Ryu, J. H., D. H. Choi, and S. J. Kim. "Numerical optimization of the thermal performance of a microchannel heat sink." *International Journal of Heat and Mass Transfer* 45.13 (2002): 2823–2827.	0.092 0.117 0.111	0.11		2.56	2.56	
[52] Tsai, Tsung–Hsun, and Reiyu Chein. "Performance analysis of nanofluid–cooled microchannel heat sinks." *International Journal of Heat and Fluid Flow* 28.5 (2007): 1013–1026.	0.0657 0.0642	0.065		2.27	2.27	

Table 1 (*continued*)

[53] Chein, Reiyu, and Jason Chuang. "Experimental microchannel heat sink performance studies using nanofluids." *International Journal of Thermal Sciences* 46.1 (2007): 57–66.	1.16–1.71	1.435		0.006 0.009 0.013	0.009	
[54] Zhang, Lian, et al. "Measurements and modeling of two–phase flow in microchannels with nearly constant heat flux boundary conditions." *Microelectromechanical Systems, Journal of* 11.1 (2002): 12–19.	1.216	1.216				
[55] Husain, Afzal, and Kwang–Yong Kim. "Shape optimization of micro–channel heat sink for micro–electronic cooling." *Components and Packaging Technologies, IEEE Transactions on* 31.2 (2008): 322–330.	0.116 0.105 0.085	0.102		0.05	0.05	
[56] Kawano, Koichiro, et al. "Development of micro channel heat exchanging." *JSME International Journal Series B Fluids and Thermal Engineering* 44.4 (2001): 592–598.	0.1	0.1		0.1	0.1	

Table 2
A comparative analysis of innovative microchannel heat sinks for electronic cooling.

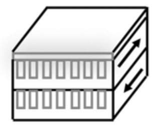
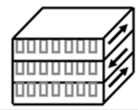
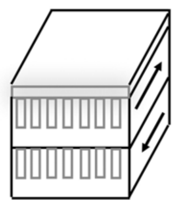
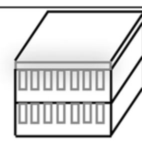
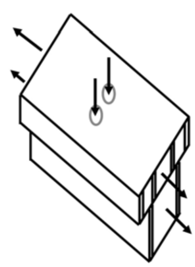
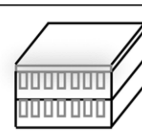
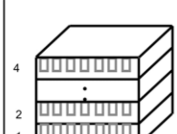
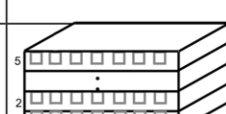
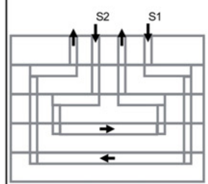
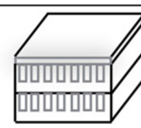
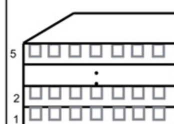
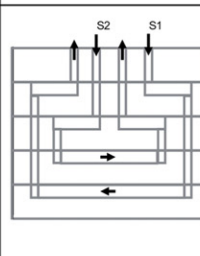
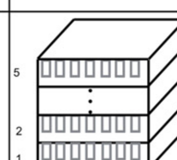
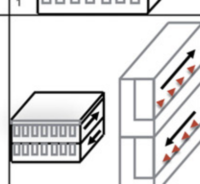
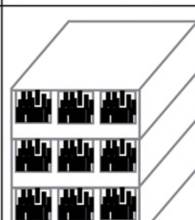
Reference	Number of layers	Main characteristics	Icon diagram	Advantages and disadvantages	Thermal Resistance R(°C·m²/W)	Pumping power Ω(W/cm)
[2] Vafai, Kambiz, and Lu Zhu. "Analysis of two-layered micro-channel heat sink concept in electronic cooling." International Journal of Heat and Mass Transfer 42.12 (1999): 2287-2297.	2	1. Water in silicon and two-layer with counterfow 2. $1/2W_{ch}$=30μm; $1/2W_{fin}$ = 30μm; H_{ch1} = H_{ch2}=100μm;D_{h1} = D_{h2} = 92.3μm; L=800μm;Δp=0.24Pa;Re =143.6; q=30W /cm² T=25°C		Advantages: 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 flowrate	0.17	
[4] Vafai, Kambiz, and Lu Zhu. "Multi-layered micro-channel heat sink, devices and systems incorporating same." U.S. Patent No. 6,675,875. 13 Jan. 2004.	2&3	1. Water in silicon. 2. Stacked-microchannel with counter flo		Advantages: 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 flowrate	0.17	
[5] Chong, S. H., K. T. Ooi, and T. N. Wong. "Optimisation of single and double layer counter flow microchannel heat sinks." Applied Thermal Engineering 22.14 (2002): 1569-1585.	1&2	1. Water in silicon and two-layer with counterfow 2. For laminar flow: T_{in} = 300K;N=80; L=365.98μm;W_{fin} = 38.08μm; W_{ch}=86.45μm;Re=713.09;u_{in} =3.68m/s; Δp=56.4kPa; h = 29526.78W / m^2K; 3. For turbulent flow: N=27; L=449.25μm; W_{fin} = 113.17μm; W_{ch}=252.9μm; Re=3823.1;u_{in} =8.53m/s;		Advantages: 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 flowrate	0.058(Laminar) 0.066(Turbulent)	1.05
[6] Wei, Xiaojin, and Yogendra Joshi. "Optimization study of stacked micro-channel heat sinks for micro-electronic cooling." Components and Packaging Technologies, IEEE Transactions on 26.1 (2003): 55-61.	3	1. Water in silicon and two-layer 2.L=1cm;W=1cm; H_{ba} = 500μm;Δp<4bar; Q<1000ml/min; W_{fin} = 41μm; W_{ch}=107μm; α = 3.8		Advantages: 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 flowrate	0.14(3-layers)	0.01
[7] Khaled, A-RA, and K. Vafai. "Control of exit flow and thermal conditions using two-layered thin films supported by flexible complex seals." International journal of heat and mass transfer 47.8 (2004): 1599-1611.	2	1. Flow and heat transfer inside an oscillatory disturbed two-layered thin fil channel supported by flexible complex seals in the presence of suspended ultrafine particles. 2. Main flow passes through the lower la where its lower plate is fixed and its upp plate is insulated and free to move in the vertical direction. 3. Secondary flow (parallel or counter to the main flow direction)passes through the upper layer. 4. The flow can be the fuel flow or fuel-ai mixture prior to combustion or flow of a biofluid in a fluidic cell. 5. Applications in internal combustion industry .		Advantages: 1. Increase the flow rate and heat transfer in the main thin film channel 2. Increase the stability of the intermediate plate with the increment of thermal dispersion and thermal squeezing parameter for the secondary layer 3. More stable under a relatively large pulsating frequency. 4. No additional mechanical control or external cooling devices.		
[8] Patterson, Michael K., et al. "Numerical study of conjugate heat transfer in stacked microchannels." Thermal and Thermomechanical Phenomena in Electronic Systems, 2004. ITHERM'04. The Ninth Intersociety Conference on. IEEE, 2004.	2	1. Water in silicon and two-layer with parallel flow, counterflow ,series flow. 2.A_{sub}=1cm×1cm; W_{ch}=107μm; W_{fin} = 41μm; H_{ba} = 500μm; T_{in} = 300K; Re=130		Advantages: 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 flowrate 5. Improve the temperature uniformity with counter-flow layout. 6. Reduce the peak temperature with parallel-flow arrangement.	0.17	0.148
[9] Skandakumaran, P., et al. "Multi-layered SiC microchannel heat sinks-modeling and experiment." Thermal and Thermomechanical Phenomena in Electronic Systems, 2004. ITHERM'04. The Ninth Intersociety Conference on. IEEE, 2004.	1,2&4	1. Water in SiC and multi-layered; 2. Experimental parameters: A_{sub}=1.27cm×2.54cm; D_{h1}=639μm; D_{h2}=601μm; D_{h4}=593μm; Δp=200pst; Q_{max} = 210ml/min; 3. Numerical geometric: D_h = 500μm; W_{fin} = 500μm;H_{ba} = 500μm		Advantages: 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 flowrate 5. Benefits SiC-based substrates heat sinks, like RF and microwave devices and high power electronics devices. Disadvantage: Low thermal conductivity of SiC(15W/m°C) as an ideal thermal conductor	0.05	0.77
[10] Wei, Xiaojin, and Yogendra Joshi. "Stacked microchannel heat sinks for liquid cooling of microelectronic components." Journal of Electronic Packaging 126.1 (2004): 60-66.	1-5	1. Water in silicon and two-layer; 2.T_{in} = 25°C ;Δp=0.5Pa; K_s=48W /m°C; K_f = 0.614W /m°C; W_{ch} = 71μm; W_{fin} = 71μm; α = 6.0;β = 70		Advantages: 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 flowrate	Fixed ΔP: 0.082	2-layer: 0.416 3-layer: 0.264 4-layer: 0.279 5-layer: 0.282

Table 2 (*continued*)

[11] Wei, Xiaojin, Yogendra Joshi, and Michael K. Patterson. "Stacked Microchannel Heat Sinks for Liquid Cooling of Microelectronics." ASME 2004 International Mechanical Engineering Congress and Exposition. American Society of Mechanical Engineers, 2004.	s	1. Manifold microchannel: two layers of microchannels and two layers of manifolc and one fluid connection layer. All these ε made of silicon. 2. Counter-flow and parallel-flow carried c on the same structure. 3. Allow different flow rate flowing througl the upper and bottom layer. 4. $W_{unit,ch}$=0.1mm; W_{ch1}=0.056mm; W_{ch2}=0.054mm; W_{ch3}=0.061mm; W_{ch4}=0.053mm; H_{ch1}=0.284mm; H_{ch2}=0.243mm;H_1=0.5mm;$H_2 = 0.5mm$		Advantages: 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 flowrate 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 by 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	
[12] Jeevan, K., I. A. Azid, and K. N. Seetharamu. "Optimization of double layer counter flow (DLCF) micro-channel heat sink used for cooling chips directly." Electronics Packaging Technology Conference, 2004. EPTC 2004. Proceedings of 6th. IEEE, 2004.	2	1.Double-layer microchannel with countei flow. 2.H_{ch}= 365.98μm; W_{ch} = 864.5μm; u_{in} = 3.68m/s; Δp=56.4kPa; Re=713.09; h=29526W/m^2K		Advantages: 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 flowrate 5. Reduce the thermal resistance.	0.058	1.054
[13] Lei, N., P. Skandakumaran, and A. Ortega. "Experiments and modeling of multilayer copper minichannel heat sinks in single-phase flow." Thermal and Thermomechanical Phenomena in Electronics Systems, 2006. ITHERM'06. The Tenth Intersociety Conference on. IEEE, 2006.	1-5	1 Single and multilayer water-copper minichannel heat sinks. 2. L = 30.5mm;W = 12.7mm; W_{ch}=0.508mm; H_{ba} = 0.508mm; W_{fin}=1.016mm; N=5; H_{ch1}=1.52mm; H_{ch2}=2.54mm; H_{ch3}=3.56mm; H_{ch4}=4.57mm; H_{ch5}=5.59mm;		Advantages: 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 flowrate 5. Low cost in fabricating compared with the microchannel. Disadvantages: Occurrence of laminar/turbulent transitional flow at high flow rates.	0.3	2-layer: 0.02 3-layer: 0.0125 4-layer: 0.01 5-layer: 0.0075
[14] Wei, Xiaojin, Yogendra Joshi, and Michael K. Patterson. "Experimental and numerical study of a stacked microchannel heat sink for liquid cooling of microelectronic devices." Journal of Heat Transfer 129.10 (2007): 1432-1444.	2	1. Manifold microchannel: two layers of microchannels and two layers of manifolc and one fluid connection layer. All these ε made of silicon. 2. Counter-flow and parallel-flow carried c on the same structure. 3. Allow different flow rate flowing througl the upper and bottom layer. 4. $W_{unit,ch}$=0.1mm; W_{ch1}=0.056mm; W_{ch2}=0.054mm; W_{ch3}=0.061mm; W_{ch4}=0.053mm; H_{ch1}=0.284mm; H_{ch2}=0.243mm;H_1=0.5mm;$H_2 = 0.5mm$		Advantages: 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 flowrate 5. Distribute coolant uniformly to microchannles with the help of manifolds. 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 by 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 localized heating effects with the optimized heat source locations.	0.09	
[15] Saidi, M. H., and Reza H. Khiabani. "Forced convective heat transfer in parallel flow multilayer microchannels." Journal of Heat Transfer 129.9 (2007): 1230-1236.	1-5	1. Water in silicon 2. A_{sub}=1cm×1cm; L=365μm; W_{ch}=57μm; q= 200W / cm^2		Advantages: 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 flowrate	0.067	0.002
[16] Cheng, Y. J. "Numerical simulation of stacked microchannel heat sink with mixing-enhanced passive structure." International communications in heat and mass transfer 34.3 (2007): 295-303.	2	1. Air-in-silicon stacked two-layer micrichannel with enhanced mixing passive microstructure. 2.The delta wing and V-shape rib can provide the best thermal performance. 3.W_{ch}=30μm; W_{fin} =30μm; H_{ch1}=H_{ch2} = 100μm; L=5000μm; H_{ba1}=H_{ba2} = 30μm; H_{rib}=10,20,30μm; $H_{ribpitch} = 10H_{rib}$;Re=14.8		Advantages: 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 flowrate 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 microstructure. 7. Enhance heat transfer by increasing the secondary flow motion. 8. Improve mixing mechanism of cold and hot fluid in the present configuration.	0.12	0.0056
[17] Dixit, Pradeep, et al. "Silicon nanopillars based 3D stacked microchannel heat sinks concept for enhanced heat dissipation applications in MEMS packaging." Sensors and Actuators A: Physical 141.2 (2008): 685-694.	3	1.Silicon nanopillars based multilayer water-cooled heat sink. 2. Small diameter (0.5-2μm) and large height(~100μm) 3.Q=100ml/min; A_{sub}=1cm×1cm; H=500μm;H_{fin}=400μm; W_{ch}=50μm; $W_{fin} = 25\mu m$; N=100; $D_{np} = 2\mu m$; $H_{np} = 100\mu m$;$N_{np} = 15910$; $\rho_{np} = 0.1$;		Advantages: 1. Enhance the overall thermal performance of electronics 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 require less coolant flow rate , resulting in less pumping power. 4. Simple, low cost, easy to fabricate and smaller overall packaging area. Disadvantages: Damage/fracture of nano pillars by the continuous coolant flow.	0.98	

(*continued on next page*)

Table 2 (*continued*)

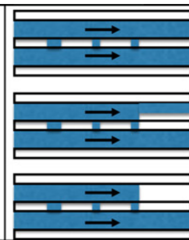
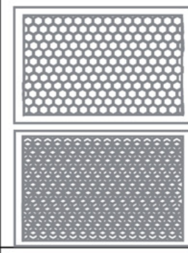
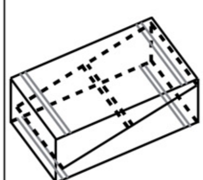
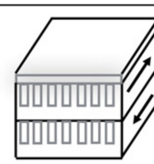
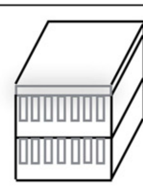
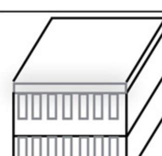
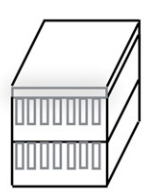
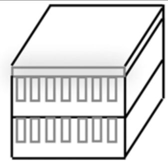
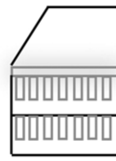
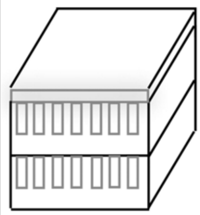
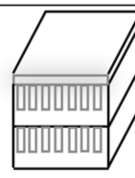
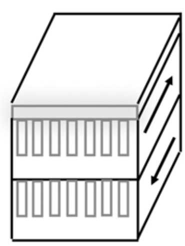
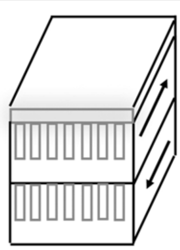
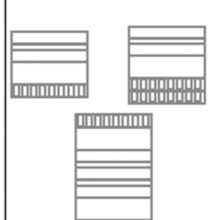
[18] Morshed, A. K. M. M., and Jamil A. Khan. "Numerical analysis of single phase multi layered micro-channel heat sink with inter-connects between vertical channels." 2010 14th International Heat Transfer Conference. American Society of Mechanical Engineers, 2010.	2	1. Water in silicon microchannel with vertical interconnections. 2. Three different sizes of interconnection has been placed. 3. W_{ch}=57μm; H_{ch}=180μm; W_{fin1} = 43μm; W_{fin2} = 220μm 4. Laminar flow: Re=450		Advantages: 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 flowrate. 5. Enhance heat removal capacity of the heat sink with the cross-flow between the channels disrupting boundary layer. 6. Improve the heat performance compared with the heat sink without interconnection. Disadvantages: The vertical channels act as a thermal resistance to the heat flow in the solid matrix.	0.15	0.15
[19] Liu, Y. L., X. B. Luo, and W. Liu. "Cooling behavior in a novel heat sink based on multilayer staggered honeycomb structure." J. Energy and Power Engineering 4 (2010): 22-28.	15	1. Water in brass heat sink. 2. Staggered honeycomb cell microchannels. 3. Off-set fins and multilayer channels structure construction with a cost-effecti way. 4. Double fluid flow inlets and outlets 5. 15 honeycomb layers in each heat sinl (40×20×0.16mm) 6. D=2.49mm; W_{fin} = 0.2mm		Advantages: 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 flowrate. 5. Obtain more uniform substrate temperature distribution in comparison of the single inlet and outlet ones. 6. Reduce the flow rate as a result of the hydrodynamic head loss of separator and combinational flow in double pipes. 7. Break in the development of thermal boundary layer. 8. Easy to fabrication. 9. Benefit the long- distance electronic products cooling applications under small flow rate.	2.26	0.18
[20] Khaled, A-RA, and K. Vafai. "Cooling augmentation using microchannels with rotatable separating plates." International Journal of Heat and Mass Transfer 54.15 (2011): 3732-3739.		1. (A) Flexible microheat exchanger and (B) double layered (DL) microchannels separated by rotatable plates 2. Anti-leaking flexible seals supports the separating plate. 3. Only the rotational motion about a pivc rod is allowable.		Advantages: 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 flowrate. 5. Higher effectiveness and the heat transfer rate per unit pumping power for the flexible microheat exchanger than that for the rigid one. 6. Provide more cooling effects per unit pumping power for DL-flexible microchannels devices by improving flow Reynolds numbers bstiffness number and aspect ratio.		
[21] Levac, ML-J., H. M. Soliman, and S. J. Ormiston. "Three-dimensional analysis of fluid flow and heat transfer in single-and two-layered micro-channel heat sinks." Heat and mass transfer 47.11 (2011): 1375-1383.	1&2	1. Water in silicon and double layer microchannel heat sink. 2. H_{ch}=100μm ; 1/2W_{ch}=30μm; H_{ba}=20μm; H=240μm;W = 60μm; L = 8000μm; Re=1160; T_{in} = 25°C		Advantages: 1. Significantly reduce the overall thermal resistance 2. Increase the uniformity of the temperature under the chip 3. Improve the temperature uniformity with counter-flow layout. 4. Reduce the peak temperature with parallel-flow arrangement.	0.0465(Re=40) 0.0068(Re=1160)	11.49
[22] Xie, Gongnan, et al. "Numerical investigation of heat transfer and pressure loss of double-layer microchannels for chip liquid cooling." ASME 2012 Heat Transfer Summer Conference collocated with the ASME 2012 Fluids Engineering Division Summer Meeting and the ASME 2012 10th International Conference on Nanochannels, Microchannels, and Minichannels. American Society of Mechanical Engineers, 2012.	2	1. Water in silicon double layer microchannel with parallel flow and counter flow lay out. 2. A_{sub}=35mm×35mm; N=200; H_{ch}=0.4mm; W_{ch}=0.1mm; W_{fin} = 0.075mm H_{ba} = 0.05mm; K =148W /(m·K)		Advantages: 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 flowrate 5. Better heat dissipation by changing the layout(parallel/counter flow) according to the provided pumping power.	0.037	0.057
[23] Hung, Tu-Chieh, Wei-Mon Yan, and Wei-Ping Li. "Analysis of heat transfer characteristics of double-layered microchannel heat sink" International Journal of Heat and Mass Transfer 55.11 (2012): 3090-3099	2	1. Four different types of substrate materials(copper, alμmina, silicon, and steel) and three different coolants (water, ethylene glycol, and glycerol). 2. L=10mm; W=10mm; 3. For α=5, β = 0.6 , the total thermal resistance decreases and then increases with N=71. (down-and-up trend)		Advantages: 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 flowrate. 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
[24] Hung, Tu-Chieh, and Wei-Mon Yan. "Enhancement of thermal performance in double-layered microchannel heat sink with nanofluids." International Journal of Heat and Mass Transfer 55.11 (2012): 3225-3238.	2	1. Al_2O_3(TiO_2&GuO)-water nanofluid silicc double layer microchannel heat sink. 2. L=10mm; W=10mm; H_{ba} = 0.1mm ;W_{fin} = 0.05mm; β = 0.4 ~ 0.95;α =2 ~ 13 N = 35 ~ 170;		Advantages: 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 flowrate. 5. Enhance the thermal performance (27%) with the Al2O3 (1%)–water nanofluid. 6. Obtain the lowest total thermal resistance by properly optimizing the geometric parameters Disadvantage: Decline of the effectiveness under high pumping power.	0.098(Ω=0.1) 0.055(Ω=0.9)	0.1 0.9

Table 2 (*continued*)

[25] Hung, Tu-Chieh, et al. "Optimal design of geometric parameters of double-layered microchannel heat sinks." International Journal of Heat and Mass Transfer 55.11 (2012): 3262-3272.	2(with the channel height change)	1. Water in silicon double-layered microchannels 2. A_{sub}=1cm×1cm; $H_{ch}=0.7mm$ $H_{ba}=0.05mm$ N =112;β = 0.37; $\alpha_1=10.32$; α_2=10.93		Advantages: 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 flowrate.	0.12	0.1
[26] Xie, Gongnan, et al. "Computational study and optimization of laminar heat transfer and pressure loss of double-layer microchannels for chip liquid cooling." Journal of Thermal Science and Engineering Applications 5.1 (2013): 011004.	2	1. Water in silicon double-layered microchannel heat sinks with laminar parallel flow and counter flow layout. 2. $A_{sub}=35\text{mm}\times35\text{mm}$; N=200; $H_{ch}=0.4mm$; $W_{ch}=0.1mm$; $W_{fin}=0.075mm$; $H_{ba}=0.05mm$ K =148W /(m·K);Q=0.5L/min		Advantages: 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 flowrate 5. Improve the temperature uniformity with counter-flow layout. 6. Reduce the peak temperature with parallel-flow arrangement.	0.037	0.057
[27] Wong, Kok-Cheong, and Fashli Nazhirin Ahmad Muezzin. "Heat transfer of a parallel flow two-layered microchannel heat sink." International Communications in Heat and Mass Transfer 49 (2013): 136-140.	2	1. Water in silicon double-layered microchannel heat sinks with parallel flow 2. Fixed parameters: $A_{sub}=10\text{mm}\times10\text{mm}$; H=800μm;W=200μm; 1/2$W_{fin}$=80μm; $T_{in}=300\text{K}$ 3. Three cases: a. H_{ch} =320μm; W_{ch} =56μm; Q=4.7cm^3/s; R_{th}=0.108K/W; b. $H_{ch}=$ 287μm; W_{ch} =55μm; Q=6.5cm^3/s; R_{th}=0.113K/W; c.$H_{ch}=$ 302μm; W_{ch} =50μm; Q=8.6cm^3/s; R_{th}=0.093K/W;		Advantages: 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 flowrate 5. Improve the temperature uniformity with counter-flow layout. 6. Reduce the peak temperature with parallel-flow arrangement. 7. Better thermal performance with thinner middle-rib thickness.	0.07	
[28] Lu, Bin, W. J. Meng, and Fanghua Mei. "Experimental investigation of Cu-based, double-layered, microchannel heat exchangers." Journal of Micromechanics and Microengineering 23.3 (2013): 035017.	2	1. Gu-based double-layered microchannel and Gu-based , double-layered, liquid-liquid (hot-cool water) counter-flow Microchannel. 2. A_{sub}= 41.8mm ×28mm; N=92; $D_h=$ 368μm; $W_{fin}=$ 600μm;H=6.65mm 3. $A_{sub}=36\text{mm}\times40\text{mm}$; N=60; $H_{ba2}=1.6mm$;$H_{ba1}=H_{ba3}$ =9.5mm $W_{ch}=$ 210μm;H=650μm		Advantages: 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 flowrate 5. Increase mechanical robustness and thermal performance with Gu-based MCHS.	0.289	0.08
[29] Lin, Lin, et al. "Optimization of geometry and flow rate distribution for double-layer microchannel heat sink" International Journal of Thermal Sciences 78 (2014): 158-168.	2	1. Water in silicon double-layered MCHS $A_{sub}=10\text{mm}\times10\text{mm}$; H=800μm;W=200μm; 1/2$W_{fin}$=80μm; $T_{in1}=T_{in2}=288.16\text{K}$ 2. Ω = 0.05W : N=69; $H_{ch1}=$ 254μm; W_{fin} =56μm; H_{ba1}= 50μm; H_{ba2}= 50μm; u_{in}=0.896m / s 3. Q=200cm^3/min : N=111; $H_{ch1}=$ 319μm; $W_{fin}=$ 60μm; H_{ba1}= 50μm; H_{ba2}= 300μm; u_{in}=2.93m / s 4. Δp = 100kPa : N=81; $H_{ch1}=$ 179μm; $W_{fin}=$ 48μm; H_{ba1}= 50μm; H_{ba2}= 300μm; u_{in}=1.71m / s		Advantages: 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 flowrate	0.131 0.102 0.089	0.05
[30] Wu, J. M., J. Y. Zhao, and K. J. Tseng. "Parametric study on the performance of double-layered microchannels heat sink." Energy Conversion and Management 80 (2014): 550-560.	2	1. Water in silicon double-layered MCHS in counter flow arrangements. 2. $A_{sub}=1\text{cm}\times1\text{cm}$; H=740μm $H_{ch1}=H_{ch2}=$ 250μm; $H_{ba1}=$ 160μm; H_{ba2} =40μm; a. $W_{ch}=$ 70μm; W_{fin} =70μm,48μm,36μm; N = 100,120,133; b. $W_{ch}=$ 50μm; W_{fin} =50μm,33μm,25μm; N = 71,84,94; c. $W_{ch}=$ 40μm; W_{fin} =40μm,25μm; N = 153,125;		Advantages: 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 flowrate. 5. Reduce the thermal resistance by improving the width ratio 6. Better the uniformity of temperature distribution with a better width ratio at a given pumping power. 7. Improve the thermal performance with the investigation on aspect ratio and number of channel. 8. Enhance the overall performance by adjusting the inlet velocity of upper channels to be smaller than that of bottom channels at a given pumping power.	0.07	1.3
[31] Sakanova, Assel, et al. "Optimization and comparison of double-layer and double-side micro-channel heat sinks with nanofluid for power electronics cooling." Applied Thermal Engineering 65.1 (2014): 124-134.	2/double side	1. Double-layered(DL) and double-side (sandwich) with water as coolant microchannel and counter flow layout heat sink. 2. Integrated inside the Gu-layer of direc bond copper. 3. Water based Al_2O_3(with concentration 1%and 5%) nanofluid. 4. 300μm × 635μm ×300μm; $H_{ch}=$ 300μm; $T_{in}=297K$; u_{in}=2m/s; Optimal Geometry: $A_{sub}=1\text{cm}\times1\text{cm}$; N = 125; β = 0.7; W_{ch}= 56μm; W_{fin} =24μm		Advantages: 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 flowrate. 5. Improve the electrical performance by the elimination of wirebonding interconnections. 6. Substantially enhance the thermal performance as the heat generated by the power module can be removed from both sides. 7. The results indicate the nanofluids at a higher concentration yield a better cooling performance by about 17.3% at 5% concentration while 10.6% at 1% concentration. 8. Compared with the conventional SL structure, the DL and sandwich structures show reduction in thermal resistance by 15% and 59% respectively. 9. Temperature distribution for the sandwich structure is almost ideally uniform. The sandwich structure shows best performances in heat removal, uniformity of temperature distribution and reliability.	0.132(DL) 0.064(sandwich) 0.105(with nanofluids)	0.63(DL) 0.64(Sandwich)

(*continued on next page*)

Table 2 (*continued*)

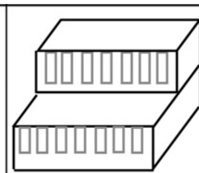
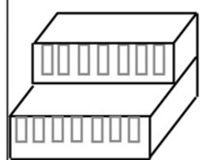
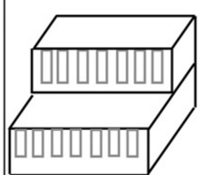
[32] Leng, Chuan, Xiao-Dong Wang, and Tian-Hu Wang. "An improved design of double-layered microchannel heat sink with truncated top channels." Applied Thermal Engineering (2015).	2(with truncated channels)	1. Water in Silicon double-layered microchannel heat sink with truncated t channels(the top channels were truncat at their downstream region). 2. $T_{in1} = T_{in2} = 300K; N = 100;$ Δp=0.1MPa; L=20mm; W=10mm; H=1.05mm; $W_{ch1} = W_{ch2} = 0.05mm;$ $H_{ch1} = H_{ch2} = 0.45mm;$ $H_{ba1} = H_{ba2} = H_{ba3} = 0.05mm;$ α = 9;β = 0.5; $\lambda_l = 0\sim1;$ H_{rib1}=$H_{rib2} = 25mm$		Advantages: 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 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.	0.2	0.1
[33] Leng, Chuan, et al. "Optimization of thermal resistance and bottom wall temperature uniformity for double-layered microchannel heat sink." Energy Conversion and Management 93 (2015): 141-150.	2	1. Water in silicon doubler-layered microchannel. 2. L=10mm; W=10mm; H=1.20mm; H_{ch1}+$H_{ch2} = 1mm;$ $T_{in} = 300K$		Advantages: 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 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.	0.13	0.05
[34] Leng, Chuan, et al. "Multi-parameter optimization of flow and heat transfer for a novel double-layered microchannel heat sink." International Journal of Heat and Mass Transfer 84 (2015): 359-369.	2	1. Water in Silicon double-layered microchannel heat sink with truncated t channels(the top channels were truncat at their downstream region). 2. $T_{in1} = T_{in2} = 300K; N = 100;$ Δp=0.1MPa; L=20mm; W=10mm; H=1.05mm; $W_{ch1} = W_{ch2} = 0.05mm;$ $H_{ba1} = H_{ba2} = H_{ba3} = 0.05mm;$ α = 9;β = 0.5; $\lambda_l = 0\sim1;$ a. q=100W /cm² Ω=0.05W : N=55; $W_{ch} = 0.116mm$; H_{ch}=0.525mm; λ_l=0.28 b. Q = 200ml / min : N=79; $W_{ch} = 0.026mm$; H_{ch}=0.175mm; λ_l=0.38		Advantages: 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 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. 8. Enhance the cooling effect by adjusting the inlet velocity and the truncated length.	0.102(Ω=0.05) 0.056(Ω=1) 0.093(Q=200) 0.05(Q=500)	0.025

Table 3
Comparison between single-layer microchannels and multi-layer microchannels.

References	ML–MCHS thermal resistance R(°C·m^2/W)	SL–MCHS thermal resistance R(°C·m^2/W)	Percentage of thermal resistance changed	ML–MCHS thermal pumping power **Ω**(W/cm)	SL–MCHS average pumping power **Ω**(W/cm)	Percentage of pumping power changed
[2] Vafai, Kambiz, and Lu Zhu. "Analysis of two–layered micro–channel heat sink concept in electronic cooling." International Journal of Heat and Mass Transfer 42.12 (1999): 2287–2297. U.S. Patent No. 6,457,515. 1 Oct. 2002.	0.17		−47%			
[4] Vafai, Kambiz, and Lu Zhu. "Multi–layered micro–channel heat sink, devices and systems incorporating same." U.S. Patent No. 6,675,875. 13 Jan. 2004.	0.17		−47%			
[5] Chong, S. H., K. T. Ooi, and T. N. Wong. "Optimisation of single and double layer counter flow microchannel heat sinks." Applied Thermal Engineering 22.14 (2002): 1569–1585	0.058(Laminar) 0.066(Turbulent)		−81.9% −79.4%	1.05		−40%
[6] Wei, Xiaojin, and Yogendra Joshi. "Optimization study of stacked micro–channel heat sinks for micro–electronic cooling." Components and Packaging Technologies, IEEE Transactions on 26.1 (2003): 55–61.	0.14(3–layers)		−56%	0.01		−99%
[7] Khaled, A–RA, and K. Vafai. "Control of exit flow and thermal conditions using two–layered thin films supported by flexible complex seals." International journal of heat and mass transfer 47.8 (2004): 1599–1611. US Patent # 8,684,274						
[8] Patterson, Michael K., et al. "Numerical study of conjugate heat transfer in stacked microchannels." Thermal and Thermomechanical Phenomena in Electronic Systems, 2004. ITHERM'04. The Ninth Intersociety Conference on. IEEE, 2004.	0.17		−47%	0.148	1.76	−92%
[9] Skandakųmaran, P., et al. "Multi–layered SiC microchannel heat sinks–modeling and experiment." Thermal and Thermomechanical Phenomena in Electronic Systems, 2004. ITHERM'04. The Ninth Intersociety Conference on. IEEE, 2004.	0.05		−84%	0.77		−56%
[10] Wei, Xiaojin, and Yogendra Joshi. "Stacked microchannel heat sinks for liquid cooling of microelectronic components." Journal of Electronic Packaging 126.1 (2004): 60–66.	Fixed ΔP: 0.082		−74%	2–layer: 0.416 3–layer: 0.264 4–layer: 0.279 5–layer: 0.282		−76.4% −85% −84.1% −84.0%
[11] Wei, Xiaojin, Yogendra Joshi, and Michael K. Patterson. "Stacked Microchannel Heat Sinks for Liquid Cooling of Microelectronics." ASME 2004 International Mechanical Engineering Congress and Exposition. American Society of Mechanical Engineers, 2004.	0.09		−72%			
[12] Jeevan, K., I. A. Azid, and K. N. Seetharamu. "Optimization of double layer counter flow (DLCF) micro–channel heat sink used for cooling chips directly." Electronics Packaging Technology Conference, 2004. EPTC 2004. Proceedings of 6th. IEEE, 2004.	0.058		−82%	1.054		−40%
[13] Lei, N., P. Skandakųmaran, and A. Ortega. "Experiments and modeling of multilayer copper minichannel heat sinks in single–phase flow." Thermal and Thermomechanical Phenomena in Electronics Systems, 2006. ITHERM'06. The Tenth Intersociety Conference on. IEEE, 2006.	0.3		−6%	2–layer: 0.02 3–layer: 0.0125 4–layer: 0.01 5–layer: 0.0075		−98.9% −99.3% −99.4% −99.6%
[14] Wei, Xiaojin, Yogendra Joshi, and Michael K. Patterson. "Experimental and numerical study of a stacked microchannel heat sink for liquid cooling of microelectronic devices." Journal of Heat Transfer 129.10 (2007): 1432–1444.	0.09		−72%			
[15] Saidi, M. H., and Reza H. Khiabani. "Forced convective heat transfer in parallel flow multilayer microchannels." Journal of Heat Transfer 129.9 (2007): 1230–1236.	0.067		−79%	0.002		−100%

(*continued on next page*)

Table 3 (*continued*)

[16] Cheng, Y. J. "Numerical simulation of stacked microchannel heat sink with mixing–enhanced passive structure." International communications in heat and mass transfer 34.3 (2007): 295–303.	0.12		−63%	0.0056		−100%
[17] Dixit, Pradeep, et al. "Silicon nanopillars based 3D stacked microchannel heat sinks concept for enhanced heat dissipation applications in MEMS packaging." Sensors and Actuators A: Physical 141.2 (2008): 685–694.	0.98		206%			
[18] Morshed, A. K. M. M., and Jamil A. Khan. "Numerical analysis of single phase multi layered micro–channel heat sink with inter–connects between vertical channels." 2010 14th International Heat Transfer Conference. American Society of Mechanical Engineers, 2010.	0.15	0.32	−53%	0.15	1.76	−92%
[19] Liu, Y. L., X. B. Luo, and W. Liu. "Cooling behavior in a novel heat sink based on multilayer staggered honeycomb structure." J. Energy and Power Engineering 4 (2010): 22–28.	2.26		−90%	0.18		−90%
[20] Khaled, A–RA, and K. Vafai. "Cooling augmentation using microchannels with rotatable separating plates." International Journal of Heat and Mass Transfer 54.15 (2011): 3732–3739. US Patent # 7, 654,468						
[21] Levac, ML–J., H. M. Soliman, and S. J. Ormiston. "Three–dimensional analysis of fluid flow and heat transfer in single–and two–layered micro–channel heat sinks." Heat and mass transfer 47.11 (2011): 1375–1383.	0.0465(Re = 40) 0.0068(Re = 1160)		−85.5% −97.9%	11.49		553%
[22] Xie, Gongnan, et al. "Numerical investigation of heat transfer and pressure loss of double–layer microchannels for chip liquid cooling." ASME 2012 Heat Transfer Summer Conference collocated with the ASME 2012 Fluids Engineering Division Summer Meeting and the ASME 2012 10th International Conference on Nanochannels, Microchannels, and Minichannels. American Society of Mechanical Engineers, 2012.	0.037		−88%	0.057		−97%
[23] Hung, Tu–Chieh, Wei–Mon Yan, and Wei–Ping Li. "Analysis of heat transfer characteristics of double–layered microchannel heat sink." International Journal of Heat and Mass Transfer 55.11 (2012): 3090–3099	0.115		−64%	0.1		−94%
[24] Hung, Tu–Chieh, and Wei–Mon Yan. "Enhancement of thermal performance in double–layered microchannel heat sink with nanofluids." International Journal of Heat and Mass Transfer 55.11 (2012): 3225–3238.	0.098(Ω = 0.1) 0.055(Ω = 0.9)		−69.4% −82.8%	0.1 0.9		−94.3% −48.9%
[25] Hung, Tu–Chieh, et al. "Optimal design of geometric parameters of double–layered microchannel heat sinks." International Journal of Heat and Mass Transfer 55.11 (2012): 3262–3272.	0.12		−63%	0.1		−94%
[26] Xie, Gongnan, et al. "Computational study and optimization of laminar heat transfer and pressure loss of double–layer microchannels for chip liquid cooling." Journal of Thermal Science and Engineering Applications 5.1 (2013): 011004.	0.037		−88%	0.057		−97%
[27] Wong, Kok–Cheong, and Fashli Nazhirin Ahmad Muezzin. "Heat transfer of a parallel flow two–layered microchannel heat sink." International Communications in Heat and Mass Transfer 49 (2013): 136–140.	0.07		−78%			
[28] Lu, Bin, W. J. Meng, and Fanghua Mei. "Experimental investigation of Cu–based, double–layered, microchannel heat exchangers." Journal of Micromechanics and Microengineering 23.3 (2013): 035017.	0.289		−10%	0.08	1.76	−96%

Table 3 (*continued*)

[29] Lin, Lin, et al. "Optimization of geometry and flow rate distribution for double–layer microchannel heat sink." International Journal of Thermal Sciences 78 (2014): 158–168.	0.131 0.102 0.089		−59.1% −68.1% −72.2%	0.05		−97%
[30] Wu, J. M., J. Y. Zhao, and K. J. Tseng. "Parametric study on the performance of double–layered microchannels heat sink." Energy Conversion and Management 80 (2014): 550–560.	0.07		−78%	1.3		−26%
[31] Sakanova, Assel, et al. "Optimization and comparison of double–layer and double–side micro–channel heat sinks with nanofluid for power electronics cooling." Applied Thermal Engineering 65.1 (2014): 124–134.	0.132(DL) 0.064(sandwich) 0.105(with nanofluids)		−58.8% −80% −67.2%	0.63(DL) 0.64(Sandwich)		−64.2% −63.6%
[32] Leng, Chuan, Xiao–Dong Wang, and Tian–Hu Wang. "An improved design of double–layered microchannel heat sink with truncated top channels." Applied Thermal Engineering (2015).	0.2		−38%	0.1		−94%
[33] Leng, Chuan, et al. "Optimization of thermal resistance and bottom wall temperature uniformity for double–layered microchannel heat sink." Energy Conversion and Management 93 (2015): 141–150.	0.13		−59%	0.05		−97%
[34] Leng, Chuan, et al. "Multi–parameter optimization of flow and heat transfer for a novel double–layered microchannel heat sink." International Journal of Heat and Mass Transfer 84 (2015): 359–369.	0.102(Ω=0.05) 0.056(Ω=1) 0.093(Q=200) 0.05(Q=500)		−68.1% −82.5% −70.9% −84.4%	0.025		−99%

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.

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[2] K. Vafai, Z. Lu, Analysis of two-layered micro-channel heat sink concept in electronic cooling, Int. J. Heat Mass Transf. 42 (12) (1999) 2287–2297.

[3] Vafai, Kambiz, and Lu Zhu. "Two-layered micro channel heat sink, devices and systems incorporating same." U.S. Patent No. 6,457,515. 1 Oct. 2002.

[4] Vafai, Kambiz, and Lu Zhu. "Multi-layered micro-channel heat sink, devices and systems incorporating same." U.S. Patent No. 6,675,875. 13 Jan. 2004.

[5] S.H. Chong, K.T. Ooi, T.N. Wong, Optimisation of single and double layer counter flow microchannel heat sinks, Appl. Therm. Eng. 22 (14) (2002) 1569–1585.

[6] X. Wei, Y. Joshi, Optimization study of stacked micro-channel heat sinks for micro-electronic cooling, IEEE Trans. Compon. Packag. Technol. 26 (1) (2003) 55–61.

[7] Khaled, A-RA, and K. Vafai. "Control of exit flow and thermal conditions using two-layered thin films supported by flexible complex seals." Int. J. Heat Mass Transf. 47.8 (2004): 1599–1611. US Patent # 8,684,274

[8] M.K. Patterson, et al., Numerical Study of Conjugate Heat Transfer in Stacked Microchannels, Thermal and Thermomechanical Phenomena in Electronic Systems, 2004. ITHERM'04, The Ninth Intersociety Conference on. IEEE, 2004.

[9] P. Skandakumaran, et al., Multi-Layered SiC Microchannel Heat Sinks–Modeling and Experiment, Thermal and Thermomechanical Phenomena in Electronic Systems, 2004. ITHERM'04, The Ninth Intersociety Conference on. IEEE, 2004.

[10] X. Wei, Y. Joshi, Stacked microchannel heat sinks for liquid cooling of microelectronic components, J. Electron. Packag. 126 (1) (2004) 60–66.

[11] X. Wei, Y. Joshi, M.K. Patterson, Stacked Microchannel Heat Sinks for Liquid Cooling of Microelectronics, ASME 2004 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers, 2004.

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[13] N. Lei, P. Skandakumaran, A. Ortega, Experiments and Modeling of Multilayer Copper Minichannel Heat Sinks in Single-Phase Flow, Thermal and Thermomechanical Phenomena in Electronics Systems, 2006. ITHERM'06, The Tenth Intersociety Conference on. IEEE, 2006.

[14] X. Wei, Y. Joshi, M.K. Patterson, Experimental and numerical study of a stacked microchannel heat sink for liquid cooling of microelectronic devices, J. Heat Transf. 129 (10) (2007) 1432–1444.

[15] M.H. Saidi, R.H. Khiabani, Forced convective heat transfer in parallel flow multilayer microchannels, J. Heat Transf. 129 (9) (2007) 1230–1236.

[16] Y.J. Cheng, Numerical simulation of stacked microchannel heat sink with mixing-enhanced passive structure, Int. Commun. Heat Mass Transf. 34 (3) (2007) 295–303.

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[19] Y.L. Liu, X.B. Luo, W. Liu, Cooling behavior in a novel heat sink based on multilayer staggered honeycomb structure, J. Energy Power Eng. 4 (2010) 22–28.

[20] Khaled, A-RA, and K. Vafai. "Cooling augmentation using microchannels with rotatable separating plates." Int. J. Heat Mass Transf. 54.15 (2011): 3732–3739. US Patent # 7, 654,468

[21] M.L.-J. Levac, H.M. Soliman, S.J. Ormiston, Three-dimensional analysis of fluid flow and heat transfer in single-and two-layered micro-channel heat sinks, Heat Mass Transf. 47 (11) (2011) 1375–1383.

[22] G. Xie, et al., Numerical Investigation of Heat Transfer and Pressure Loss of Double-Layer Microchannels for Chip Liquid Cooling, ASME 2012 Heat Transfer Summer Conference Collocated with the ASME 2012 Fluids Engineering Division Summer Meeting and the ASME 2012 10th International Conference on Nanochannels, Microchannels, and Minichannels, American Society of Mechanical Engineers, 2012.

[23] T.-C. Hung, W.-M. Yan, W.-P. Li, Analysis of heat transfer characteristics of double-layered microchannel heat sink, Int. J. Heat Mass Transf. 55 (11) (2012) 3090–3099.

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[26] G. Xie, et al., Computational study and optimization of laminar heat transfer and pressure loss of double-layer microchannels for chip liquid cooling, J. Therm. Sci. Eng. Appl. 5 (1) (2013) 011004.

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[32] C. Leng, X.-D. Wang, T.-H. Wang, An improved design of double-layered microchannel heat sink with truncated top channels, Appl. Therm. Eng. (2015).
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