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Comparative Study of Rectangular and Trapezoidal Microchannels Using Water and Liquid Metal

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Abstract

With increasing demand for higher computational speed and emerging microsystems, efficient thermal management is need of the hour. Microchannels using liquid coolant are apt solution to this problem. Their efficiency depends greatly upon channel's cross-section and liquid media. In this study the performance of trapezoidal (with two configurations A and V-type) and rectangular microchannels are analyzed and compared for two different coolants, liquid gallium and water. Performance is compared on the basis of maximum temperature at heated surface. For water as coolant the performance of rectangular type is found to be superior in terms of both flow rate and pump power. For liquid gallium as a coolant, microchannels having A-type cross-section is found to be performing better followed by V-type then rectangular type at same flow rate. However on comparison on basis of pump power the rectangular type of geometry is found to be more suitable.

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Nomenclature

a	half-width of larger side of trapezoidal duct (μm)
A	cross sectional area of duct
b	half-width of smaller side of trapezoidal duct (μm)
D_h	hydraulic diameter
$H_{\text{CH,R}}$	channel height in rectangular configuration (μm)
$H_{\text{CH,TR}}$	channel height in trapezoidal configuration (μm)
$H_{\text{TOTAL,TR}}$	height of computational domain of trapezoidal configuration (μm)
$H_{\text{TOTAL,TR}}$	height of computational domain of trapezoidal configuration (μm)
P	Pressure (Pa)
q''	heat flux (W/m^2)
S	Perimeter of duct
T	Temperature (K)
V	velocity (m/s)
$W_{\text{CH,R}}$	channel width in rectangular configuration (μm)

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$W_{TOTAL,R}$	width of computational domain of rectangular configuration (μm)
$W_{TOTAL,T}$	width of computational domain of trapezoidal configuration (μm)
$W_{S1,R}$	substrate thickness in rectangular configuration (μm)
$W_{S2,R}$	substrate thickness in rectangular configuration (μm)
$W_{S,TR}$	substrate thickness in trapezoidal configuration (μm)
<i>Greek symbols</i>	
ρ	density (kg/m^3)
μ	Dynamic viscosity (Pa-s)
α	thermal diffusivity
Δ	change in variable
<i>Subscripts</i>	
<i>ch</i>	channel
<i>f</i>	fluid
<i>R</i>	rectangle
<i>s</i>	solid
<i>TR</i>	trapezium

1. Introduction

The need for cooling in high power dissipation (100 W/cm^2) systems in several scientific and commercial applications such as microelectronics require something beyond the conventional cooling solutions of finned heat sink structures and forced air cooling. The peak power consumption in high performance desktop applications is expected to touch 198 W mark by 2015 [1]. To meet these requirements, various solutions have been proposed [2], of which liquid cooling using microchannels have gained significant attention owing to their several advantages such as high heat transfer coefficients, direct integration on the substrate and negligible contact resistance. Significant amount of work has been carried out pertaining to various geometrical shapes of microchannels and have been extensively reviewed [3-5]. Various correlations for thermal entrance region as well as Nusselt number have been proposed for rectangular [4] as well as trapezoidal geometries [5] of various aspect ratios. To further meet the demand of efficient cooling, use of liquid metals have been proposed by Liu and Zhou [6] owing to their various characteristics such as high vapor pressure and high thermal conductivity. In addition to providing excellent heat transfer, the high electrical conductivity typical in this class of fluids offers the potential of efficient, compact pumping. Of various such metals reviewed in literature [7] liquid gallium has been found to be most suitable candidate. The experimental study of Miner and Ghoshal [8] showed that heat transfer coefficients of the order $10 \text{ W/cm}^2/\text{K}$ are achievable using gallium alloy, $\text{Ga}^{68}\text{In}^{20}\text{Sn}^{12}$. The studies of Li et al. [9] further support superior cooling obtained using liquid gallium. It was found that under different flow and heat dissipation rates, temperature drop in case of liquid gallium was 46.7°C against 51.9°C with water.

It is well known that the performance of microchannels is largely dependent on its hydraulic diameter as well as fluid properties. Therefore, similar geometry may not yield same results for different liquid medium used. Hence there is a need to evaluate the performance of different cross-sectional ducts and find the one most suitable for the type of coolant used. Since for same cross sectional area, lower hydraulic diameter is observed for trapezoidal ducts, which results in increase heat transfer and pump power as well, the best suitable cross sectional geometry for water and liquid gallium is evaluated. Two different configurations of trapezoidal duct (namely A and V type) are compared with rectangular of same cross sectional area using three dimensional conjugate heat transfer analysis. The dimensions of solid region are kept such that total volume of the substrate remains the same for all configurations which is necessary for appropriate comparison. This is because in conjugate heat transfer, thermal conduction resistance of solid also affects the performance of microchannel. The performance in each case is evaluated on the basis of maximum base temperature attained which represents thermal resistance.

2. Analysis

2.1. Computational domain

Figure 1 shows various configurations of microchannel ducts analyzed. As mentioned earlier, all configurations shown have same cross sectional area i.e. have same mass flow rate at same velocities. $W_{S,TR}$, $W_{S1,R}$ and $W_{S2,R}$ represent thickness of substrate in case of trapezoidal and rectangular duct respectively. Similarly, $W_{TOTAL,R}$, $W_{TOTAL,T}$, $H_{TOTAL,R}$ and $H_{TOTAL,T}$ denote total width and height of computational domain in case of rectangular and trapezoidal configuration. The

length of microchannel is 8000 μm while other dimensions used have been selected based on dimensions available in literature [5, 10]. Various dimensions used in the analysis are described in Table 1.

Table 1. Various Dimensions (in microns)

$W_{S,TR}$	$W_{SI,R}$	$W_{TOTAL,TR}$	$W_{TOTAL,R}$	$W_{CH,R}$	$H_{TOTAL,R}$	$H_{CH,R}$
30	155	342.5	342.5	187.5	280	30
$W_{S,TR}$	$D_{h,TR}$	$D_{h,R}$	a	b	$H_{CH,TR}$	
30	257.35	300	312.5	62.5	250	

The analysis is based on the following assumptions:

- Steady state flow.
- Incompressible fluid.
- Laminar flow.
- Constant properties of both fluids and solid.
- Effects of viscous dissipation are negligible.

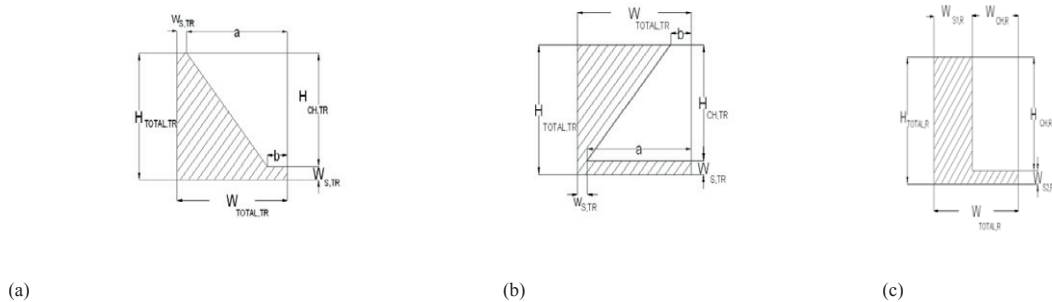


Figure 1: Different geometries used in analysis (a) V-type (b) A-type (c) Rectangular

2.2. Governing Equations

Based on the above assumptions the governing equations of mass, momentum and energy as applied to the fluid region were:

$$\text{Continuity:} \quad \nabla \cdot \vec{V}_f = 0 \quad (1)$$

$$\text{Momentum:} \quad \rho_f \vec{V}_f \cdot \nabla \vec{V}_f = -\nabla P_f + \mu_f \nabla^2 \vec{V}_f \quad (2)$$

$$\text{Energy:} \quad \vec{V}_f \cdot \nabla T_f = \alpha_f \nabla^2 T_f \quad (3)$$

where the variables \vec{V} , μ , ρ and α represent fluid velocity, viscosity, density and thermal diffusivity respectively. 'P' and 'T' denote pressure and temperature while the subscript 'f' denotes fluid. For solid region, the following energy equation was solved.

$$\text{Energy (for heat transfer):} \quad \nabla^2 T_s = 0 \quad (4)$$

' T_s ' represents the temperature of solid region with subscript 's' representing solid region. Since we are to compare the performance of two different duct shapes, it is necessary to evaluate hydraulic diameters which are tabulated in Table 1.

$$\text{Hydraulic diameter was calculated as:} \quad D_h = 4A/S \quad (5)$$

Here A and S are the area and wetted perimeter of the single channel respectively.

2.3. Boundary Conditions

The following boundary conditions are applied to the computational domain in the present study. The adiabatic conditions were applied to the top surface, as the heat sink cover is usually made of poorly conducting material. Similarly,

at the entrance and exit walls of the solid region, adiabatic conditions were assumed considering heat transfer due to fluid as dominant factor and while outer wall of solid region was assumed to be adiabatic owing to symmetry condition.

Uniform heat flux, $q'' (=10^6 \text{ W/m}^2)$ is applied at the base, while uniform velocity and temperature was imposed at the inlet. For water inlet temperature as assumed to be 300 K while in case of liquid gallium, owing to its melting point ($29.8 \text{ }^\circ\text{C} \approx 303\text{K}$ [7]) inlet temperature was assumed to be 305K. Continuity of temperature and heat flux as well as no slip condition was assumed at solid-liquid interface. Further, symmetry conditions were imposed on the plane $x=0$ in all the cases. The solid region was assumed to be made of silicon.

2.4. Solution methods and Grid Independence

The continuity, momentum, and energy equations were solved using general purpose finite volume based code, FLUENT. The standard scheme for pressure discretization, SIMPLE algorithm for pressure velocity coupling and the first order upwind scheme for momentum and energy equations were used. For grid independence, three grid sizes were tested separately for each geometrical configuration and further refinement of grid was stopped when variation in results upon further decrease in grid size was below 1% in lieu of computational resources and time

3. Results and Discussions

The performance of microchannels having trapezoidal (A and V configurations) and rectangular cross-section are compared using liquid gallium and water as coolant. The range of flow rate considered for comparison varies from $2.8 \times 10^{-8} \text{ m}^3/\text{s}$ to $1.22 \times 10^{-7} \text{ m}^3/\text{s}$ which corresponds to Reynolds number 251 to 879 for liquid gallium and $8.44 \times 10^{-8} \text{ m}^3/\text{s}$ to $3.66 \times 10^{-7} \text{ m}^3/\text{s}$ which corresponds to Reynolds number 230 to 805 for water.

3.1. Comparison for liquid gallium

The performance of various aforementioned microchannel ducts is compared on the basis of flow rate and is shown in figure 2(a). It is observed that for the range of flow rates under study, the performance of A and V-type is superior for liquid gallium. This may be attributed to the lower hydraulic diameter in case of trapezium shaped duct resulting in enhanced heat transfer. Further for comparison among A and V type we define following expression.

$$T_V - T_A = T_{V-A}$$

(6)
where T_V and T_A are the maximum temperatures corresponding to V and A type configurations respectively. As can be seen from the figure 2(b), the performance of A-type is superior at all flow rates as can be deduced from increasing trend of T_{V-A} . Better results obtained for A-type amongst all configurations may be due to the fact that it has maximum amount of coolant flowing close to the heated surface and thereby resulting in maximum heat transfer.

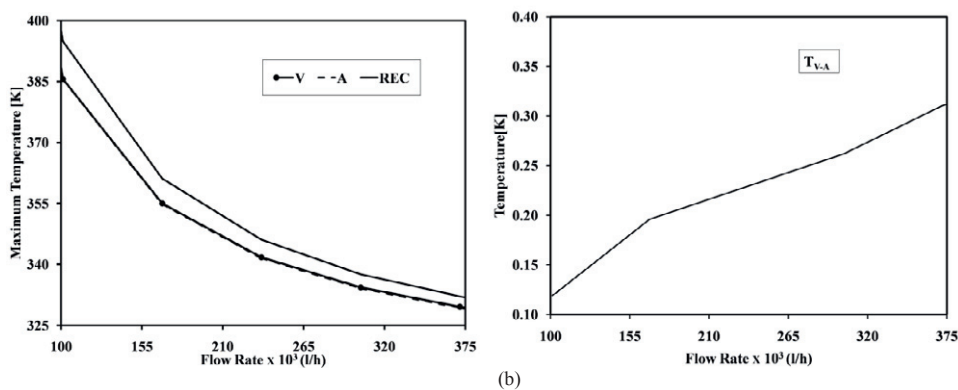


Figure 2 : (a) Maximum Temperature versus Flow rate (b) T_{V-A} versus Flow rate

Whereas decrease in hydraulic diameter increases heat transfer it also increases in pump power. Figure 3(a) shows comparison on the basis of pump power which shows that in case of rectangular geometry maximum temperature attained is lower at same pump power. This suggests that in case of liquid gallium the effect of decrease in hydraulic diameter is more predominant on increasing pump power than in heat transfer. Similar results are found in case of minimal temperature variation (difference between maximum and minimum temperature attained at heated surface) as shown in figure 3(b).

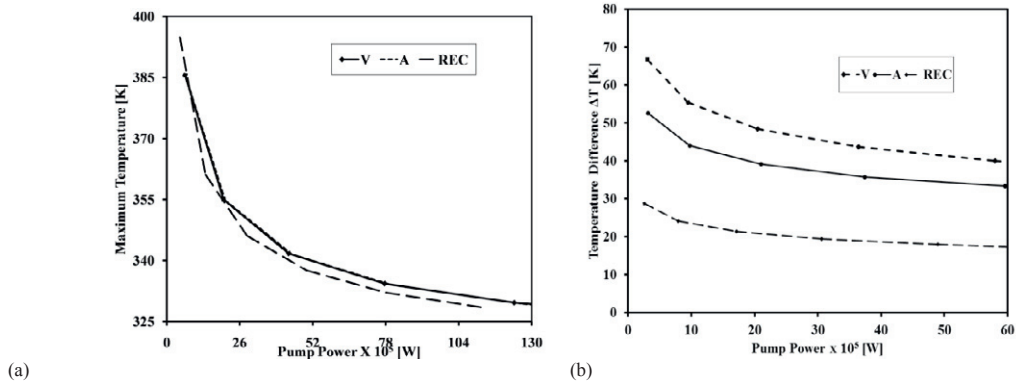


Figure 3: (a) Maximum Temperature versus Pump Power (b) ΔT versus Pump Power

3.2. Comparison for water

In this section results pertaining to water as coolant are presented. The major difference is heat transfer phenomenon of liquid gallium and water is due to difference in their Prandtl number. High Prandtl number of water causes heat transfer mainly governed by thermal boundary layer whereas in case of liquid gallium it is mainly governed by its thermal conductivity. Figure 4(a) shows maximum temperature versus flow rate with water as cooling medium. It can be seen that rectangular cross-section shows better performance at same flow rate followed by A and V-type as can be observe from the figure 4(a). Further, similar results are obtained on the basis of pump power as shown in figure 4(b). This can be better understood with the help of temperature contours of fluid region for rectangular and V-type geometry. These are depicted in figure 5(a-b) for rectangular and V-type respectively. The free stream region (i.e. the volume of fluid which is yet to feel the effect of heat) governs heat transfer greatly because this region has the lowest temperature. With less fluid region coming in contact with substrate surface nearest to base in case of V-type, heat transfer is largely affected. Further in case of rectangular duct the core region has yet to feel the effect of heat is evenly distributed thereby allowing for efficient heat transfer. Whereas in case of V-type most of this region is far from heated surface offering longer path and hence offering more thermal conduction resistance, for A-type reduction in volume of this region as we go away from base may explain its inferior performance.

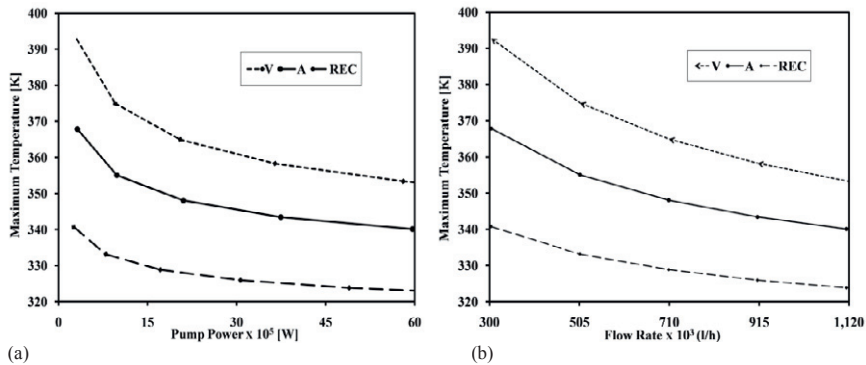


Figure 4: (a) Maximum Temperature versus Pump Power, (b) Maximum Temperature versus Flow Rate

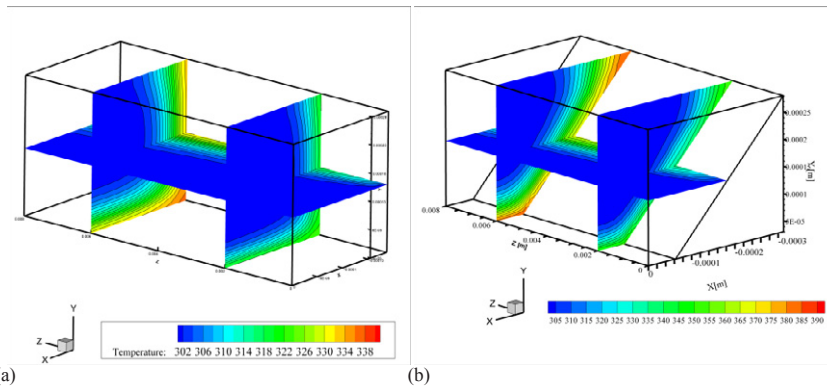


Figure 5: Temperature contours of fluid region for (a) Rectangular type and (b) V-type.

4. Conclusion

The performance of the rectangular and trapezoidal duct using water and gallium is compared. It can be deduced that for effective cooling by micro-channels, cross-section and type of coolant plays an important role and has to be analyzed carefully. At same flow rate for all geometric configurations, geometry having A-type trapezoidal configuration makes a suitable choice and if our only concern is to provide cooling effect without considering the power consumed A-type geometry is favored in case liquid gallium is to be used. However owing to larger pressure drop due to reduced hydraulic diameter, rectangular configuration is favored. In case water is used as coolant rectangular geometry seems to be the right choice in terms of Pump power and Flow rate. Further comparative study with different trapezoidal geometries need to be done for better understanding.

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