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Performance Comparison of Single and Double Layer Microchannel Using Liquid Metal Coolants: A Numerical Study

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Abstract - **With increase in demand for new cooling solutions, double layer configuration of microchannels has been extensively studied. Recently liquid metals have also been proposed to further improve cooling owing to their high thermal conductivity. However, their advantages with double layer system are yet to be explored. A comparative study is made between single and double layer microchannel using liquid metals (liquid gallium) as the cooling medium. The type of configuration (counter or parallel) best suited is analysed and the results are compared with single layer for four different lengths. The cross-sectional area of single layer is such that it has same flow area as that of double layer microchannel. The performance of both is compared under the conditions of same flow rate and pump power. It is judged on the basis of maximum temperature attained and minimal temperature variations at the heated surface. It is observed that with liquid metal (gallium) as coolants, the double layer arrangement doesn't prove much advantageous and better results can be obtained using single layer. Results also favour liquid metals for small lengths of microchannels showing their favourability for miniaturized cooling systems.**

Keywords: **Conjugate heat Transfer, Double layer, Liquid metals, Single layer**

I. Introduction

With recent developments in field of microelectronics and ever increasing demand for higher computational speed and superior performance, power density levels have increased several manifolds. The peak power consumption in high performance desktop applications is expected to touch the 198 W mark by 2015[1] and expected dissipation of heat flux in next generation microprocessors and microelectronic components is over 1000W/cm^2 [2]. Consequently, dissipation of large amount of heat within a small space has increased temperature levels. To ensure consistent operating parameters and reliability of the circuits, there is a need to maintain operating temperatures within certain limits. The conventional cooling systems such as air cooling, heat pipes, thermoelectric cooling etc. are either incompatible with new microelectronic components or seem to have reached their practical limit. This has motivated researchers to come with several solutions which have been summarized in , according to their heat removal capacity. Among these, of the coolant temperature at entrance and exit. As a result, large temperature gradients prevail in substrate which over a period degrade the performance and reduce the components reliability. Several solutions have been proposed to overcome this problem. The concept of flexible microchannel heat sink, which utilized flexible soft seals to enhance heat transfer, was proposed by Khaled and Vafai and has been discussed in detail in their work [13, 14].

A significant amount of work has also been done regarding flow pattern to reduce such gradients. The liquid cooling using microchannel have caught most of the attention owing to their several advantages such as their direct integration on the substrate (electronic chip) which can reduce thermal contact (internal) resistance almost to zero. Moreover, reduced hydraulic diameters allow for significantly high values of heat transfer coefficients, of the order 10^3 W/m^2.

Tuckerman and Pease were the pioneers who introduced the concept of microchannel cooling. They demonstrated that with microchannels 50 µm wide and 300 µm deep, very small thermal resistance (9×10^{-6} K/ (W/m^2)) is possible with power density of 790 W/cm^2. Following this, significant contributions have come up in this field with investigations related to hydraulic and thermal performance of microchannels which can be classified as experimental and numerical [5-8]. Several review articles have also been published pertaining to geometrical, experimental and numerical reviews[9-12]. Despite several advantages, heat dissipation within small region results in significant variation early work of Missaggia and Walpole presented single layer counter flow heat sink in which flow of water took in opposite directions in adjacent channels which reduced on chip temperature variations. A novel concept of double layer microchannel was proposed by Vafai and Zhu [16] which mainly addressed the issue of reducing temperature gradients and variations at the heated surface. It consisted of two layers of heat sink in which flow of coolant (water) in opposite directions aided in reducing temperature variations at the heated surface. Following this, substantial research has been done in this field to further investigate and explore the advantages of such kind of system. The concept of double layer microchannel has been further extended to stacked microchannels[17,18] .

Majority of the work discussed so far was carried out using water as cooling medium or similar high Prandtl number fluids. Recently, use of liquid metals with low melting point for cooling of high power density devices has been proposed by Liu and Zhou [19]. All such possible liquids have been reviewed in detail by Kunquan and Liu [20] amongst which liquid gallium and its alloys were considered most suitable owing to their overall superior thermo-physical properties. These can be summarized as high thermal conductivity, low melting point, non-toxic nature, boiling point higher than 2200°C eliminating power density as a limiting factor etc. The experimental study of Miner and Ghoshal [21] showed that heat transfer coefficients of the order 10W/cm^2/K are achievable using gallium alloy,$Ga^{68}In^{20}Sn^{12}$. Further, experiments performed by Li *et al* [22]. under different flow and heat dissipation rates using liquid gallium showed that temperature drop in case of liquid gallium was 46.7^{o}C against 51.9^{o}C with water. The need for smaller radiator size was also observed when using liquid gallium as cooling medium.

Whereas high thermal conductivity of liquid metals is advantage on one hand, their low specific heat is a disadvantage which may cause higher temperature difference at fluid inlet and exit. The difference in thermo-physical properties of liquid metals as compared to high Prandtl number fluids has motivated the current study to compare the performances of double layer and single layer microchannels. Further, investigating the performance dependence of double layer microchannel on type of fluid was also a propelling factor for this work.

In this study, the performance of single and double layer microchannel is compared using conjugate heat transfer analysis using liquid gallium as the cooling medium. Since the temperature gradients are expected to be in all the directions, a three dimensional model is adopted in the present work. To see if there is any effect of length on the performance, four different lengths have been considered. For sake of brevity SL, DLCF, DLPF is used throughout representing single layer, double layer counter flow and double layer parallel flow configurations respectively.

II. Analysis

In this section, various aspects related to analysis are described briefly. These include experimental units (computational domain), boundary conditions, assumptions etc.

A. Computational Model

Single and double layer microchannel heat sink (parallel and counter configurations depicted using arrows) along with the coordinate system is shown in Fig.1 (a-b) respectively. These also represent computational domains under study.

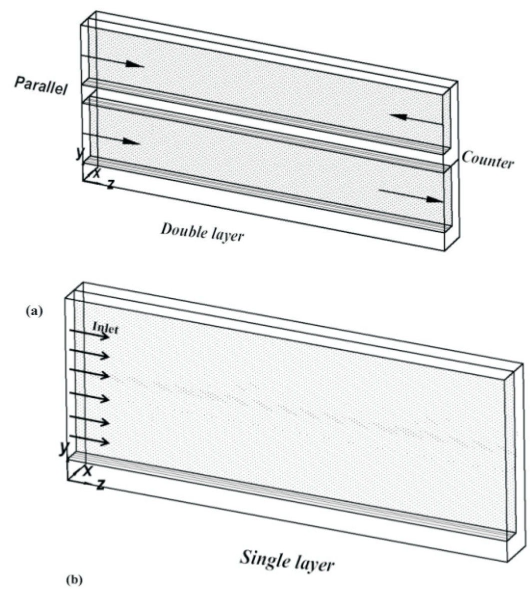

Fig. 1 Three dimensional computational domains
(a) Double Layer Microchannel (b) Single Layer Microchannel

The cross section of the geometry used in this analysis is same as used by Vafai and Zhu[16] . For comparing both the systems, total flow area (inlet cross sectional area) of SL is same as that of DL system. Only one half of both the type of heat sinks has been included in the computational domain owing to symmetry conditions. '$H_{ch,DL}$' and 'W_{ch}' represent the height and width of each channel of DL respectively. '$H_{total,DL}$' and 'W' denote the total height and width of the computational domain, respectively. 'W_s' is the thickness of solid region while 'L_1, L_2, L_3 and L_4' represent four different lengths considered for analysis. For SL system, '$H_{ch,SL}$' and '$H_{total,SL}$' denote channel height and computational height respectively. Rest of the dimensions are same as that of DL heat sink. Table 1 summarizes all the dimensions. These are also represented pictorially in Fig. 2.

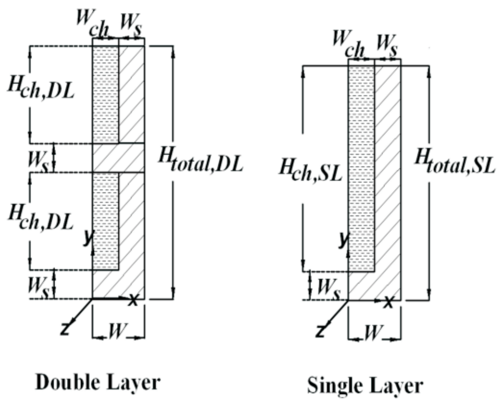

Fig. 2 Various Dimensions Used in analysis

The analysis is based on the following assumptions:

i. Steady state flow.
ii. Incompressible fluid.
iii. Laminar flow.
iv. Constant properties of both fluids and solid.
v. Effects of viscous dissipation are negligible.

TABLE I VARIOUS DIMENSIONS USED IN THE ANALYSIS

Variable	Dimension (in µm)
W_{ch}	30
W_s	30
W	60
$H_{ch,DL}$	100
$H_{ch,SL}$	200
$H_{total,DL}$	260
$H_{total,SL}$	230
L_1	2000
L_2	4000
L_3	6000
L_4	8000
D_{UC}	75
D_{LC}	75
D_{SL}	92.3

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

Continuity:

$$\nabla . \vec{V_f} = 0 \quad (1)$$

Momentum:

$$\rho_f \vec{V_f} . \nabla \vec{V_f} = -\nabla P_f + \mu_f \nabla^2 \vec{V_f} \quad (2)$$

Energy:

$$\vec{V_f} . \nabla T_f = \alpha_f \nabla^2 T_f \quad (3)$$

where the variables $\vec{V}$, μ, ρ and α prepresent fluid velocity, viscosity, density and thermal diffusivity respectively. *'P'* and *'T'* denote pressure and temperature while the subscript 'f' denotes fluid. The following energy equation was applied to solid region. Energy (for heat transfer):

$$\nabla^2 T_s = 0 \quad (4)$$

'T_s' represents the temperature of solid region with subscript's' representing solid region.

Further, hydraulic diameters (required to calculate Reynolds Number) are calculated as:

i. Double Layer system

$$D_{UC,LC} = \frac{4a_{UC,LC}}{S_{UC,LC}} = \frac{4(2W_{ch})H_{ch,DL}}{2(2W_{ch} + H_{ch,DL})}) \quad (5)$$

ii. Single layer system

$$D_{SL} = \frac{4a_{SL}}{S_{SL}} \left(= \frac{4(2W_{ch})H_{ch,SL}}{2(2W_{ch} + H_{ch,SL})}\right) \quad (6)$$

Here *'a'* and *'S'*, are the area and perimeter of the channel respectively while subscripts UC,LC and SL denote upper and lower channel of DL systems and SL respectively. The hydraulic diameters are also tabulated in Table I.

The Reynolds number is defined as

$$Re = \frac{\rho_f w_{avg,f} D_{UC,LC,SL}}{\mu_f} \quad (7)$$

where '$w_{avg,f}$' is mean flow velocity of the fluid while *'D'* denotes the hydraulic diameter of channel and other subscripts have same meaning as described before.

B. Boundary Conditions

In any computational analysis, boundary conditions play a significant role describing the type of analysis and nature of equations that are being solved. The boundary conditions as applied to computational domain in present study are shown in Fig. 3. Uniform heat flux, q'' (=10^6 W/m^2) is applied at the base, at y = 0 µm. The adiabatic conditions were applied at the following faces:

i. Top surface as the heat sink cover is usually made of poorly conducting material.
ii. The entrance and exit walls of the solid region considering heat transfer due to fluid as dominant factor.

iii. Outer wall of solid region owing to symmetry condition.

Uniform velocity and temperature conditions were imposed at the inlet of both the systems. For DLCF, Z=0 represents inlet for lower channel and outflow for upper channel while for DLPF it denotes former for both the channels. For SL system, inlet conditions were imposed at Z=0. Uniform pressure condition at the outlet was applied in all cases. Continuity of temperature and heat flux as well no slip condition was assumed at solid-liquid interface while symmetry conditions were imposed on the plane X=0 in all the cases.

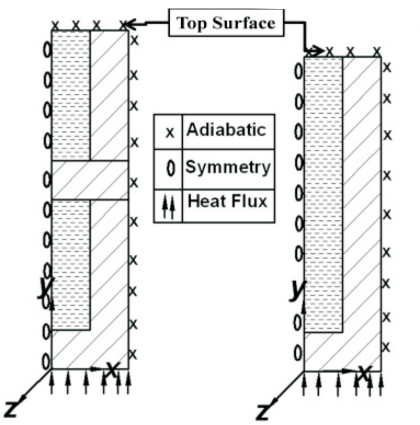

Fig. 3 Boundary Conditions

The solid region was assumed to be made of Silicon. Table II lists all the material properties used in this present study. Since melting point of gallium is 29.8°C ($\approx$ 303 K) [20], the inlet temperature was assumed to be 305 K and thermo-physical properties of liquid gallium at 313 K were used.

TABLE II PROPERTIES OF MATERIALS

Property \ Material	Silicon	Liquid Gallium
Density (kg-m^{-3})	2328	6088[a]
Specific Heat (J-kg^{-1}K^{-1})	705	400[b]
Thermal Conductivity (W-m^{-1}K^{-1})	150	29
Viscosity (Ns-m^{-2})	-	.000187[c]

a,c: from Ref. b: from Ref.

C. Solution Method and Grid Independence

The continuity, momentum, and energy equations were solved using general purpose finite volume based commercial code, FLUENT. The standard scheme for pressure discretization, SIMPLE algorithm for pressure velocity coupling and the second order upwind scheme for momentum and energy equations were used. For grid independence, three grid sizes were tested separately for each length using counter flow arrangement in case DL system. In lieu of computational resources and time, further refinement of grid was stopped when variation in results upon further decrease in grid size was below 1%. Similar procedure was adopted for SL system. For example, grid size of '24x66x50' and '24x76x50' was used (in x x y x z directions) for DL and SL system (L_1 length).

III. RESULTS AND DISCUSSION

The performance of liquid gallium in counter and parallel arrangement for DL and SL is compared for each length. The range of flow rate considered for comparison varies from $0.72x10^{-8}$ m^3/s to $3.6x10^{-8}$ m^3/s, which corresponds to Reynolds number 147 to 732 for DL and 180 to 902 for SL. It is to be noted that flow rate mentioned here is the total flow rate in DL microchannel (i.e. sum of flow rate in upper and lower channel). The following abbreviations have also been used extensively for the sake of simplicity, 'PF' for parallel flow, 'CF' for counter flow, 'UC' for upper channel 'LC' for lower channel and L_1, L_2, L_3, and L_4 representing lengths of the microchannel as described in Table I. The term flow rate has been used instead of total flow. In addition, where results follow same trend for all lengths, results pertaining to only two of the lengths have been shown.

A. Comparison Based on Maximum Temperature Attained at the Heated Surface

In this section the performance of both the systems is evaluated on the basis of maximum temperature attained at the heated surface. This forms one of the basic criteria in any comparison as it is always desired to keep maximum temperature as low as possible.

1. Maximum Temperature Versus Flow Rate

Fig. 4 (a-b) shows maximum temperature reached at different flow rates for DLCF, DLPF and SL system for lengths L_1 and L_3 considered in the study.

It is observed that for both the lengths and at all flow rates, maximum temperature reached in DLCF is much higher as compared to DLPF and SL system. This behaviour of liquid gallium may be attributed to its low specific heat which results in significant rise of temperature of liquid gallium in DLCF. This is attributed to heat flow at inlet of LC not only from base but also from UC and vice-versa in case of UC which doesn't happen in case of DLPF. This prevents significant rise in temperature of coolant (liquid gallium). It can also be seen that the difference between maximum temperature attained at low and high flow rate is quite significant for counter arrangement in comparison to DLPF and SL configurations, especially for longer length. In other words, rate of decrease of maximum temperature attained at the base with flow rate is significantly higher for DLCF whereas it tends to remain nearly same for other two configurations under study. This is true for all the lengths considered. This means the performance of DLCF is significantly affected by flow rate. This may be explained as follows. The temperature attained by liquid gallium at exit decreases with increasing flow rates. This means flow of heat from UC to LC and vice versa is lower thereby allowing for more efficient heat transfer and distribution.

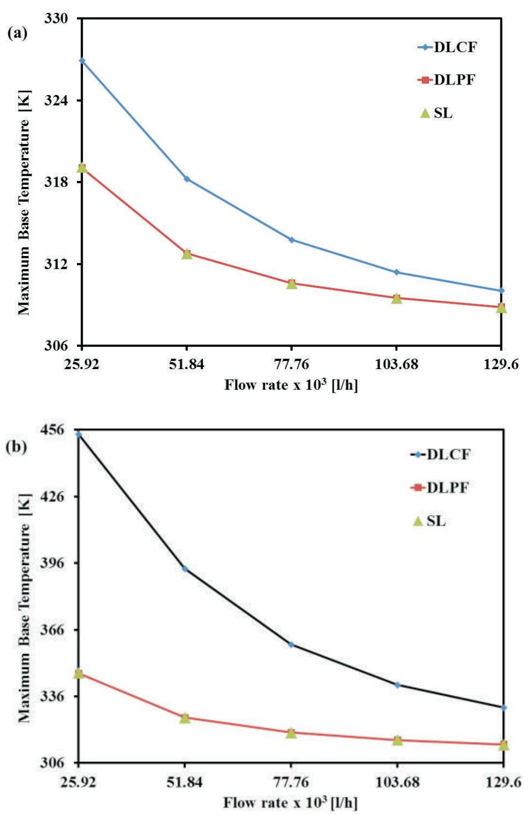

Fig. 4 Maximum Temperature reached at the base for all three configurations i.e. SL,DLCF,DLPF for the following lengths (a) L_1 (b) L_3

For further analysis of the results, difference between maximum temperature attained for DLPF and DLCF w.r.t SL system is depicted in Fig. 5 for L_2 length. It is defined as:

$$\Delta T_{(DLCF-SL)} = T_{max,DLCF} - T_{max,SL} \tag{8}$$

Here, 'T_{max}' is maximum temperature attained at base and this relation is defined for same flow rate. Similar relations hold for parallel configuration.

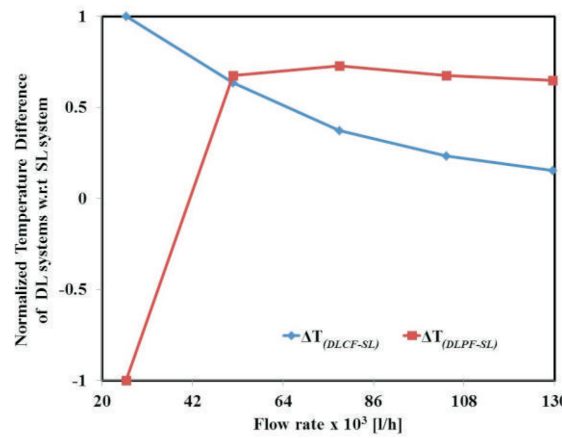

Fig. 5 Difference between Maximum t emperature attained in DLCF and DLPF w.r.t SL system (Normalized) versus Flow Rate (L_2 length)

The results shown are normalized (w.r.t absolute value) for each category. It is to be noted that since, similar pattern was observed in maximum temperature versus flow rate for all four lengths, only one length is considered here for sake of brevity. However the results for remaining lengths have been tabulated in Table III. It is interesting to note that superior performance between DLPF and SL system is flow rate dependent. This is evident from negative values at low flow rates which shows lower temperature attained in case of DLPF. The same trend is followed for all four lengths as can be seen from Table III. It can be deduced from the Fig. 5 and Table III that at low flow rates, performance of DLPF is superior whereas with increase in flow rate, SL heat sink system is more suitable.

TABLE III NORMALIZED TEMPERATURE DIFFERENCE OF DL SYSTEM CONFIGURATIONS W.R.T SL SYSTEM FOR L_1 L_3 AND L_4

Flow Rate x 10^3 [ml/h]	L_1		L_3		L_4	
	ΔT DLCF-SL [K]	ΔT DLPF-SL [K]	ΔT DLCF-SL [K]	ΔT DLPF-SL [K]	ΔT DLCF-SL [K]	ΔT DLPF-SL [K]
0.6	1	-1	1	-1	1	-1
1.2	0.70	0.73	0.62	0.66	0.63	0.67
1.8	0.41	0.81	0.37	0.70	0.38	0.66
2.4	0.25	0.78	0.23	0.68	0.23	0.64
3.0	0.16	0.76	0.15	0.62	0.15	0.59

Another important observation to note is that there is first increase in normalized temperature difference followed by its decrease at all the lengths. This shows that after a certain flow rate, even though the performance of single layer is superior, but its rate decreases beyond a certain flow rate. However, this should not be of much concern because at higher flow rates, the flow regime may become turbulent requiring different analysis.

B. Thermal Resistance Versus Pump Power

In practical approach, the performance of heat sink is limited by flow rate which depends on available pumping power. Further, thermal resistance addresses the performance more appropriately as it accounts for both heat flux and maximum temperature rise. Hence, for further understanding the phenomena of cooling using liquid gallium (metals) in DL and SL systems and making the analysis more relevant to practical systems, thermal resistance versus pump power is shown in Fig. 6 (a-b) for lengths L_2 and L_4.

We define, thermal resistance as:

$$R_{th} = \frac{T_{base,max} - T_{f,in}}{q''} \tag{9}$$

Similarly pump power can be defined as:

$$PP = \Delta P Q_F \tag{10}$$

Here 'ΔP' represents pressure drop while 'Q_F' represents the total flow rate. For sake of transience, only results pertaining to DLPF are evaluated owing to its superior performance as shown in previous section. Further, results are shown only for L_2 and L_4 length. As seen from Fig.6 (a-b), SL offers lower thermal resistance at same pump power for both the lengths.

This may be attributed to additional conduction resistance due to base of upper channel. The base behaves like a fin which has certain effectiveness which may reduce overall effective area thereby increasing convective resistance. Since the overall thermal resistance, in addition to bulk fluid resistance, is affected by combination convective and conduction resistances, dominance of latter may explain the observed phenomena.

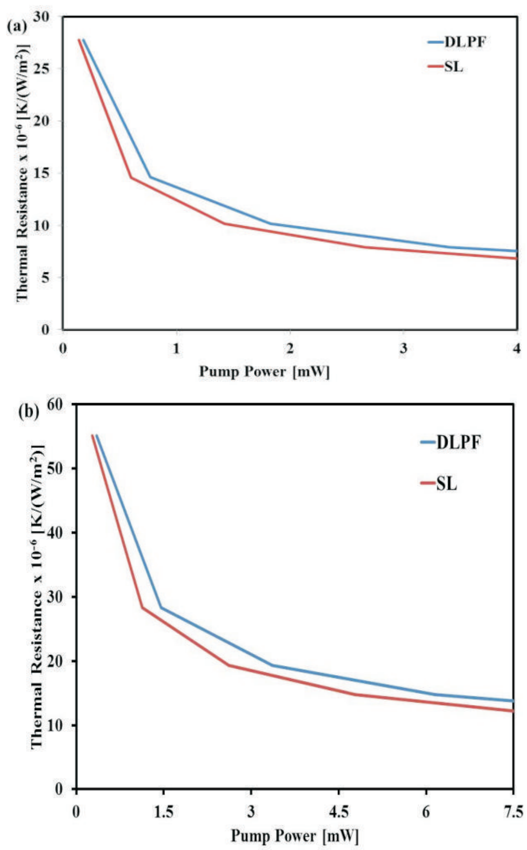

Fig. 6 Thermal Resistance versus Pump Power for lengths: (a) L_2 (b) L_4

C. Comparison on the Basis of Minimum Temperature Variations

The main idea of DL system as proposed by Vafai and Zhu[16] was to minimize temperature variations along the flow direction. This prevents thermal stresses to accumulate over a period which may otherwise lead to failure of the component. This aspect is also important for higher reliability of the system. Hence it is important to analyse whether such a system holds any advantage while using liquid gallium (metals).

1. Minimum Temperature Variations Versus Flow Rate

Fig. 7 shows flow rate versus temperature variations for L_2 length for DLCF, DLPF and SL. For remaining lengths, these are listed in Table IV.The temperature variation is defined as:

$$\Delta T = T_{max} - T_{min} \text{ (at base of heated surface)} \tag{11}$$

It is observed that performance of DLPF is better at low flow rate in terms of minimal temperature variations at the base of heated surface. However, with increase in flow rate,

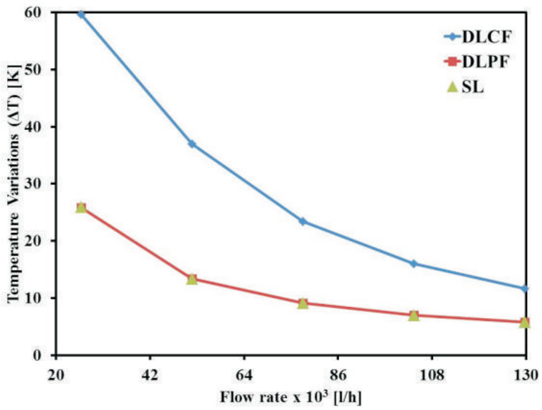

Fig. 7 Tempertaure variations at heated surface (base) for Maximum Temperature reached at the base for L_2 length.

TABLE IV TEMPERATURE VARIATION (ΔT [K]) AT HEATED SURFACE FOR L_1, L_3 AND L_4

Length / Flow Rate x 10^3 [ml-h^{-1}]	L_1 (ΔT [K])		
	DLCF	DLPF	SL
25.92	15.54	12.14	12.27
51.84	10.10	6.56	6.55
77.76	6.82	4.60	4.58
103.68	4.98	3.62	3.59
129.6	3.89	3.03	3.00

Length / Flow Rate x 10^3 [ml-h^{-1}]	L_3 (ΔT [K])		
	DLCF	DLPF	SL
25.92	131.63	39.51	39.65
51.84	80.84	20.24	20.24
77.76	50.16	13.72	13.71
103.68	33.47	10.46	10.44
129.6	23.92	8.51	8.48

Length / Flow Rate x 10^3 [ml-h^{-1}]	L_4 (ΔT [K])		
	DLCF	DLPF	SL
25.92	226.29	53.20	53.34
51.84	141.57	27.08	27.08
77.76	87.09	18.29	18.27
103.68	57.48	13.88	13.86
129.6	40.60	11.24	11.22

SL shows superior results as compared to DLPF at same flow rate conditions as can be deduced from Table IV. Moreover, there is increase in minimum flow rate beyond which performance of SL is superior with length as can be observed from Table IV. For example, at length L1, DLPF performs better up to flow rate 0.72x10^{-8} m^3/s whereas this increases to 1.44x10^{-8} m^3/s for the remaining lengths. It is to be noted that the limits described here are due to values of flow rates considered in this study. For exact limits, more values of flow rates need to be considered.

In continuation of results from previous sections, it can be seen that the performance of SL is superior both in terms of maximum temperature attained at the base as well as minimum temperature variations at the base at higher flow rates. The difference being very minimal, which may also be attributed to computational limit or error, creates the need to investigate the performance of DLPF and SL further i.e. on the basis of pump power.

2. Pump Power Versus Minimum Temperature Variations

As explained above, pumping power is one of the major constraints in the area of microchannel applications. The use of DL system was proposed to achieve minimum temperature variations as compared to SL systems at the cost of low pump power. This was possible in the studies in Vafai and Zhu[16] and others due to high specific heat of water which showed positive results for such a design, especially in counter flow arrangement. However, for liquid gallium (metals) the case may not be true as can be deduced from above sections. Further insight in this regard is found by considering Fig. 8 which depicts temperature variations against pump power for DLPF and SL. For sake of brevity only results corresponding to L_2 and L_4 length have been shown while those of DLCF have been omitted owing to its inferior performance.

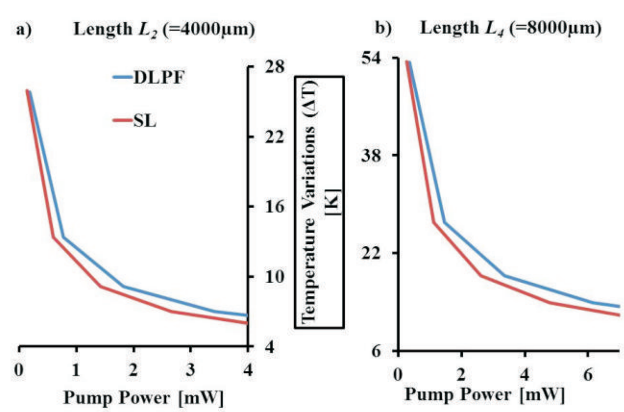

Fig. 8 Pump Power versus Temperature variations at base for lengths: (a) L_2 (b) L_4

It is observed that SL channel is suitable in terms of temperature uniformity at the base. Even though at low flow rate conditions, performance of DLPF was better under same evaluation criteria, lower hydraulic diameter in case of DL system deteriorated its overall performance. Hence it can be deduced that use of DL system may not prove advantageous in case of liquid metals and creates a need to for an alternate design. This also suggests while using liquid gallium (or metals) as coolants, the complications and reliability aspects practically linked with DL system will not be encountered. This further supports use of liquid gallium (metals) as cooling medium for compact systems as suggested in the studies of Li [22].

IV. Conclusion

Three dimensional conjugate heat transfer analysis is carried out to compare the performance of single and double layer microchannel with liquid gallium as cooling medium. Owing to different thermo-physical properties of liquid metals especially high conductivity and low specific heat, the performance of single layer microchannel system is found to be superior as compared to double layer system. Under the condition of same flow rate, single layer configuration was favoured under both the evaluation criteria i.e. maximum temperature at the base as well as minimum temperature variations beyond certain flow rate for all the lengths considered in the study. However, comparison on the basis of same pump power showed that the overall performance of single layer is superior in all aspects. Since pump power is more realistic approach, it can be concluded that under the conditions of same flow rate in both the channels of DL system and equivalent total flow rate in SL system, single layer heat sink is suitable while using liquid gallium (metals) as cooling medium. This also suggests that liquid gallium (or metals) is more suited for compact and reliable systems.

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Nomenclature

a	Cross sectional area of microchannel
D	Hydraulic diameter (μm)
DLCF	Double layer counter flow
DLPF	Double layer parallel flow
$H_{ch,DL}$	Height of each channel in double layer microchannel (μm)
$H_{ch,SL}$	Height of channel in single layer microchannel (μm)
$H_{total,DL}$	Total height of computational domain in case of double layer microchannel (μm)
$H_{total,SL}$	Total height of computational domain in case of single layer microchannel (μm)
L	Length of microchannel (μm)
LC	Lower channel
P	Pressure (Pa)
PP	Pump power (mW)
q''	Heat flux (W/m2)
Q_F	Flow Rate
R_{th}	Thermal Resistance (K/(W/m2))
R*e*	Reynolds Number
S	Cross sectional perimeter (μm)
SL	Single layer (microchannel)
T	Temperature (K)
UC	Upper channel
$w_{avg,f}$	Mean flow velocity in z direction
W	Total width of computational domain in double and single layer microchannel systems (μm)
W_s	Width of solid region (substrate) (μm)
W_{ch}	Width of microchannel (μm)
x,y,z	coordinate system (μm)

Subscripts

base	base of microchannel (y= 0 μm)
ch	channel
ch,DL	channel of double layer system
ch,SL	channel of single layer system
f	fluid
LC	lower channel
max	maximum
min	minimum
s	solid region
UC	upper channel
1,2,3,4	lengths of microchannel (2000, 4000, 6000 and 8000 μm respectively)

Greek Letters

α	thermal diffusivity
ρ	density
μ	dynamic viscosity
Δ	delta (change in Pressure)

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