THERMAL MODELLING AND NUMERICAL INVESTIGATIONS ON A DOUBLE LAYERED MICROCHANNEL HEATSINK

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Abstract - 1-D thermal model is developed in the present study to find the complicated relationship between the overall thermal performance of a DL-MCHS with counter flow configuration, different geometrical parameters and flow conditions. Numerical investigationsarealso carried out to analyse the thermal resistance, pumping power and temperature distribution in the substrate of a DL-MCHS. The results of the present study show a good agreement of the developed 1-D thermal resistance model of a DL-MCHS with the existing literatures and present numerical results. It is observed that the thermal resistance is decreased by 6.01% and temperature uniformity is increased by 42.57% for counter flow DL-MCHS as compared to SL-MCHS with similar geometric and flow configurations.

Keywords - Double Layered Microchannel Heat Sink, Thermal performance, Pumping power;

I. INTRODUCTION

Thermal management of the electronics and computer industries for high-end applications in 21st century becomes substantial in order to improve reliability and prevent premature failure of the system. However major issues ofhigher power density and higher temperature non-uniformity are still associated with microelectronics cooling. Since the invention of liquid cooled Single-Layered Microchannel Heat Sink (SL-MCHS) in 1981 by Tuckerman and Peace [1], it has become an efficient and preferable cooling technique for such higher heat dissipation requirement commercially compared to other cooling techniques. However, over the years it is perceived that non-uniformity of substrate temperature and higher-pressure drop are the shortcomings of SL-MCHS which leads to local overheating, degraded reliability and short lifetime of the devices.In order to improve the uniformity of substrate temperature distribution in a SL-MCHS, Vafai and Zhu [2] came up with the concept of Double layered MCHS (DL-MCHS). Subsequently many researchers have started investigations on a stacked MCHS which is recently reviewed by Lu and Vafai [2]. A comprehensive review summarized that DL-MCHS and ML-MCHS designs reduce the problem of high streamwise temperature rise and they reduce the thermal resistance and pumping power to a large degree. However, the detailed thermal modelling of a DL-MCHS is found ambiguous in the available literatures. Therefore, the thermal characteristics of counter flow DL-MCHS is compared with the SL-MCHS using thermal modelling and numerical approach in present study.

II. THERMAL MODELLING OF A DL-MCHS

The schematic diagram of a DL-MCHS is shown in Figure1. The geometrical parameters involve heat sink base size (L_{hs} and W_{hs}) and channel size (W_c, W_w and H_c). Number of channels are estimated as $n= W_{hs}/(W_c+W_w)$. The hydraulic diameter D_h is calculatedas$2W_cH_c/(W_c+H_c)$. L_{hs} is the base length of a heat sink, W_{hs} is the base width of a heat sink, W_c is the Width of a channel, W_w is the Width of a fin and H_c is the channel height. Channel Aspect ratio is defined as $\alpha=H_c/W_c$. The influence of these geometrical parameters on thermal performance of SL-MCHS is detailed by Patel et al. [3].

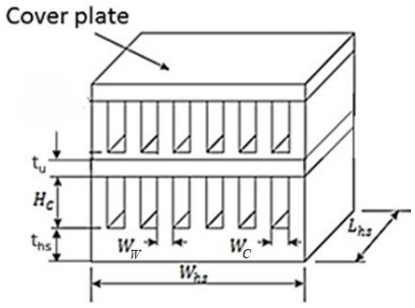


Figure 1:Schematic of DL-MCHS

In DL-MCHS, two stacks of SL-MCHS are configured one atop the other. The fluid is flowing through both the layers simultaneously either in counter or parallel direction depending upon the flow configurations.Here, in the present study, heat transfer and pressure drop analysis of upper and lower channel of DL-MCHS is carried out by considering the specific layer as SL-MCHS. Hence, similar equations of Nusselt number and pressure drop of SL-MCHS are used for the specific layer of DL-MCHS. As the assumed condition is thermally developing in each layer, the average Nusselt number correlation for four-sided heating and thermally developing flow condition is determined from the equations proposed by Lee and Garimella [4]. Though the network of thermal resistance is different from SL-MCHS,the thermal resistance network of counter flow DL-MCHS is implemented as single

repetitive unit of upper and lower layers. The thermal resistance network of counter flow DL-MCHS, which was developed by Chong et al. [5] is adopted for the present analysis. However, it is observed in the present analysis that the thermal resistance network developed by Chong et al. [5] under-predicts the total thermal resistance of counter flow DL-MCHS. It is observed that Chong et al.[5] have not consider the thermal resistance formed in the base and top cover of the DL-MCHS. Moreover, conduction through fins in the upper layer was also not considered in their model. Therefore, a thermal resistance model for counter flow DL-MCHS is developed in the present study with some modification. The comparison of analytical results with numerical results shows good accuracy with modified thermal resistance model.

Since the geometrical parameters such as heat sink base size, channel dimensions and fluid inlet temperature and velocity of the fluid at the inlet of the channel are known, the other parameters can be calculated from the following equations. In present analysis, velocity of fluid is given at the inlet of the upper and lower channel.

The total thermal of the heat sink is given by Eq. 1

$$R_{total} = (T_{s,max} - T_{in})/Q \quad (1)$$

Where, $T_{s,max}$= maximum temperature of the base of substrate T_{in} = inlet temperature of coolant and Q is the heat flux supplied at the bottom of the substrate.

For counter flow DL-MCHS, R_{total} consists of thermal resistance of upper and bottom layer. The total thermal resistance of the single repetitive unit of counter flow DL-MCHS can be expressed as shown in Eq. 2.

$$\frac{1}{R_{total}} = \frac{1}{R_{lower}} + \frac{1}{R_{upper}} \quad (2)$$

Where, R_{lower} and R_{upper} are the thermal resistance in the lower layer and upper layer respectively.If there are n repetitive units (number of channels), then overall thermal resistance can be expressed as$R_{total,overall} = R_{total}/n$

The total thermal resistance consists of lower channelthermal resistance and upper channel thermal resistance,

Which are describe as follows:

The lower channel thermal resistance can be expressed as Eq. (3)

$$R_{lower} = R_{base} + R_{cond,lower} + R_{conv,lower} + \left(\frac{1}{R_{cap,lower}} + \frac{1}{R_{cross}}\right)^{-1} \quad (3)$$

Where, R_{base} is the conduction thermal resistance in the base of the substrate in the lower channel layer, which can be calculated by to Eq. 3 considering the dimensions of channel. $R_{conv,lower}$is the convective thermal resistance which can be calculated by as (1/ (h_{lower} * A_{eff})). Same way, $R_{cap,lower}$ is the capacitive thermal resistance in lower channel layer, which can be calculated by $1/\rho_f C_{p_f} \dot{V}$.Where, ρ_f is the Density fluid and C_{p_f} is the specific heat capacity of working fluid and $\dot{V}$ is the total volumetric flow rate.$R_{cond,lower}$ is the thermal resistance associated with the fins of MCHS and can be calculated as, $R_{cond,lower} = \frac{H_c}{K_s W_w L_{hs}}$. R_{cross} is the cross channel thermal resistance which is the thermal resistance associated with the rib between the upper and lower layer and can be calculated by Eq. 5.

$$R_{cross} = \left(\frac{1}{U_0 A_0}\right) \quad (4)$$

$$U_0 A_0 = \left(\frac{1}{h_{lower} A_{lower}} + \frac{t_u}{K_s W_w} + \frac{1}{h_{upper} A_{upper}}\right)^{-1} \quad (5)$$

Here, A_{lower}, A_w and A_{upper} is calculated as (($W_c * L_{hs}$)/2) and $A_0 = A_{eff}$ for the lower channel. t_u is the thickness of the rib between the two layers. h_{lower} and h_{upper} are the heat transfer coefficient in the lower and upper layer respectively.The upper channel thermal resistance, R_{upper} is defined as

$$R_{upper}=R_{cond,upper} + R_{Conv,upper} + R_{Cap,upper}+R_{cover} \quad (6)$$

Where, R_{cover} is the conduction thermal resistance in the top cover of the MCHS, which can be calculated by $t_{cover}/(K_s(W_C + W_w)L_{hs})$considering the dimensions of top cover. $R_{conv,upper}$is the convective thermal resistance in upper layer. Same way, $R_{cap,upper}$ is the capacitive thermal resistance in upper channel layer. $R_{cond,upper}$ is the thermal resistance associated with the fins of MCHS and can be calculated as, $R_{cond,lower} = H_c/K_s W_w L_{hs}$.

A. Numerical details

The numerical investigations on a SL- and DL-MCHS is carried out using 3D solid fluid conjugated thermal model. In order to compare the performance of a DL-MCHS with SL-MCHS, the total channel height is kept same such as $H_c = (H_{c,u} + H_{c,l})$. Where, H_c is the height of channel in SL-MCHS and $H_{c,u}$ and $H_{c,l}$ are the channel heights of upper and lower layers in a DL-MCHS respectively. The other geometrical parameters are shown in table 1.

Table 1 Geometrical Parameters of SL- and DL-MCHS

Parameters	SL-MCHS	DL-MCHS
Heat sink total Width, W_{hs} (μm)	10,000	10,000
Heat sink total Length, L_{hs} (μm)	10,000	10,000
Heat sink total Height, H_{hs} (μm)	700	740
Channel width, W_c(μm)	50	50
Fin width, W_w(μm)	50	50
Channel height, H_C (μm)	500	-

$H_{c,u}$(μm)		250
$H_{c,l}$ (μm)		250
Number of channels, n	100	100 × 2
Thickness of substrate, t_{hs} (μm)	160	160
Thickness of middle rib t_u(μm)	-	40

III. RESULTS AND DISCUSSION

The modified 1-D thermal resistance model of a counter flow DL-MCHS is first verified with the experimental results of Wei et al. [6] as shown in Fig. 2 and found in good agreement. After validating the 1-D model with experimental results, the numerical simulations are carried out following the requisite numerical procedure for coupled fluid flow and heat transfer to know the insight of a counter flow DL-MCHS.

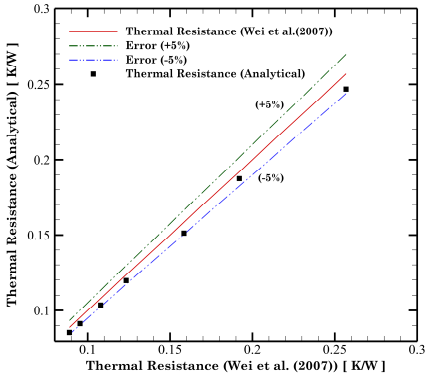


Figure2:Validation of modified 1-D thermal resistance model of DL-MCHS with Wei et al. [6]

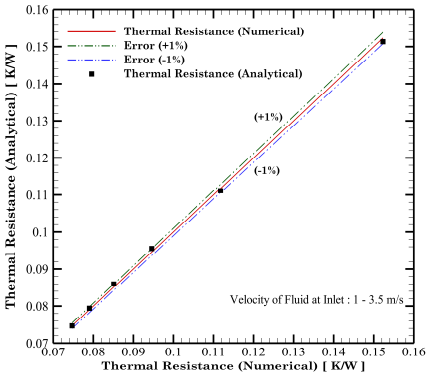


Figure3:Validation of modified 1-D thermal resistance model of DL-MCHS with present Numerical Study

The grid independence study is first carried out to ensure that the numerical results are independent of grid size. The mesh size of 4,20,000 (x = 20, y = 70 and z = 150) is confirmed for all numerical simulations. The numerical results are compared with the modified 1-D thermal resistance model as shown in Fig. 3 and found in agreement with the error range of less than 1%.

A. Influence of velocity of fluid on thermal resistance of SL-MCHS and DL-MCHS

The analytical and numerical investigations of a SL-MCHS with channel parameters shown in Table 1 is simulated and compared with that of the counter flow DL-MCHS case having same channel width (W_{ch}= 50 μm), fin width (W_w = 50 μm) and channel number of 2 × 100. For DL-MCHS, identical velocity (U_{in}= 1,1.5,2,2.5,3,3.5 m/s) is always assigned to the upper and bottom channels inlet. Heat flux of 200 W/cm^2 is applied at the bottom of the channel.

The variation in thermal resistance according to different inlet velocities is shown in Figure4. The total thermal resistance is observed to decrease with an increase in velocity of the fluid at inlet of the channel. It is due to fact that higher mass flow rate dissipates more amount of heat from the channel and diminish $T_{s,max}$.

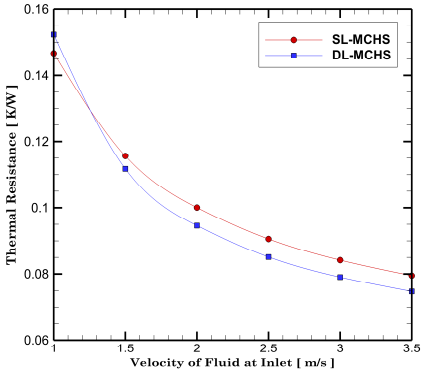


Figure4:Effect on thermal resistance

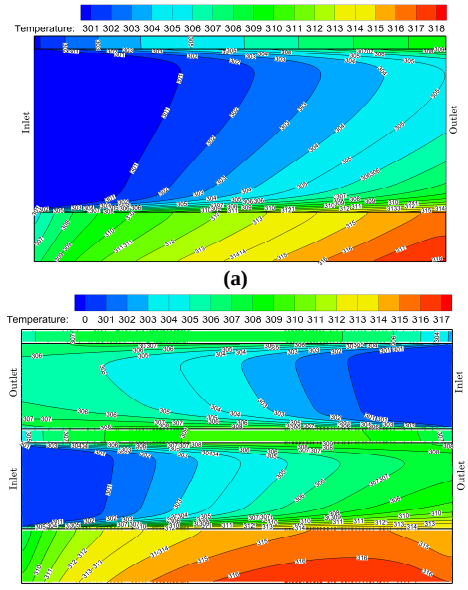


Figure5:Temperature contours at U_{in} = 2.5 m/s for (a) SL-MCHS and (b) Counter flow DL-MCHS

For MCHS, the heat generated by the heating surface is transferred to the solid ribs of the heat sink, and then the heat is dissipated by the convection heat transfer of coolant. Due to the unidirectional flow of coolant in SL-MCHS, the bulk temperature of coolant increases monotonically along the flow path, which leads to a high temperature gradient appeared at the bottom wall of the heat sink in SL-MCHS. However, in DL-MCHS with counter flow arrangement, temperature of the top coolant is lower than that of the bottom coolant in the outlet region of bottom

channels. Thus, the top coolant will cool the bottom one, which leads to heat transfer enhancement in the bottom channels. Therefore, it is observed from the Figure 4 that for a specific velocity of fluid at the inlet of the channel, thermal resistance of counter flow DL-MCHS is lower compared to SL-MCHS. The improvements are attributed to the fact that the streamwise temperature rise for coolant and substrate in each layer is compensated through conduction between the two layers. It is clearly observed from temperature contours shown in Figure 5 that the temperature in the lower substrate of counter flow DL-MCHS is lower compared to SL-MCHS. Moreover, effective heat transfer surface is for DL-MCHS is also higher compared to SL-MCHS.

B. Influence of velocity of fluid on temperature uniformity in substrate for SL-MCHS and counter flow DL-MCHS

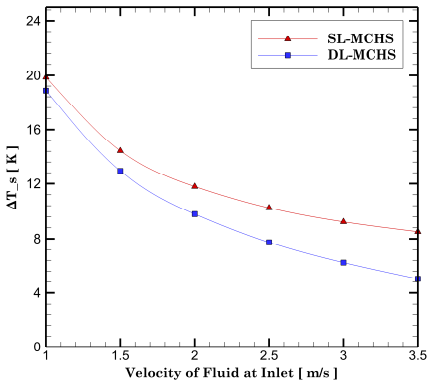


Figure6:Effect on Temperature non-uniformity

The comparison in the overall temperature uniformity in the bottom substrate for SL-MCHS and counter flow DL-MCHS is shown in Figure 6. Where ΔT_s stands for the difference between the maximum and minimum temperature in the bottom substrate of both MCHS. It is clearly observed from the Figure 6 that temperature uniformity is effectively improved in counter flow DL-MCHS compared to SL-MCHS. Such an advantage of counter-flow layout is helpful to reduce thermal stress caused by the temperature difference and improve the reliability of electronic devices.

C. Influence of velocity of fluid on Pumping power ofSL- MCHS and DL-MCHS

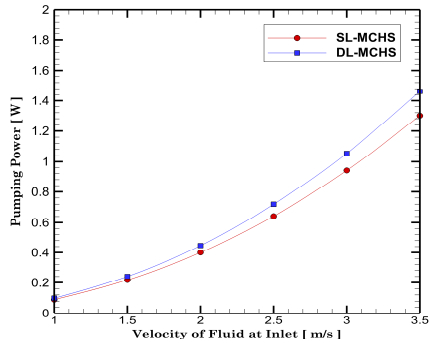


Figure7: Effect on Pumping Power

The influence of velocity on pumping power of SL-MCHS and counter flow DL-MCHS is shown in Figure 7. It is observed that as the velocity of fluid at inlet of the channel increases, the pumping power to drive the fluid across the channel increases because of the obvious reason of increment in pressure drop across the channel. Moreover, it is seen that pumping power is slightly higher for counter flow DL-MCHS as compared to SL-MCHS for the same velocity of the fluid at the inlet of the channel, because reduction in the channel height for DL-MCHS entails higher shear stresses throughout the channel.

CONCLUSIONS

The comparison of SL- and DL-MCHS is carried out using 1-D thermal resistance model and 3-D numerical analysis. From this analysis following conclusions are drawn:

1. A modified 1-D thermal resistance model ofa DL-MCHS with counter flow configuration shows agreement in the error range of ± 5% with the available experimental studies in the literature. Moreover, the modified 1-D thermal model shows agreement with the error range of ± 1%or less with the present numerical study.
2. The comparison of SL- and DL-MCHS with counter flow configuration having similar geometrical parameters using water as coolant shows 6.01% decrement in thermal resistance for DL-MCHS at same total volumetric flow rate. Moreover, it shows that temperature uniformity in the substrate of the DL-MCHS is observed to increase maximum up to 42.57% for counter flow DL-MCHS. However, the total pumping power is increased maximum up to 12% for DL-MCHS.

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