Numerical investigation of inter-linked parallel micro-channel heat sinks

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Abstract. Parallel micro-channel heat sinks linked with a joint are investigated in this paper. Channels are analyzed for laminar flow (water) under constant heat flux. The considered channels with same hydraulic diameter (776 µm) are investigated for two different dimensional variations of connecting link with parallel flow and the comparison of parallel and counter flow in the channels. It is found that the varying dimension of joining link has a little influence on the over-all thermal hydraulic performance. Performance index decreases in the cases of either increasing the height (J) or width (W) of the joint at higher Reynolds number (1000 and 1200). Convective heat transfer (Nu) marginally improves with the increasing J. Inter-linked micro-channels with counter flow has given improved convective heat transfer but with an increase in frictional factor. The Nu with counter flow is found almost 15% higher than that with parallel flow at Re = 1200. The design can be further explored based on present calculations for a positive addition of designing micro-channel heat sinks.

1. Introduction
The demand for micro-electronic systems is growing rapidly and provides a tough task in a high expanse of thermal control. In this perspective, several methods are being established to keep the device temperature under the critical limit where high heat flux is generated. Application of micro-channel heat sinks is an advanced temperature reduction methodology for the removal of a large amount of heat from a small area [1, 2]. However, straight smooth channels are not enough to meet the desired needs [3, 4]. Sasaki and Kishimoto [5] reported the effect of channel height and width at various pressure drop conditions and found that optimized dimensions are needed for a better performance of micro-channel. Ghajar et al. [6] investigated micro-tubes and found the significant increase of friction factor with decreasing hydraulic diameter of channel (D < 1372 µm). Lin and Kandlikar [7] experimentally examined the rough micro-channels. The heat transfer enhancement for surface roughness height of 96 µm (Dc = 690 µm) in the laminar fully developed region was 3.78 times higher than that of smooth channels, while the increase of corresponding friction factor was also around 3.7 times. Moradikazerouni et al. [8] studied the flow performance of micro-channel heat sinks with air as the working fluid. Five different configurations (rectangular, circular, triangular, hexagonal and a straight slot) of channels were investigated for D = 2.47 mm to 10.85 mm. The results demonstrated that, among all the channel configurations, the triangular shape provides the maximum thermal performance for cooling a micro-channel heat sink. Fan et al. [9] conducted a heat transfer
analysis of heat sinks (mini-channel) for various oblique angles, varying widths of the secondary channels, and for different Reynold numbers under the (laminar) flow condition. The authors stated the improvement in performance (heat transfer) and decrease in the pressure drop penalty only for cylindrical oblique finned heat sinks. The Literature shows that the micro-channel flow and heat transfer characteristics vary with the dimensional and shape variations. It is further noted that the innovative shapes and modifications of micro-channels can improve the heat transfer but also lead to higher pressure drop [10-12]. Therefore, in this research inter-linked parallel micro-channels are considered for the analysis. The size of “joint” is varied to study the effects on the thermal-hydraulic performances. The channels are also further explored for counter flow and characteristics are compared with the parallel flow.

2. Physical model and numerical methods

2.1 Configurations of micro-channel heat sinks

Rectangular inter-linked (Parallel and 3D) micro-channels are considered for the investigation. The upper and lower channels are connected through a joint at the centre of the channels, as shown in Fig. 1. The width, length, height, and hydraulic diameter of the channels are represented as ‘W’, ‘L’, ‘H’ and D, respectively. The working fluid (water) flows along the channel length and along the x-axis (Fig. 1(b)). Where J and G are the height and width of the joint (connecting the channels), respectively. The dimensional parameters of the channels are given in Table 1.

![Fig. 1. Schematic of inter-linked micro-channels: (a) isometric view; (b) Front view.](image)

Table 1. Parameters of inter-linked micro-channels.

| Parameters | H (µm) | D (µm) | J (µm) | G (mm) | Flow type |
|------------|--------|--------|--------|--------|-----------|
| Dimensions | 400    | 776    | 50, 200 | 0.5, 1, 2 | Parallel, Counter |

Note: Bold faced parameters remain constant in other variations.

2.2 Governing equations and evaluation parameters

Parallel micro-channels (3D) are analysed, and the flow is assumed steady and incompressible with constant properties. The gravitational force is not considered in this work. The channel walls are
heated, while thermo-physical properties are assumed to be constant. The assumptions of non-slip boundary condition, flow continuum, and Navier-Stokes equation are reasonable in laminar flow regime of the study. The governing equations of continuity, momentum, and energy are written based on the above assumptions:

Continuity equation: \( \nabla \cdot \vec{V} = 0 \)  
Momentum equation: \( \rho (\nabla \cdot \vec{V}) = -\nabla P + \nabla \cdot (\mu \nabla \vec{V}) \)  
Energy equation: \( \rho C_p (\nabla \cdot \vec{V}) = k_f \nabla^2 T_f \)  

where \( P, \rho, \mu, T_f, \) and \( k_f \) are fluid pressure, specific heat, dynamic viscosity, fluid temperature, and thermal conductivity, respectively.

For the convenient evaluation of results, Reynolds number \( (Re) \), Fanning friction factor \( (f) \), and Nusselt number \( (Nu) \) are defined as:

\[ Re = \frac{\rho UL}{\mu} \]  
\[ f = \frac{\Delta p L}{2 \mu U^2} \]  
\[ Nu = \frac{h D}{k_f} \]  
\[ h = \frac{q}{\Delta T} \]  
\[ \eta = \frac{\left( \frac{f}{f_p} \right)^{1/3}}{N} \]  

where \( U, \rho, h, q, Nu_p, f_p \) and \( \eta \) are inlet velocity, fluid density, convective heat transfer coefficient, heat flux, Nusselt number of simple smooth channels, Fanning friction factor of simple smooth channels and overall performance index, respectively. The \( Nu_p \) and \( f_p \) are also calculated for the evaluation of overall performance.

2.3 Boundary conditions and solution method

The velocity and temperature at the channel inlet: \( u = u_{in}, v = w = 0, T = T_{in} \). The upper wall of upper channel and lower wall of lower channels are kept under constant heat flux \( (q = 1200 \text{ W/m}^2) \) (Fig. 2(b)). The remaining walls of the channels are assumed adiabatic, \( \partial T/\partial x = \partial T/\partial y = \partial T/\partial z = 0 \). For the outlet, the pressure is set as \( P_{out} = 0 \). The above mentioned governing equations and boundary conditions are solved by the finite volume method with Fluent program [13]. The Second-order upwind scheme for discretization of governing equations along with the SIMPLE algorithm for the velocity-pressure coupling is utilized to perform the numerical analysis. The residual criteria of \( 10^{-6} \) are set to verify the convergence of continuity, momentum, and energy equations.

3. Results and Discussion

The inter-linked parallel micro-channel heat sinks are investigated for varying dimensions of linking “joint” and “flow types”. The discussion is divided into three different sections. The model is first validated before the analysis which shows good agreement with the reference study [7] and laminar flow theory [11]. The deviations of the values calculated by the present model and reference values are not more than 3%.

3.1 Effect of varying width of the joint of the parallel micro-channel heat sinks

In this section, parallel connected channels (Fig. 1) with parallel type of flow are studied for the varying width of connecting link (Table 1). Fig. 2(a) shows the effect on friction factor in terms of Reynolds number. The trends of \( f \) are found consistent within the considered range of variations. The difference of \( f \) among the considered cases is not more than 2%. Fig. 2(b) elaborates that the effect of \( G \) variations on \( Nu \). It is observed that for lower value of \( G (0.5 \text{ mm}) \) and at higher \( Re \), the value of \( Nu \) is lesser than the other variations \( (G = 1 \text{ and } 2 \text{ mm}) \). It seems that the effect of flow mixing is lesser with lower size of \( G \). The difference of \( Nu \) between the channels of \( G = 2 \text{ mm} \) and \( G = 0.5 \text{ mm} \) is
almost 4% at $Re = 1000$. However, the $Nu$ of all the channels increases with increasing $Re$. The performance index is calculated to get the overall performance evaluation and comparison with the respective smooth channels. Fig. 2(c) shows that the overall performance index decreases with the increase of $Re$. Fig. 2(c) further shows that $\eta$ is very closer to “1” and additional rise of $Nu$ is compensated by the additional pressure drop.

Velocity streamlines of channels with $G = 1$ mm and 2 mm are plotted in Figs. 2(d) and (e). It shows with the increasing size of $G$, the fluid has started stagnated between the channel and not adding anything to the flow modification. Therefore, the overall analysis of Fig. 2 show that the channel with $G = 1$ seems the better choice in the considered range of dimensions.

3.2 Effect of varying height of the link, connecting the parallel channel heat sinks
In this section, the inter-linked micro-channels are investigated for varying link height ($J$) and parallel flow type. Fig. 3(a) shows that the effect of varying $J$ on $f$ is almost negligible and the trends are consistent. However, Fig. 3(b) elaborates that the decrease of $J$ (link height) results in lower value of $Nu$. The difference of $Nu$ among them is around 3% at $Re = 1000$. It seems that lowering the height of link ($J$) gives less time to the fluid for mixing and decreases the contact time. The overall performance index is plotted in Fig. 3(c), which shows that at the lower value of $Re$ (400) the channels with $J = 200 \, \mu m$ give slightly better performance than $J = 50 \, \mu m$. However, no significant enhancement of performance is noted at any of the $Re$ values and either of the cases.
3.3 Comparison of parallel and counter flow in inter-linked micro-channel heat sinks

It is deduced from the above cases that addition of inter-link between the channels with parallel flow is adding only subtle improvement in the performance of micro-channel heat sinks. To further explore the design, considered inter-linked micro-channels are also investigated for counter flow. The comparisons have been made in Fig. 4. Fig. 4(a) indicates that the counter flow in parallel channels is adding to pressure drop. The increase of friction factor is more than 23% at $Re = 500$. Fig. 4(b) shows that counter flow improves the over-all heat transfer of the considered channels. The difference between the $Nu$ values of both the flow type is also increasing with increasing $Re$. The difference of $Nu$ between them is almost 15% at $Re = 1200$. The rise of convective heat transfer seems due to the more flow mixing, which is also the reason of higher friction factor. Discussion of Figs. 4(a) and (b) lead to the need of performance index calculations. Fig. 4(c) presents the performance comparison of both types of channel. It shows that the overall performance of counter flow is slightly higher than the parallel flow due to the respectively higher friction factor values.

Figs. 4 (d) and (e) show the velocity streamlines of both the flow type. It shows that the flow velocities are higher for counter flow (Fig. 4(d)) with more mixing and generation of the secondary flow can also be seen at the joining point of channels. However, the flow in parallel flow is consistent as in normal smooth channels and the flow is stagnated at the joining point and has less influence on the flow mixing. This shows that the counter flow type can be used where the higher heat transfer is a dare need.

**Fig. 4.** Comparison of parallel and counter flow (a): $f$ vs. $Re$; (b) $Nu$ vs. $Re$; (c) $\eta$ vs. $Re$. Velocity streamlines at $Re = 500$. (d) Counter flow; (e) Parallel flow

**Conclusions**

The flow and heat transfer characteristics of inter-linked paralell micro-channels are investigated in this research. These channels are studied for dimensionaial variations of the joint connecting the channels. For further details, performance comparison of parallel and counter flow types are also made in this study. Following conclusive points are noted:
The parameteric (dimensional) variation of joining link has a little influence on the over-all thermal hydraulic performance of the inter-linked channels.

$Nu$ slightly improves with the increasing height of joint ($J$). However, the variation of $J$ has negligible effect on $f$.

Inter-linked micro-channels with counter flow give improved convective heat transfer, though together with higher pressure drops. The $Nu$ is found almost 15% higher than the parallel flow at $Re = 1200$.

The design can be further explored on the basis of dimensional parameters and could be a positive addition in the designing of micro-channel heat sinks.

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