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Effect of Inlet Plenum on Pressure Drop and Velocity in Fractal Micro Channels

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ABSTRACT:

The computational analysis for micro channel flow in a branched network was investigated by three dimensional CFD approach. The effect of the change of Inlet Plenum (IP) size at a constant Aspect Ratio (AR) of the outermost channel on pressure drop in a fractal branched micro channel was investigated. The properties are compared along a particular path. It was observed that the pressure drop along a bifurcated path has considerably less effect when compared to that of the outer most straight branched channel for a constant AR model. Pressure does not change significantly if we change the IP radius even when all other parameters are constant. Velocity in the inner channel after a straight run has reduced significantly even for same AR and Reynolds Number.

KEYWORDS:

Fractal; Microchannel; Aspect ratio; Pressure drop; Computational fluid dynamics

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NOMENCLATURE:

IP	Inlet Plenum
AR	Aspect ratio
Re	Reynolds number
L	Channel branch length
β	Branching length ratio
γ	Branching length ratio
d	Hydraulic diameter
n	No. of branches emerging at each bifurcation
R	Radius of Inlet Plenum (IP)
H	Depth of channel
W	Width od channel
k	Branch level
V	Velocity of fluid

1. Introduction

In the growing need to fix maximum transistors in less space we need to increase the calculation capacity of a microprocessor. This compels us to explore on new methods to deal with very high heat flux generated by the microprocessors. Straight parallel micro channels are one such solution to enhance the cooling capacity of heat exchangers. These channels increase the total convective area which further contributes to enhance the convective coefficient. This technique also has some drawbacks with it such as high pressure drop and uneven temperature distribution. This non uniform temperature gradient results in thermal stress which could alter the electronic properties and could lead to damage of the device. This idea of cooling with straight channels came a long since its conception by Tuckerman et al [1]. Lee et al [2] established that the classical correlations are equally valid for macro and micro channel flow predictions. Medawar et al [3] presented a good agreement between the experimental and theoretical results based on conventional energy and Navier Stroke equations.

Nature is always a source of inspiration. Fractal and non-fractal networks (branching) exist in nature and it works optimally. West et al [4] used power law and shown that circulatory system is perfect example of Fractal system. Banavar et al [5] said that the blood flow in artery or vein is entirely laminar having Re less than 1000. Pence et al [7] assumed that thermal and metabolic systems are analogous and the branching pattern can be used to analyse the transportation (thermal and fluidic) processes in micro fluidic systems. Cheng et al [8] also backed the idea of adapting branched structured from nature by showing that it has more heat transfer capacity and less power consumption as compared to that of the traditional straight method. The constructal theory proposed by Bejan [9] for any flow will take a path of least resistance and analysed it for transportation networks that emerged from one source and then occupies the whole flow domain.

Pence et al [10] compared the fractal design flow parameter with straight flow micro channel. They also verified the basic assumptions made the boundary layer to reinitiate at each bifurcation level. Bejan et al first did a geometric optimization of a parallel plate and round tube channels based on constructal theory [9, 11, 12]. They also demonstrated that for a disc shaped system bifurcation from one to two channels instead of three or more is desirable as the higher order bifurcation design became complex and the difference of desired properties between these complex models became small. Pence et al suggested that for a disc shape the bifurcation angle's role in global pressure drop is significant [13, 14]. IP size provides a constraint to maximum number of channels emerging from IP and this can affect the output parameters. In the straight channels, Sehgal et al [15] showed that the AR of the channel IP reduces the pressure drop in straight channels. No such knowledge regarding relation of IP and the outermost channel AR with the flow parameters in fractal shape channel is available.

2. Method

Fractal shapes exist extensively and work efficiently in nature where fluid flow and heat rejection are required with minimum flow resistance. For example, fluid flow and heat transfer in plant leaves and web of veins to carry blood in human body use circular heat exchanger [6]. This flow arrangement consists fractal shaped micro channels having characteristics which are governed by the scaling laws as given in [4]. Following are the scaling diameter ratio and length ratio,

$$\beta = \frac{dk+1}{dk} = n^{-1/3} \quad (1)$$

$$\gamma = \frac{Lk+1}{Lk} = n^{-1/2} \quad (2)$$

A full disk shape micro channel heat sink has many symmetric and similar channels. We are assuming that all these have same flow patterns. So, one such micro channel was investigated and it is shown in Fig. 1. Here d is hydraulic diameter and L length of micro channels respectively. Each microchannel branch is further bifurcated into two new branches and this is represented by n = 2. Order of the branch at bifurcation is represented by a subscript k. k and k+1 represent lower and higher order of branched channels. The channel emerging from circular IP is the base channel and is the zero order branch. This will be represented by k = 0. Direction of flow is from the IP to the outlet plenum. Flow is bifurcated four times then reaches to the outlet plenum by 16 channels. The size of whole heat sink is fixed by the distance between the center of IP and the outer boundary of outlet plenum represented by R. Any change in IP diameter will be simultaneously reflected in the size of outlet plenum. Length of micro channel is measured radially. For k ≥ 1, the channel is bifurcated asymmetrically.

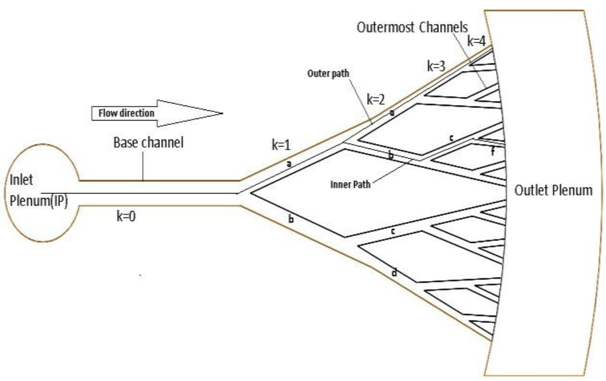

Fig. 1: Shape and flow path of cooling fluid

In present study, the effect of Reynolds number (Re), channel and Plenum AR on pressure drop and velocity profiles in a fractal micro channel is analysed using three dimensional CFD analyses. Ansys fluent is used for this purpose and results are validated by experimental flow analysis. Dimensions of the network are given in Table 1 with changing AR of outer most channels in the Table 2. By changing channel depth (H) and keeping width constant due to physical constrains of the machine. H is constant throughout one type of model. IP AR is varied keeping total distance between IP center and outer wall of outlet plenum is kept as constant. Water is used as a working fluid. This whole arrangement is studied for fixed Re at the entry of zeroth level branch. This is executed by nine mass flow rates. A heat flux of 100W/cm^2 is also applied at the wall of channel to include the effect of temperature rise on the fluid properties. This analysis had taken place at 300 K room temperature and water outlet of the heat sink is kept open to atmospheric temperature.

Table 1: Dimensions of three work pieces (AR = 4)

Level (k)	H (mm)	w (mm)	D (mm)	L (mm)	AR
0	1	1.016	1.008	8.000	1.0
1	1	0.667	0.800	5.657	1.5
2	1	0.465	0.635	4.000	2.1
3	1	0.337	0.504	2.828	3.0
4	1	0.250	0.400	2.000	4.0

Table 2: Working parameters

AR	Inlet channel Re	IP radius (mm)
4	2000	2
4	2000	3
4	2000	4

The continuity and momentum equations under steady and incompressible conditions are used to predict the flow environment as follows,

$$\frac{\partial V_i}{\partial x_i} = 0 \quad (3)$$

$$\rho\left(\frac{\partial (V_i V_j)}{\partial x_i}\right) = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial V_j}{\partial x_i}\right) - \frac{\partial p}{\partial x_i} \quad (4)$$

Simple approach as available in Ansys Fluent is used for pressure velocity coupling. To reduce the errors due to mesh second order accuracy is applied. Under-relaxation factors of 0.2, 0.7 and 0.95 are applied for pressure, momentum and energy respectively. Slandered convergence criteria are applied. Bulk water temperature of 300 K is used at the IP. Flow conditions are assumed as laminar at base channel entrance from IP, no slip and impermeable flow conditions are assumed at walls, mass flow rate is fixed at IP entrance and Re number is assumed at beginning of k = 0 channel.

3. Results and discussion

3D study of fluid flow model is performed and the results were compared with the earlier for validation of the work with smaller dimensions. Garimella concluded that existing fluid flow laws are valid for small and large-scale flow so scaling does not affect the properties. In the same model with different control variables fluid flow is assumed to be laminar but within that regime a Re = 2000 were investigated. In these arrangements the pressure distribution is not decreasing smoothly over the whole length of channel but continuously changing after smooth and steep decrease at the inlet of base channel from IP. For fixed AR and fixed Re the pressure distribution is remaining almost unchanged. Fig. 2 highlights the fluid flow branch and all the properties are measured along this highlighted line from IP to the outer channels. As in this first case we can see in the pressure graph that for R_{ip} = 2mm and AR = 4 of outer most channel, the pressure drop is maximum during flow through IP and it reduces further sharply from IP to bifurcation of k0 channel.

On first bifurcation there is pressure recovery at branching location which is not very visible in contour but shows a noticeable bump in the graph. This is due to boundary layer generation on outer wall of the k1a channel. Boundary layer generation in this system is very common at branching junctions and more visible when bifurcation is asymmetric such as at 2nd, 3rd and 4th inner bifurcations than respective outer bifurcation junctions. There is considerable pressure drop difference between the inner and outer channel as mentioned in Table 3 for inner channel (Kip, K0, K1a, K2b, K3c, K4f) and outer channel (Kip, K0, K1a, K2a, K3a, K4a).

For Re = 2000, the overall pressure drop increases as the flow approaches towards the transient region. Pressure increases by three-fold as Re increases by two-fold. Percentage pressure drop with respect to maximum in IP and K0 branch is always more than 40% of maximum pressure of whole channel and reduces in subsequent channel portions (K1a, K2b, K3c, K4f) which is always less than 10% of maximum channel pressure. Pressure drop within every single branch is always more than 45% of maximum pressure in the same channel branch. The pressure drop in the outer most channel branch is always higher than their corresponding inner branch and generally more than 70% pressure drop is observed within that branch. So, the pressure recovery in channel also depends upon the path taken by the fluid within the channel network. Similarly, for second and third case with AR = 4, the pressure drops are also calculated for R_{ip} = 3mm and R_{ip} = 4mm at Re = 2000. Here we again noticed similar trend as in the first case. As AR and Re are same for all three cases, the mass flow rate is also constant.

Table 3: Different bifurcation channels

Inner channel (MPa)			Outer channel (MPa)		
Branch	ΔP max	ΔP ch	Branch	ΔP max	ΔP ch
Kip	47.73962	47.73962	Kip	47.73962	47.73962
K0	40.06567	76.66547	K0	40.06567	76.66547
K1a	9.941767	63.02706	K1a	9.941767	63.02706
K2b	3.104727	53.35777	K2a	7.585234	73.54649
K3c	1.240437	45.76339	K3a	3.647714	74.31625
K4f	1.470788	100	K4a	2.686705	100

For 2mm radius, the boundary layer has affected the flow at first unsymmetrical bifurcation. Overall the change in IP at constant AR and Re does not show many changes in the overall pressure drop. Although the pressure drop is very similar for all the cases at constant AR and Re, it is not the same for velocity of these cases as shown in Fig. 2. For least IP radius, the velocity increases at K1a bifurcation significantly and continues to increase up to next bifurcation then decreases. There is a slight increase in velocity for IP3 but not as much as in IP2. When the IP is the largest (IP4), the velocity decreases further and then there is a sudden increase in the velocity at the entry of next bifurcation point.

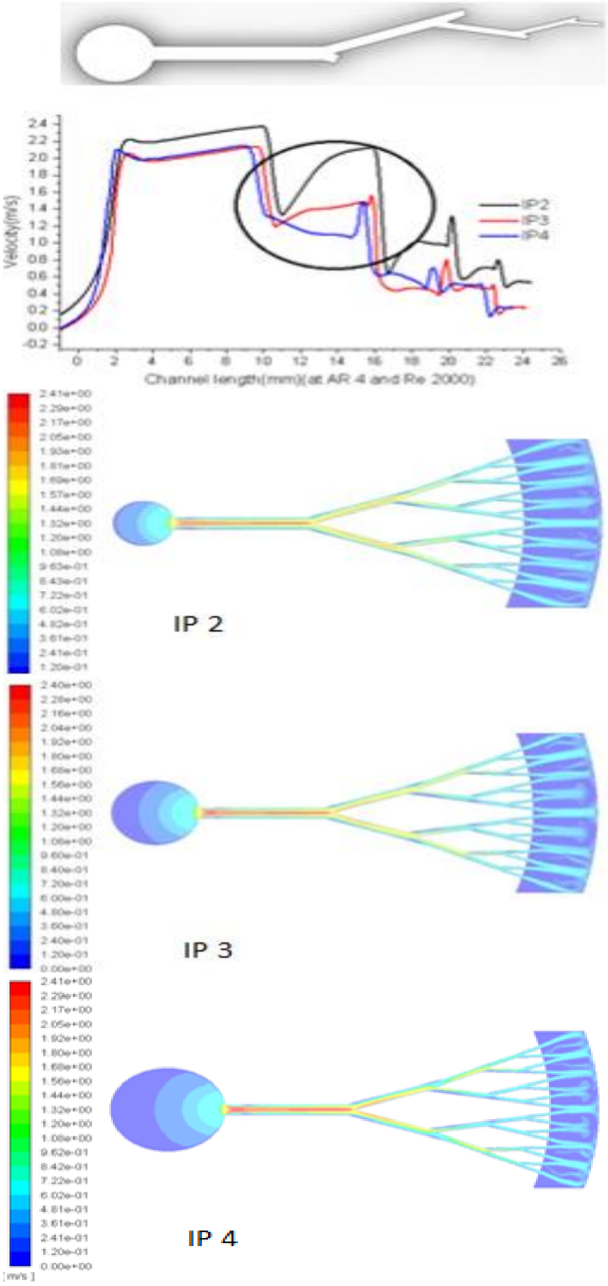

Fig. 2: Velocity for IP radius = 2mm, 3mm and 4mm at Re = 2000

4. Conclusion

In present study the effect of change in IP radius on pressure drop and the velocity profile for fractal branched microchannel heat sink is investigated. For constant aspect ratio (AR = 4), radius of IP was varied as 2mm, 3mm and 4mm for laminar flow (Re = 2000). It was concluded that pressure drop is not significantly affected by change in IP radius. Maximum pressure drop out of whole fractal system is observed in the inlet.

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