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Simulation of Fractal Like Branching Microchannel Network on Rectangular Heat Sink for Single Phase Flow

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Bukhari Manshoor[1,*], Azwan Sapit[1], Normayati Nordin[1], Azian Hariri[2], Hamidon Salleh[2], Mohd Azahari Razali[2], Izzuddin Zaman[3], Amir Khalid[4], Mohd Fairusham Ghazali[5], Muneer Khalifa Alsayed[6]

[1] Flow Analysis, Simulation, and Turbulence Research Group (FASTREG), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Malaysia
[2] Centre for Energy and Environment Studies (CEIES), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Malaysia
[3] Noise, Vibration and Acoustic Research Group (NOVA), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Malaysia
[4] Advanced Technology Centre (ATC), Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Malaysia
[5] Advanced Structural Integrity and Vibration Research (ASIVR), Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Malaysia
[6] Brega Bright Star University, Marsa Bregha, Libya

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ABSTRACT

Performance of microelectronic devices has been greatly enhanced owing to the development of the very large-skill technology. However, with the increase of circuit density and operating speed, more heat was generated by the microelectronics devices. So, the objective of this project is to do a comparative study between two different types of fractal microchannel at the same size and boundary condition by using Computational Fluid Dynamics (CFD) Besides that, this study also will investigate the hydrodynamic and thermal characteristics of T-shaped and Tree-shaped fractal microchannel network heat sinks by solving three-dimensional Navier–Stokes equations and energy equation, taking into consideration the conjugate heat transfers in microchannel walls. For the simulation, ANSYS software was used with the inlet temperature set to be 300 K, inlet velocity will be in the range of 0.1 m/s to 0.5 m/s and uniform heat flux be set at 325 W/cm^2. From this study, it was found that due to the structural limitation of right-angled fractal-shaped microchannel network, hotspots may appear on the bottom wall of the heat sink where the microchannel are sparsely distributed. With slight modifications in both fractal-shaped structure of microchannel network, great improvements on the hydrodynamic and thermal performance of heat sink can be achieved. A comparison of the performance of modified fractal-shaped microchannel network heat sink with parallel microchannel heat sink is also conducted numerically based on the same heat sink dimensions. It is found that the modified fractal-shaped microchannel network is much better in terms of thermal resistance and temperature uniformity under the conditions of the same pressure drop or pumping power. Therefore, the modified fractal-shaped microchannel network heat sink appears promising to be used for microelectronic cooling in the future.

Keywords:
CFD; heat sink; fractal microchannel

* *Corresponding author.*
E-mail address: bukhari@uthm.edu.my (Bukhari Manshoor)

1. Introduction

The performance of microelectronic devices has been greatly enhanced owing to the development of the very large-scale integration (VLSI) technology. However, with the increase of circuit density and operating speed, more heat is generated by microelectronic devices. It is anticipated that the next generation of microprocessors and microelectronic components will have to dissipate more heat flux. Traditional air cooling is insufficient to dissipate such a high heat flux, and therefore other means of thermal management must be developed for the cooling of microelectronic chips in the future. Hence, understanding the heat and fluid flow phenomena through the microchannel are the major thrust area of electronic packaging engineers. Microchannel embedded chips are the possible solution to ultra-compact electronics gadgets. Since the development of the first electronic digital computers in the 1940s, the effective removal of heat has played a key role in ensuring the reliable operation of successive generations of computers.

Different kinds of microchannel networks geometries are possible as shown in Figure 1. There are six types of microchannel networks, including straight, serpentine, spiral and fractal shaped microchannel networks of curve, I-shaped and parallel [1]. The most common ones are T-shape whose cross-section can be round, square, elliptical, hexagonal or any other suitable geometry. Straight microchannel that have rectangular cross sections are widely used. Depending on the spacing among the microchannel of a heat sink, flow requirements and pressure drops may differ. Design engineers try to achieve the minimum thermal resistance with the pressure drop as low as possible by modifying the fin shapes.

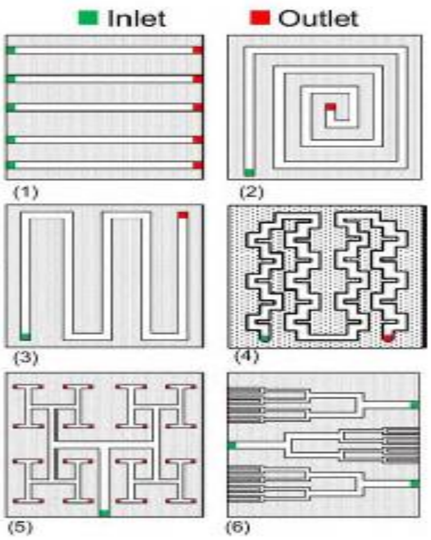


Fig. 1. Type of microchannel network

To improve the temperature uniformity without increasing the pressure drop the fractal-like flow network was designed using fixed diameter and length scale ratios between consecutive branching levels [2-3]. Using an optimization approach to minimize pumping power while adhering to a minimal volume constraint, a new fractal like branching flow network, in which each new branch (daughter) has a smaller diameter than that from which it originates (mother) [4]. The same branching level ratios analysed the optimization of networks in a disk-shaped body considering the minimum overall resistance for the volume-to-point problem [5,6]. Using a 3D Computational Fluid Dynamics (CFD) approach, the intrinsic advantages of fractal-like microchannel net such as low flow resistance, temperature uniformity, and reduced danger of blockage compared with the traditional parallel channel [7]. The electronic chips are usually of rectangular shape [8], a design of fractal branching microchannel for rectangular electronic chips was studied and the analyses show that fractal branching channel net has a stronger heat transfer capability while requires a lower pumping power than that of the traditional parallel microchannel [9-11]. In other words, the fractal branching microchannel net has a higher thermal efficiency than that of the parallel microchannel net [12,13], optimize the performance of several classes of simple flow systems consisting of T-shaped and Y-shaped assemblies of duct, channels and streams with the constant channel wall temperature [14-16] and the constant heat flux, separately. The general performance evaluation criterion is proposed for evaluation and comparison of the effectiveness of different parallel-shaped design heat exchangers.

In microchanels heat sinks, a large amount of heat generated by the semiconductor chips is carried out from the package by a relatively small amount of coolant, resulting in a high-temperature rise along the microchannels [17]. This condition will cause the non-uniform temperature distribution on the chips. This non-uniformity of temperature is undesirable for several reasons such as the spatial temperature gradient may adversely affect the performance of electronic devices. At the same time, large temperature non-uniformity can produce potentially destructive thermal stresses in elements and packages due to the differences in the thermal expansion coefficient, which poses potential reliability concerns to the devices [18,19]. The bulk temperature rises along the channels can be reduced by increasing the mass flow rate of the coolant, which however causes a larger pressure drop, thereby consuming more pumping power, generating more noise and requiring bulkier packaging to resist higher pressure [20].

Based on the previous literature, it is obvious that the fractal microchannel have an effectiveness capability in enhancing the heat transfer in semiconductor chips. However, to authors' best knowledge there is no research that has been done on comparison of the performance of fractal microchannels by using the CFD for T-shape and Tree-shape microchannels. Thus, the main objective of this research is to carry out a comparative study between two different types of fractal microchannel at the same size and boundary condition by using CFD. Besides that, this research also will carry out a numerical computation by solving three-dimensional Navier-Stokes equations and the energy equation in order to identify the better pattern of fractal-like branching microchannel network that is suitable for a rectangular heat sink. The results from this research are important because it gives a clear view to show an effect of fractal microchannel network on rectangular electronic ships, Furthermore, the significance of this study is to identify the better pattern of fractal-like branching microchannel network, which is suitable for a rectangular heat sink.

2. Fractal Like Branching Microchannel Network

Fractal like branching flow network are based on studies of bifurcating flow networks found in nature, such as the circulatory and respiratory systems of mammals and the vascular system of plants. The goal of the present study is to develop a reasonably accurate and efficient three-dimensional model of fractal branching channel tree shape for cooling rectangular heat sink, by using a 3D approach and compared with improved design of fractal branching channel networks in a T-Shaped body [13]. The three-dimensional fluid flow and heat transfer in a rectangular microchannel heat sink are analysed using water as the cooling fluid. A schematic of the structure of a rectangular microchannel heat sink as shown in Figure 2. The micro-heat sink model consists of a 20 mm long (L=20 mm) aluminium wafer having a width, w = 20 mm and height, h = 6 mm. A uniform heat flux is applied at the bottom surface of the heat sink 325 (W/cm2). Heat transferred in the heat sink is a conjugate problem which combines heat conduction through the solid and dissipated away by convection of the cooling fluid in microchannel.

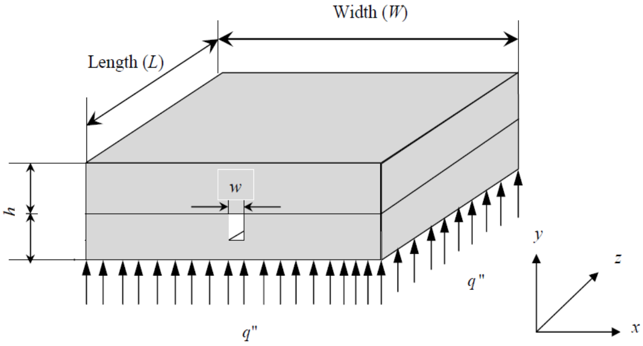


Fig. 2. Schematic of microchannel heat sink

The bottom surface of heat sink is uniformly heated with a constant heat flux, q = 325 W/cm2), also the adiabatic conditions are applied at the other boundaries. Fluid flowing through the channel at temperature 20°C. The direction of the fluid flow parallel to the *z*-axis as shown in Figure 3 and 4. The flow is assumed to be laminar and both hydro dynamically and thermally fully developed. Also the thermos-physical properties are assumed to be constant. The geometric dimensions of the microchannel are listed in Table 1.

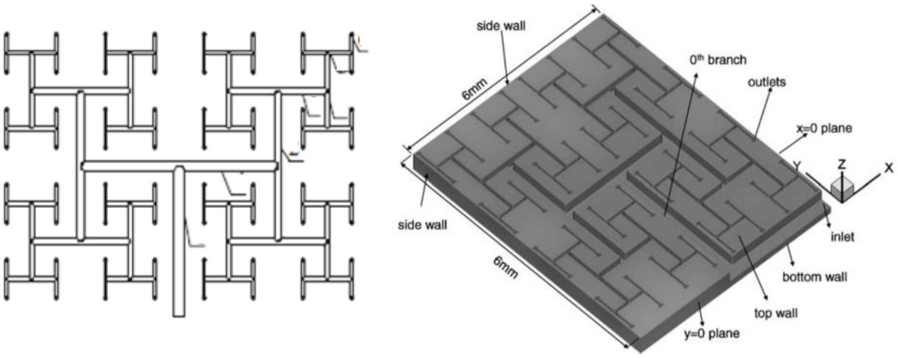


Fig. 3. Constructed T-shaped microchannel

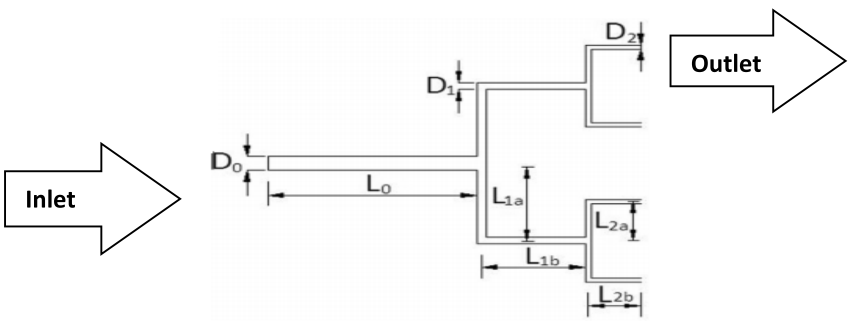


Fig. 4. Constructed Tree-shaped microchannel

Table 1
Geometric dimensions of microchannel

Branches	K1	K2	K3	K4	K5	K6	K7
Length (mm)	10	5	5	2.5	2.5	1.25	1.15
Width (mm)	1	1	0.5	0.5	0.25	0.25	0.25
Height (mm)	2	2	2	2	2	2	2

3. Numerical Model

Consider the fractal-shaped microchannel network in a square heat sink as shown in Figure 3 and 4. In order to simplify the numerical simulation, only channel network plate is included in the computational domain by neglecting the heat transfer between the coolant manifold and the silicon base since the manifold is made of thermal insulation material. Water is used as the coolant in the present study. For the simulation work, there are several mathematical assumptions have been made to make sure the simulation can be performing successfully. The assumptions included the hydraulic diameter of microchannel under consideration ranges from about 0.04 mm to 0.5 mm, which yields a typical Knudsen number for water between 7.5 x 10^{-7} and 1.0 x 10^{-5}. Besides that, the conservation equations based on the continuum model which is Navier-Stokes equations and the non-slip boundary condition on walls are applicable. The transport processes are considered to be at steady state and the fluid flow is incompressible and laminar for the simulation while thermal radiation and convection heat transfer to the environment are neglected, the viscous dissipation effect is neglected and gravity effects are negligible in momentum equations in fluid flow in microchannel.

Under the above assumptions, the conservation equations of mass, momentum and energy can be written for the fluid and conservation of energy for the solid respectively as follows

Conservation of mass,

$$\nabla . V = 0 \tag{1}$$

Conservation of momentum,

$$\nabla . VV = -\frac{1}{\rho}\nabla p + -\frac{1}{\rho}\nabla . \tau \tag{2}$$

where $\tau = 2\mu\left(\frac{1}{2}[(\nabla . V) + (\nabla . V)^T]\right)$ is the stress vector.

Conservation of energy for fluid,

$$\nabla\left(c_p T V\right) - \nabla . (k\nabla T) = 0 \tag{3}$$

Conservation of energy in the walls,

$$\nabla . (k\nabla T) = 0 \tag{4}$$

Boundary conditions are needed to close the mathematical formulation. A uniform heat flux, q is imposed at the bottom wall of heat sink, while all other external walls are taken to be perfectly thermally insulated with no radiation and convective heat transfer to the environment. Symmetric boundary conditions are applied to the planes at x = 0 and y = 0, which are the symmetric planes of the heat sink. The velocity (or mass flow rate) and temperature of the fluid entering the inlets of the heat sink are specified, while a constant pressure boundary condition is applied at the outlets. The continuity of temperature and heat flux is used as the conjugate boundary condition to couple the energy equations for the fluid and in the walls. Eq. (1) – (4) along with the above described boundary conditions were solved numerically using a finite-volume CFD solver (FLUENT). Structural grids were used for fluid flow in the channel, while non-structural grids were adopted in the walls. The total energy conservation was examined through comparing the input heat for the system from the bottom wall of heat sink and the increase of coolant internal energy, which was calculated as the difference of the total coolant internal energy at the inlet and the outlets. For all of the cases computed in this study, the relative error was controlled within 0.05%.

3.1 Grid Independent Test

Grid independent test is first conducted to ensure that the mesh of the microchannel heat sink is appropriate to provide a reliable result for heat transfer and flow characterization. The percentage of deviation of the analysis results must be less than 5 % in order to ensure that the results are not affected by further mesh refinement. For this simulation, 4 different mesh configurations are used to assess the grid quality on the accuracy of the simulation results. The test results are summarized in Table 2. From the table, it is clearly shown that the average temperature and pressure drop for the T-shaped and Tree-shaped microchannel are almost constant for the 4 different mesh systems. The variation in average temperature for the T-shaped microchannel is about 3.833 % from mesh 1 to mesh 2, 0.263 % from mesh 2 to mesh 3 and 0.526 % from mesh 3 to mesh 4. Furthermore, the variation in the pressure drop for T-shaped microchannel is about 6.637 % from mesh 1 to mesh 2, 1.896 % from mesh 2 to mesh 3 and 1.641 % from mesh 3 to mesh 4. Hence, mesh 4 with 3,561,245 elements is sufficient to characterize the performance of the T-shaped microchannel. Similar trend is also observed for the average temperature and pressure drop development in the Tree-shaped microchannel. The variation in average temperature for Tree-shaped microchannel is about 3.056 % from mesh 1 to mesh 2, 0.282 % from mesh 2 to mesh 3 and 0.142 % from mesh 3 to mesh 4. The variation of pressure drop is about 3.671 % from mesh 1 to mesh 2, 1.766 % from mesh 2 to mesh 3 and 0.189 % from mesh 3 to mesh 4. Therefore, Tree-shaped microchannel with 3,765,213 elements is sufficient to characterize the heat transfer and flow performance.

Table 2
Grid independent test result for T-shaped and Tree-shaped microchannel

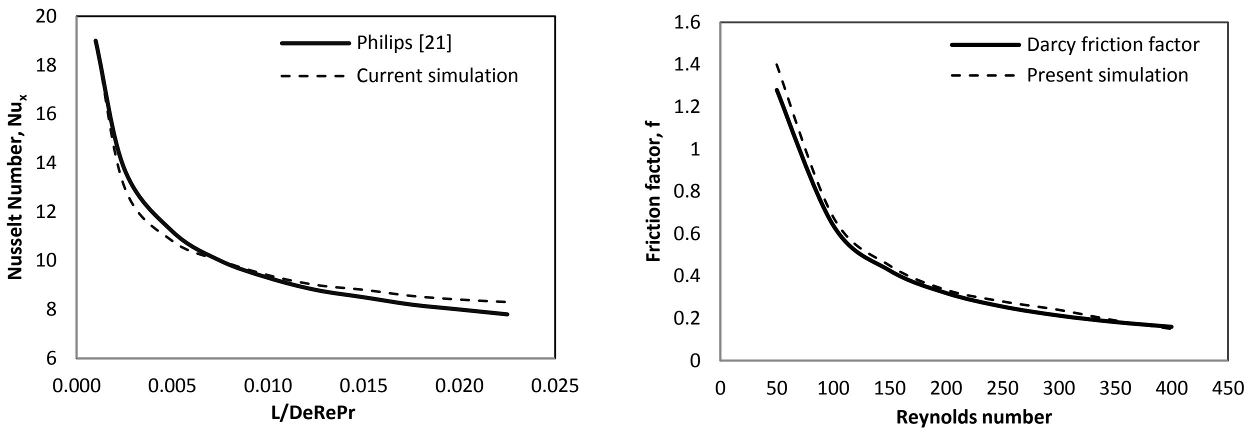
Mesh No.	Mesh 1	Mesh 2	% Deviation	Mesh 3	% Deviation	Mesh 4	% Deviation
T-Shaped microchannel							
No. of elements	705,123	931,295		1,886,254		3,561,245	
Pressure drop, Pa	2732.14	2532.13	6.637 %	2484.12	1.896 %	2443.34	1.641 %
Ave. of Temperature, ^{o}C	25.57	26.55	3.833 %	26.62	0.263 %	26.48	0.526 %
Tree-Shaped mcrochannel							
No. of elements	925,346	1,562,134		2,845,632		3,765,213	
Pressure drop, Pa	14923.1	14575.3	3.671 %	14121.3	1.766 %	14005.7	0.819 %
Ave. of Temperature, ^{o}C	34.36	35.41	3.056 %	35.51	0.282 %	35.46	0.142 %

4. Results and Discussion

A three-dimensional model is developed to investigate flow and conjugate heat transfer in the microchannel based heat sink for electronic packaging applications. A series of numerical calculations have been conducted by FLUENT and the results are presented in order to show the effects of temperature distribution, heat flux distribution as well as the heat transfer coefficient in the microchannel heat sinks.

4.1 Validation of Numerical Simulation

Accuracy level of the simulation analysis for this study was validated with theoretical results for conventional rectangular microchannel model. The theoretical results of local Nusselt number was correlated with Philips's correlation [21] and the average apparent friction factor has been validated by Darcy friction factor. The theoretical and present results are shown in Figure 5.



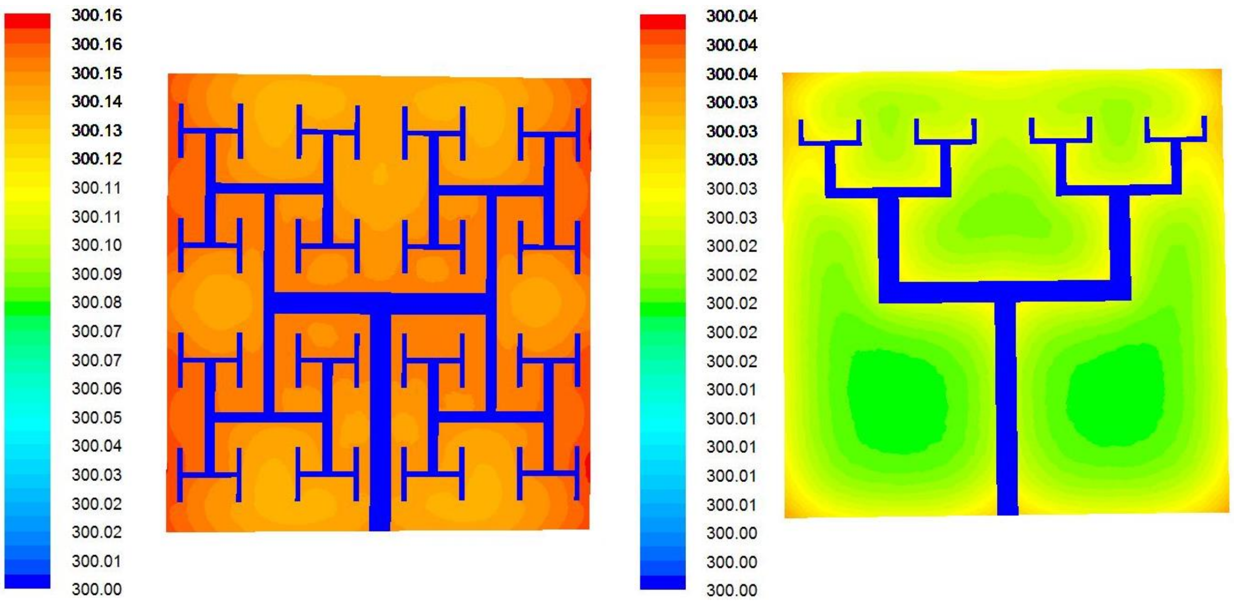
(a) (b)

Fig. 5. Simulation model validation (a) Nusselt number (b) Friction factor

Form the figure, it was shown that the present numerical simulation results are in good agreement with theoretical results. Hence, this indicates that the current numerical simulation method can be applied to predict the characteristics of heat transfer in other to study the temperature distribution characteristics of two fractals shaped microchannel in the present study.

4.2 Temperature Distribution

Numerical results on heat transfer and temperature distribution characteristics of two fractals shaped microchannel network in a rectangular heat sink with same geometry but different shape will have showed based on a detailed analysis of a baseline case. Figure 6 is the temperature distribution at the bottom. Two fractals-shaped microchannel network patterns are also projected onto the surface of the heat sink bottom wall in order to facilitate the analysis. It can be seen that the temperature distribution on the base materials beneath the first branches is much lower than those areas near the heat sink boundaries, where hotspots of the heat sink are formed. In a fractals-shaped microchannel network, the fluid flow bifurcates from *k1* branch to *k7* is being heated gradually along the flow path. So when the coolant arrives at the highest branches, it has already been heated to a relatively high temperature. As a result, the cooling capability of the coolant decreases from *k1* branch to *k7* branch. Since the coolant temperature is lower at the first branches, the cooling capability of the coolant is larger, and consequently the wall temperature beneath them is lower.



T-shaped channel Tree-shaped channel

Fig. 6. Temperature distribution at the bottom of heat sink

The formations of hotspots near the heat sink boundary as shown in Figure 6 are mainly due to two reasons. Firstly, the cooling capability of the coolant is the lowest at the highest branches. Secondly, the channel density at the highest branches is relatively low. As can be seen the large blank areas uncovered by channels are around the highest branches areas, although these blank areas are still under heating from the bottom wall of the heat sink because of a uniform heat flux is assumed in this study. Also it's shown the wall temperature beneath different highest branches is not the same, with the temperature close to the first branches being lower. This is because the base material beneath the first branches has a lower temperature, which in turn can absorb the heat from its neighbourhood through heat conduction in the base material, leading to the gradual increase of the temperature with increasing distance from the first branches.

The improvement of modified fractal shaped microchannel network heat sink was shown in term of comparison between the two types of heat sinks. The numerical simulation was conducted under the same geometry and heat flux. Numerical results of the temperature distribution at the bottom wall for the modified fractal shaped microchannel network heat sink is shown in Figure 7 for both T-shaped and Tree-shape fractal branches. Comparing the results for both types microchannel, it can be seen that great temperature uniformity has been achieved. The numerical results show that the highest temperature of heat sink decreases from 300.16 K to 300.040 K while the lowest temperature of heat sink increases from 300.02 K to 300.001 K. therefore, the modifications lead to great improvement in thermal performance, also lead to smaller pressure drop. This is because the pressure head has been much more properly distributed at branch levels by the modification of channel shape.

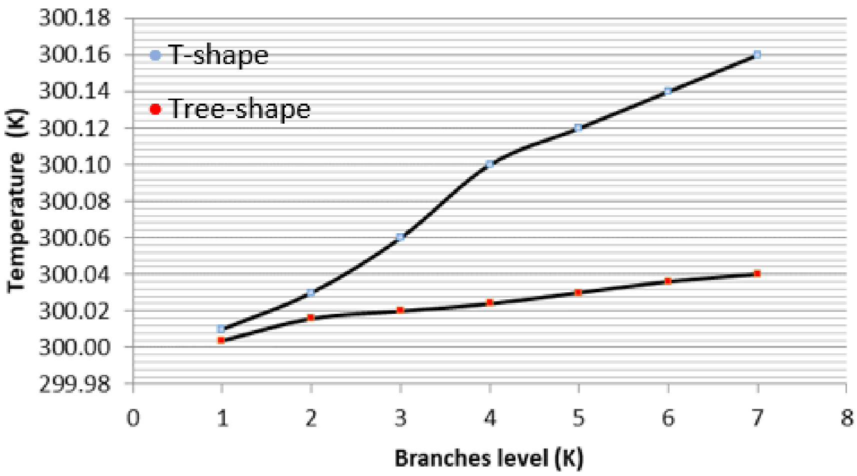


Fig. 7. Temperature distribution at constant heat flux, q=325 W/cm^2 for Tree-shaped and T-shaped fractal

4.3 Pressure Distribution

Another important parameter that becomes most consideration for heat sink design is the pressure drop along the channel. The fluid is entered through the microchannel at velocity 0.1 m/s, with constant inlet temperature 20^{o}C. After passing through all channels, the fluid discharged to the atmosphere. A constant heat flux q= 325 W/cm^2 is applied at the bottom wall of heat sink. The pressure contours inside channels as shown in Figure 8.

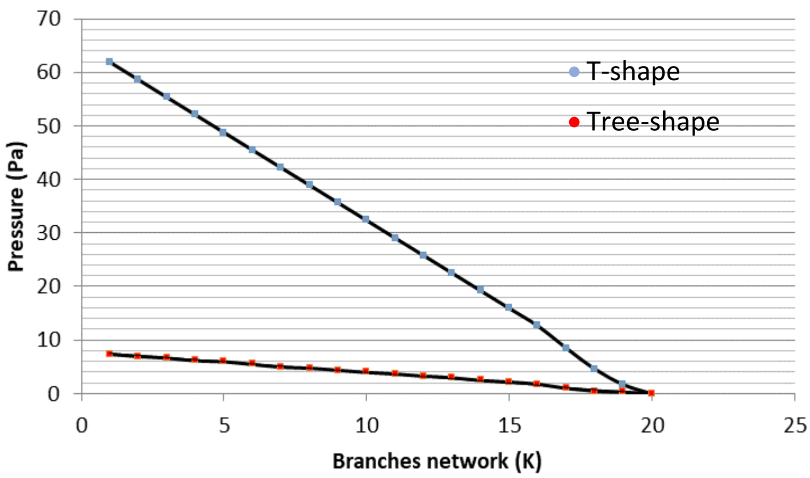


Fig. 8. Frictional pressure drop and pressure drop across a bifurcation at different branching level

Figures 8 shows the frictional pressure drop and the pressure drop across a bifurcation at different branching level for bifurcating networks from inlet to the outlet. The frictional pressure drop across the initial channel decreases with an increasing number of branching levels. The pressure drop across a bifurcation decreases from one branching level to the next. And reached to the lowest pressure drop at the outlet, the overall pressure drop is caused by splitting the flow at bifurcations. Also shows the variation of pressure drop thru the inlet and outlet for both fractals-shaped microchannel networks. It can be seen that modified fractal microchannel has higher pressure at the inlet than T-shaped microchannel, whereas T-shaped microchannel has additional pressure drop at the outlet bifurcations compared with modified fractal-shaped microchannel network, the total pressure drop of the modified fractal-shaped microchannel network is much smaller than that of the T-shaped microchannel. Indicating that the modified fractal-shaped channel structure is better than T channels for the fluid flow distribution. Thus the modifications lead to smaller pressure drop. This is because the pressure head has been much more properly distributed at different branch levels by the modification of fractal shape.

5. Conclusion

This study presents Numerical results of pressure drop and heat transfer between Tree-shape and T-shape of fractal microchannel network with same geometry and boundary condition, we found many of coefficients were affected on the performance of fractal channel network such as pressure drop, temperature and geometry of fractal channel network. According to the results obtained, it showed that the temperatures increase due to heat transfer from the heat sink wall to the fluid and this fluid is confined near the surface of the heat sink. While cold fluid moves between these branches, but it remains the distribution of temperature is similar. In term of pressure drop, the pressure distributions showed that the highest pressure at the stagnation point. Then, gradually the pressure to become little on the heat sink surfaces until occur separation to fluid on these surfaces. From this study also showed that the T-shape fractal heat sink has reduced more pressure drop and decreased heat transfer compared to the Tree-shape fractal. It was noted that the results of having small pressure drop and high average heat transfer coefficient in Tree-shape was better than from another results. Which, given small pressure drop than other and high average heat transfer coefficient.

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