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# Thermal characteristics of tree-shaped microchannel nets with/without loops

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ABSTRACT

Several tree-shaped microchannel networks with/without loops are numerically examined and compared for application in cooling of electronic components. The physical model of microchannel electronic cooling system is set up with tree-shaped networks. The tree-shaped microchannel nets are embedded in a disk-shaped heat sink, which is attached to a chip to remove the heat dissipated by a chip. The effects of total branching level and loops on the thermal and flow performances of heat sink system are investigated numerically. Results show that tree-shaped nets with loops provide a great advantage when the structure experiences accidental damage to one or more channel segments since the loop assures continuity of coolant flow. Under blockage of some branches, the channel networks only experience an increase of pressure drop while maintaining the capability to remove the heat generated by the chip.



## 1. Introduction

The efficient transport characteristics of natural tree-shaped systems such as trees, leaves, mammalian circulatory and respiratory systems, vascular tissues, neural dendrites, river basins, oil/water reservoir, street, etc. can shed light on optimal solutions of many practical problems, which have fascinated researchers in physics, chemistry, biology, physiology, engineering and geology for ages. The transport properties of the tree-shaped systems have been broadly investigated [1–5]. Recently, the constructal principle maximizing global performance in a constrained but morphing flow structure was presented as a mechanism of optimizing and designing by Bejan [1]. The constructal theory was first proposed in a problem of pure heat conduction [6], and was extended to design the structure of convective fins [7], fluid flow [8,9], and heat transfer [10,11]. Recently, it has been widely applied in design of photovoltaic cells [12], thermochemical reactor [13], prediction of droplet impact geometry and particle agglomeration [14,15], optimization of heat sinks [16], self-healing smart materials [17,18], and even green energy as well as global circulation and climate [19,20], and so on. Optimized pipe connections (topology) can be found following the constructal theory and exhibit tree-shaped branching structures [1].

The performance of tree-shaped nets can be enhanced but at the cost of increased complexity of geometry. However, the increased geometric complexity involves problems in manufacture so that we need to reduce complexity in design. Also, as discussed by Wang et al. [10], the increased complexity of the net geometries does not necessarily improve their performance. Hence, it is necessary to seek other effective ways, other than increasing the geometric complexity, to optimize tree-shaped nets, especially if potentially blockage of flow may occur in any of the channel segments, which can affect the cooling performance adversely.

Point-circle tree-shaped networks have been already recognized as useful designs for electronics cooling [21], which will be taken in the current study to investigate the heat transfer in heat sink system. If we examine the design of most leaves, we find that the channel nets have a "tree-shape" with many small loops between channel segments. With such a structure, the loops are served by the peripheral duct flow even with blockage of some channel segments. Inclusion of loops can enhance performance reliability and stability of the cooling systems while maintaining a relatively simple design of the geometry. Wechsatol et al. analytically examined the fundamental attributes of constructal networks with loops, and indicated that incorporating loop is an effective design strategy to maintain a high level of global performance reliability when the networks experience local blockage [22]. Rocha et al. discussed the cooling performance of tree architectures with loops and found that trees with two loop sizes are marginally inferior to trees with only one loop size, although the robustness of tree-with-loops architectures

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**Nomenclature**

| | |
|---|---|
| $A$ | surface area of the network, mm$^2$ |
| $c_p$ | specific heat capacity, J/kg K |
| $d$ | hydraulic diameter of channel segment, mm |
| $f$ | friction factor |
| $h$ | height, mm |
| $l$ | channel segment length, mm |
| $m$ | total number of branching levels |
| $\dot{m}$ | mass flow, g/s |
| $n$ | number of bifurcation per channel |
| $N$ | number of channels emanating from the center of the disc |
| $p$ | pressure, Pa |
| $q_0''$ | hear flux, W/m$^2$ |
| $r$ | radius of disc, mm |
| $Re$ | Reynolds number |
| $T$ | temperature, K |
| $\Delta T$ | temperature difference, K |
| $V$ | velocity, m/s |
| $w$ | width of channel segment, mm |
| $w'$ | width of loop, mm |
| $X$ | dimensionless $x$ coordinate, $X = x/r$ |
| $x, y, z$ | Cartesian coordinate, mm |

*Greek symbols*

| | |
|---|---|
| $\lambda$ | thermal conductivity, W/m K |
| $\mu$ | dynamic viscosity, Pa s |
| $\rho$ | density, kg/m$^3$ |
| $\theta$ | branching angle |

*Subscripts*

| | |
|---|---|
| c | chip |
| t | tree-shaped microchannel net |
| i,j | indices in Einstein summation convention, sequence number |
| k | branching level, 0,1,2,… |
| max | maximum |
| s | heat sink |

increases [23]. However, only conduction was considered in their analysis. Wang et al. also discussed the effect of *single* level loops in tree-shaped nets on the flow and thermal performance [11]. They found that the inclusion of loops between the outlets in the constructal nets provides a significant advantage when the structure experiences accidental damage to one or more of its sub-channel segments since the loop assures continuity of flow. In spite of blockage, the performance of network suffers only a small performance drop while experiencing increased pressure drop.

This study attempts to obtain further understanding of the key features of tree-shaped nets with *multiple* loops by Computational Fluid Dynamics (CFD) in three dimensions in conjunction with a constant heat flux boundary condition at the channel walls. The effect of branching level (geometrical complexity) of tree-shaped nets on the thermal characteristics has been calculated numerically. Comparison between tree-shaped nets with loops and those without loops, nets without blockage and those with blockage has been carried out to explore the problems.

## 2. Model and analysis

Consider a typical configuration, which is a three-dimensional heat sink with embedded looped tree-shaped microchannel networks as shown in Fig. 1. The physical model include three parts: heat sink (in silicon) at the top, tree-shaped micochannel networks embedded in the heat sink (black shaded part) and the chip at the bottom attached to the heat sink. The heat generated by the chip can be removed by the tree-shaped micochannel networks in the system. Note that the loops can be activated or de-activated for the purpose of comparison.

For the generation of tree-shaped networks, the optimal construct for fluid flow will be adopted. Although Murray's law was presented from blood vessels [24], it has been shown to be suitable for many other biology tissues, even for no-living systems [25]. According to Murray's law, the cube of the radius of a parent vessel should equal to the sum of the cubes of the radii of the daughter vessels such that the global flow resistance is minimized. Based on the suggestion made by West et al. for two-dimensional flow networks [26], Pence [21] developed a preliminary symmetrical

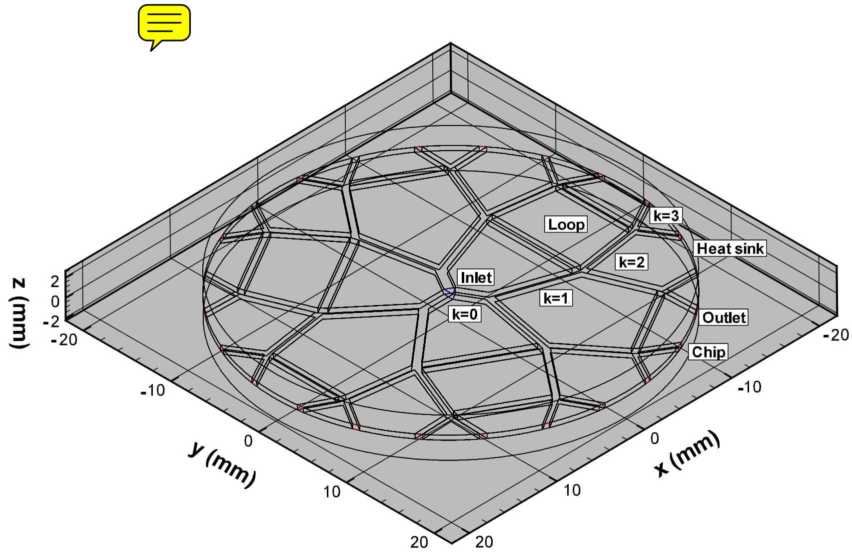


**Fig. 1.** Typical physical model of heat sink system embedded in tree-shaped microchannel nets ($n = 2$, $m = 3$).