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A conceptual structure for heat transfer imitating the transporting principle of plant leaf

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ABSTRACT

Due to the high efficiency in water transportation, the plant branching networks were widely investigated and used in designing the microchannel of mass flow and heat dissipation for electronic components. However, in current studies of fractal tree-like networks used in microchannel design, the wall was always regarded as a non-porous structure, and the porous tissue surrounding the network was overlooked, which is actually contrary to the real plant branching system, where water can penetrate into the surrounding tissue through the permeable wall. In this paper, the branching network with permeable wall and the porous media are designed to form a conceptual structure based on the real architecture of plant leaf. The effect of the permeable wall and the porous media on the performance of heat dissipation and flow is analyzed. The results show that, the permeable wall and the porous media play a very important role in heat spreader design.

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1. Introduction

With the rapid development and miniaturization of electrical components, unit density of heat flux increases dramatically, which will weaken the performance of the components, or even make them fail. Generally, how to improve the efficiency of a heat spreader which transfers the heat from the heat source to environment is a very challenging work. As widely accepted, nature branching system/network such as the tree canopy, plant roots, leaves [1], is the result of the natural evolution in that plants have to spend less energy in transporting the water so as to survive. The high efficient transport architecture of plants can provide some useful hints for optimal solutions to many engineering problems. In fact, it has fascinated many researchers in physics, chemistry, biology, physiology, engineering and geology for ages and been applied in microelectronic cooling, flow-field designs in fuel cell, fluid distributor, micro-fluidic manifolds in lab-on-a-chip systems, etc. [2–7]. The introduction of branching networks into microchannel cooling technique [8] has stimulated this field and attracted ever-increasing interest in studying heat and mass transfer properties in branching microchannels.

Chen and Cheng [9] designed a rectangular micro heat exchanger in the form of fractal tree-like networks (FTNs) with different dimensions and branching levels and revealed that the FTNs with larger dimension or larger total number of branching levels have stronger heat transfer capability and require smaller pumping power. In the experiment of thermal efficiency (defined as heat transfer rate per unit power required), they found that the FTNs have much higher efficiency than that of traditional parallel microchannels when the two heat sinks worked under the same heat transfer rate, the same temperature difference and inlet velocity [10]. Yu et al. [11] studied the hydraulic and thermal characteristics of FTNs by numerical and experimental methods, and found that the aspect ratio of microchannels has large impact on both the pressure loss and heat transfer. Xu et al. [12] created a mathematical model to investigate the hydraulic conductivity properties of the FTNs between one point and a straight line, and the results showed that the FTNs provided much higher permeability than that of the traditional parallel nets. Hong et al. [13] investigated the hydrodynamic and thermal characteristics of modified FTNs heat sinks by solving three-dimensional Navier–Stokes equations and energy equations. It was found that the heat sink with modified FTNs have better performance in pressure drop, thermal resistance and temperature uniformity. Cetkin et al. [14] made an investigation to the mechanism of vascular design in controlling the cooling and mechanical performance of a solid square slab when heated uniformly and loaded with uniform pressure. They revealed that the lowest temperature and hydraulic resistance can be achieved with radial channels. Wang et al. [15] studied the effect of the bifurcation angles of the FTNs which is used for cooling electronics with the fluid dynamics approach and demonstrated that the bifurcation angles is a very important factor which determines the performance of cooling.

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Nomenclature

Re	Reynolds number
p	pressure (Pa)
W	width (m)
H	height (m)
x, y, z	Cartesian coordinate (m)
u	velocity along the width direction (m s^{-1})
w	velocity along the length direction (m s^{-1})
v	velocity penetrating out of channel (m s^{-1})
q	flow flux of a microchannel (m^3 s^{-1})
Q	overall flow flux of the conceptual structure (m^3 s^{-1})
q_m	flow flux of the last level channel (m^3 s^{-1})
l	length ratio
m	total mumble of fractal level
N	total number of the leaf-vein-like fractal architecture
G	volume (m^3)
V	seepage velocity (m s^{-1})
V_m	flow velocity in the circumference (m s^{-1})
R	radius of the whole porous media or matrix (m)
R_m	radius of the center circular (m)
K	permeability (md)
F	volume fraction
S	surface area (m^2)
T	temperature (K)
c_p	specific heat capacity (J kg^{-1} K^{-1})

Greek letters

Δ	difference
θ	fractal angle (rad)
ϕ	flow flux penetrating out of channel (m^3 s^{-1})
η	number of microchannel
φ	porosity
β	width ratio
α	aspect ratio
ρ	density of liquid water (kg m^{-3})
τ	number of micro fin-pins
μ	dynamic viscosity (kg m^{-1} s^{-1}).

Subscripts

in	in the microchannel
out	out of the microchannel
i, j, n	indices
k	branching level, index from 0 to ∞
h	porous media
f	leaf-vein-like fractal architecture with permeable wall
e	effective permeability
eh	effective permeability of porous media

Some researchers prefer to work on the thermal conduction (with no mass transfer) of the FTNs. Yu et al. [16] studied the thermal conductivity of composites with embedded self-similar H-shaped FTNs. Their results disclosed that the FTNs can significantly reduce the thermal conductivity compared with an equivalent single cylinder. Xu et al. [17] analyzed the heat conductivity of symmetric FTNs. Their study showed that the heat conductivity is similar to mass transfer in the FTNs. Wang et al. [18] embedded the FTNs in a rectangular heat sink, and numerically investigated the characteristic of heat transfer. The results showed that the FTNs have certain advantages over conventional parallel channel nets in terms of lower and more uniform temperature distribution and better stability in case of accidental blockage in channel segments.

So far most investigators have mainly focused on the study of the FTNs with several branches, but the leaf vein system which is similar to the FTNs in branching characteristic was nearly overlooked. Wang et al. [19] firstly studied the leaf vein branching networks and established a three-dimensional model to compare the flow and heat transfer characteristics of two kinds of symmetric/asymmetric branching networks, i.e. tree-like and leaf-like networks. The results showed that the asymmetry has little impact on FNTs, but could significantly reduce pressure drop in leaf-like branching networks. However, they did not make further analysis about the real characteristics of the leaf vein system, i.e. the loops, permeable wall and etc., as well as the real behaviors in heat and mass transfer. In our recent work [20], we analyzed the polygonal loops of leaf vein system, and studied its flow performance and sucking capacity of working fluid when the structure was used as the wick in the vapor chamber. It was found that the loops of the leaf-vein-like fractal architecture (LFA) have great impact on the permeability comparing with the FTNs and prevent channels from blockage. From the viewpoint of botanist, the leaf vein system (or vascular system) is generally leaked tubes [21,22] (Fig. 1) through which the water can permeate into the mesophyll tissue, namely the destination of water transportation. However, all the up-to-date studies about the FTNs or LFA employed as the microchannel for heat dissipation are considered without permeable wall, and the surrounding porous tissue of the leaf vein system (or the vascular) was overlooked, which is not consistent with the actual structure in fact.

In this study, at first, a conceptual structure composed of LFA with permeable wall (defined as novel LFA) and porous media (including two parts: micro fin-pin arrays and porous channel) (Fig. 2) is designed for heat spreading based on the leaf vein system. The novel LFA and porous media are respectively used to simulate the leaf vein system and the mesophyll. It could be found that the novel model takes effect either as a condenser of a vapor chamber or a heat sink (used as a spreader). When used as a condenser, the mathematical model of a microchannel with permeable wall is firstly constructed. And then, the permeability, a typical parameter in evaluating the condenser performance, is calculated. When used as a heat sink, the numerical model based on Ansys Fluent (a CFD code based on the finite volume method) is established to calculate the mass flowing and heat transferring performance, and the conceptual structure is compared with the conventional structure (LFA without permeable wall).

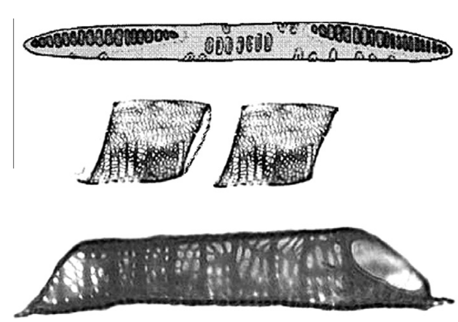

Fig. 1. Vascular with permeable wall [28].

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