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Flow boiling in constructal tree-shaped minichannel network

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ABSTRACT

Flow boiling in constructal tree-shaped minichannel network with an inlet diameter of 4 mm is numerically investigated using a one-dimensional model, taking into consideration the minor losses at junctions. The pumping power requirement, pressure drop, temperature uniformity and coefficient of performance of the constructal tree-shaped minichannel network are all evaluated and compared with those of the corresponding traditional serpentine channel, and the fluid stream undergoes a phase change from saturated liquid to saturated vapor. The effects of the length dimension and top view area (i.e. the path length) on saturated gas–liquid two-phase flow boiling heat transfer in tree-shaped minichannel networks are all analyzed and discussed. The results indicated that, the tree-shaped network configured with length dimension of two is able to maximum flow access; the path length plays a significant role in the determination of flow boiling in tree-shaped minichannel networks. In particular, compared to the traditional serpentine channel, flow boiling in constructal tree-shaped minichannnel network possesses less pressure drop, lower pumping power requirement, better temperature uniformity and higher coefficient of performance (*COP*).

1. Introduction

Since the pioneering work by Tuckerman and Pease [1], heat sinks incorporating mini/microchannels have been introduced as an attractive option for electronic cooling, due to the large surface-to-volume ratio and high convective heat transfer coefficient. However, downsizing also leads to large pressure drop, and the temperature distributions are also non-optimal in parallel or serpentine mini/microchannels. Therefore, the optimal design of flow heat transfer structure is of considerable importance for the improvement of thermal performance. Recent researches have demonstrated that the constructal theory [2,3] has been successfully used to optimize the flow configuration. Differing from the fractal geometry [4] which to describe natural phenomena by means of infinitely repetitive fracturing algorithms, the constructal theory is a completely deterministic theory of optimized and organized systems that evolve in time. The principal of the constructal theory was formulated by Bejan in 1996 as the constructal law of the generation of flow configuration: "For a finite-size flow system to persist in time (to survive) its configuration must evolve in such a way that it provides an easier access to the currents that flow through it" [5,6]. Today the constructal theory represents a new extension of thermodynamics: the thermodynamics of nonequilibrium systems with configuration, and it has played a significant role in the optimization of heat and mass transfer system.

The advanced heat and mass transfer efficiency has been found in the blood-circulating arteries and veins of human beings, which are self-organized as a branching vessel tree system. Predicting such geometric features is an essential objective of constructal theory. In this context the tree-shaped architecture by constructal theory is a promising way to bypass the huge increase in hydrodynamic resistance that comes with miniaturization. The important applications of such tree-shaped architectures have been found in electronics cooling [5], fuel cells [7], etc.

Bejan [5] first proposed tree in electronics cooling with high conductivity path. To cope with the fundamental problem of how to collect and channel to one point the heat generated volumetrically in a low conductivity volume of given size, the deterministic tree networks for fluid flow was introduced [6].

Pence [8,9] proposed a tree-shaped microchannel network for the convective cooling of microelectronic components with disk geometric shapes. The three-dimensional CFD results indicated that the pressure drop and thermal characteristics through the tree-shaped microchannel network are superior to that through the straight channel network [10,11]. In addition, Xu and Yu [12] analyzed the transport properties including electrical conductivity, heat conduction, convective heat transfer, laminar flow, and turbulent flow in the tree-like networks and derived the scaling exponents of the transport properties in the networks. Chen et al. [13] studied the effective permeability of composites embedded with self-similar fractal-like tree networks, and found that the tree networks can significantly increase the effective permeability compared to the traditional parallel nets if the structural parameters

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Nomenclature

A_w	wall surface area ($m^{2)}$
Bo	boiling number
C_{LM}	two-phase interaction parameter
COP	coefficient of performance
D	length dimension of channel
d_k	branch diameter of the kth level (m)
f_T	junction loss factor
G	mass flux (kg m^{-2} s^{-1})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
k_{lo}	pressure loss coefficient of only liquid flow through a tube bend
L_k	branch length of the kth level (m)
m	mass flow rate (kg s^{-1})
P	pressure (Pa)
P_p	pumping power requirement (W)
Q	volumetric flow rate (m^3 s^{-1})
Q_h	total heat transfer rate
q	heat flux (W m^{-2})
r	latent heat (J kg^{-1})
t	temperature (K)
U	mean velocity (m s^{-1})
v	specific volume (m^3 kg^{-1})
We	Weber number
x	steam quality

Greek symbols

α	void fraction
Δ	diameter dimension
λ	friction factor
σ	surface tension
ϕ_{lo}^2	two-phase multiplier
X^2	Lockhart–Martinelli parameter

Subscripts

k	branching level
l	liquid
lo	liquid only
$local$	local position
max, min	maximum and minimum
v	vapor
w	wall

of the tree networks are properly chosen. Yu and Li [14] studied the effective thermal conductivity of composites with embedded self-similar fractal-like tree networks, and this investigation indicated that the thermal conductivity of the H-shaped fractal-like tree networks does not obey Murray's law.

In the real application, the square or rectangular shaped heat sink is preferred due to the fact that the majority of the electronic or electrical components are square or rectangular rather than disk shape. However, the free circulation of the cooling fluid is difficult to be realized in a single layer tree-like network with a rectangular shape. In order to solve this problem, Chen and Cheng [15] designed a new sandwich structure tree-shaped channel network heat sink for cooling of rectangular chips. A comparison between the new design and the traditional parallel network showed that the new tree-like microchannel network has a stronger heat transfer capability and requires lower pumping power. Senn and Poulikakos [7] also confirmed that there are intrinsic advantages of such a sandwich structure tree-shaped channel network with respect to both heat transfer and pressure drop by using three-dimensional simulation. Hong et al. [16] proposed a modified tree-shaped microchannel network heat sink which has better performances in term of thermal resistance and temperature uniformity. Recently, Chen et al. [17] numerically and experimentally investigated heat and fluid flow in sandwich structure constructal tree-shaped minichannel heat sinks, taking into consideration the conjugate heat transfer in channel walls. Both the numerical and experimental results concluded that the constructal tree-shaped minichannel has inherent advantage of temperature uniformity companied lower pumping power requirement.

All the above implementation of tree-shaped networks [5–17] has still been limited in heat conduction and single phase flow. Due to the large latent energy, as well as the potential for improving the temperature uniformity of flow boiling, its application in tree-shaped networks is being explored both experimentally and through the use of numerical simulations [18,19]. Kwak et al. [18] experimentally observed the two-phase air-water flows in a microscale fractal-like flow network embedded in a disk-shaped heat sink. Daniels et al. [19] investigated the adiabatic flow boiling in a disk tree-shaped microchannel network through numerical simulation and experiment. Their results demonstrated that the tree-shaped network has significant advantage over corresponding parallel channel array in pressure drops. Due to the fact that the bifurcations act as a pressure recovery device (i.e. like a diffuser) for the low bifurcation angle in the disk configuration [20], the effect of bifurcation on the pressure loss can be reasonably neglected in the above analytical work for disk configuration. However, the minor losses at junctions with the 180 degree branching angle as shown in Chen et al.'s configuration with rectangular layout [15] are not negligibly small [20]. Furthermore, little research on flow boiling in this applicable sandwich structure tree-shaped minichannel network [15] is available. Therefore, this paper develops and numerically analyzes a one-dimensional model for flow boiling in the applicable sandwich structure constructal tree-shaped minichannel network, taking into consideration the minor losses due to diverging/converging flow at bifurcations. And the comparisons of the pumping power requirement, pressure drop, temperature uniformity and coefficient of performance of flow boiling in the constructal tree-shaped minichannel network with those of the corresponding traditional serpentine channel are also presented.

2. Constructal tree-shaped net of rectangular shape

As proposed by Chen and Cheng [15], a tree-shaped channel net with rectangular shape as shown in Fig. 1 can be constructed as follows:

a. Suppose that every channel is divided into two branches at the next level, so $N = 2$, the branching angle φ is 180°, and the tree-shaped net has 6 branching levels (as shown in Fig. 1(a)).
b. We define that the ratio of the length of the channel at the (k+1)th branching level to the length of the channel at the kth branching level as

$$\frac{L_{k+1}}{L_k} = N^{-1/D}. \tag{1}$$

It follows that:

$$L_k = L_0 N^{-k/D}, \tag{2}$$

where L_0 is the length at the 0th branching level and D is length dimension.