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Biomimetic Capillary Inspired Heat Pipe Wicks

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Abstract

The possibility of mimicking desirable properties from nature accelerates material improvement and generates commercial interests. For heat pipe development, many attempts have been made in heat pipe wicks to enhance its capillary performance by mimicking biology. Constructing biporous, composite, or nanopillar wicks with aim of achieving hierarchical structure has been found in many studies. Mimicking beetle shell surface to obtain hybrid wettability shows biomimetic potential in heat pipe wicks. This paper firstly reviews some fundamental studies in biomimetics, establishing a general idea of surface wetting and capillary effect. MRI scanning of two live plants (Musa X Paradisiaca and Salix Flamingo) provides the possibility of visualising internal structures *in vivo* and obtaining rates of water transport in xylem vessels. In addition, by investigating the work inspired directly or indirectly from biomimetics, the role that biomimetics plays in modern heat pipe technology is revealed. Our innovation which syntheses a low level of hierarchical structure and integrates integral wicks for different heat pipe sections including evaporator, adiabatic, and condenser is introduced. Mathematical modelling in terms of capillary pressure and capillary rise rate to characterise such new structure is provided.

Keywords: biomimetics, heat pipe, surface wetting, capillary effect, wick structure

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Nomenclature

A_w	Cross-sectional area of the wick (m^2)
D	Wick pore diameter (μm)
g	Gravitational acceleration (ms^{-2})
h	Capillary rise distance (mm)
J_v	The rate of water transport (mm·s^{-1})
K	Wick permeability (m^{-2})
L	Horizontal length (m)
P_c	Capillary pressure (Pa)
Δp_c	Capillary pressure drop along the heat pipe (Pa)
Δp_{evap}	Capillary pressure drop at evaporator (Pa)
Δp_l	Liquid pressure drop (Pa)
Δp_v	Vapour pressure drop (Pa)
r_{eff}	Effective pore radius (μm)
r_h	Hydraulic radius (m)
S	Specific surface area (m^2)
θ	Contact angle
θ_c	Contact angle at condenser
θ_e	Contact angle at evaporator
ε	Porosity
λ	Particle shape factor
μ	Water dynamic viscosity (kg·ms^{-1})
ρ	Density of water (kg·m^{-3})
ρ_s	Density of the solid (kg·m^{-3})
ρ_w	Density of the wick (kg·m^{-3})
σ	Surface tension (kg·m·s^{-2})
τ	Tortuosity (m)
$\Delta\psi_p$	Pressure drop (Pa)

Subscripts

c	Capillary or condenser
e	Effective or evaporator
eff	Effective
h	Hydraulic
l	Liquid
s	Solid
w	Wick

1 Introduction

The diversity and adaptability of the natural world fascinate mankind and enable human revolution. Our attempt in developing new manufacture methods to

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synthesize an isolated function in nature is encouraged, and the necessity to fully understand such natural process avoiding blindly copying nature is demanded. For heat pipe improvement, a change in wick structure can help generate effective results. With provision of the wick, a heat pipe can work in any orientation. The wick serves the function of further complicating the boiling process, offering additional nucleation sites beneficial for bubble formation, and modifying the movement of liquid and vapour towards or from the heated surface[1]. The associated capillary force created by the wick, notably, forms the main criteria in evaluating heat pipe performance that helps achieve the passive operation, *i.e.* pulling back the condensed liquid from the condenser to the evaporator without any external force. Therefore, it is desired to investigate some nature generated capillary effects from plants, insects and aquatic animals in terms of cell or surface structures.

Many biomimetic studies towards superhydrophobic or superhydrophilic effects[2–5] have been conducted in recent years, offering a convenient path for engineers to extract relevant details (*e.g.* surface structure, contact angles/wettability, materials in contact) for current technology development. In mimicking biology, capillary effect is always accompanied by adopting hierarchical structure for microscale or nanoscale applications, which is the response to various mechanisms including dissipation, friction and wetting[6]. It is the hierarchical structure that helps the species to achieve adaptability in diverse forms of functions based on various characteristic length scales. If such hierarchical structures help plants and creatures establish their adaptable mechanisms of energy dissipation and transition, it is possible that engineers can follow the principles in order to develop improved environment-friendly technologies. Examples can be found in heat pipe development, such as constructing biporous or bidisperse[7–10], composite (*e.g.* sintered-grooved)[11–17], micro- or nano-pillar wicks[18–20] to achieve high evaporative heat flux, high capillary pressure and relatively high vapour permeability. The hierarchical structures help overcome common deficiencies brought by single structure as well as identifying the potential of high capillary pressure and maximised thin-film evaporation. In addition, Zhao *et al.*[21] proposed a beetle inspired superhydrophobic condenser with hydrophilic bumps to accumulate condensate to achieve hybrid wettability.

This paper tries to elaborate hierarchical structure obtained from nature in terms of wetting phenomena and capillary effect, so that the fundamental parameters that characterise surface wettability and capillary effect can be recognised. A recent study performed by our research group introduces MRI scanning of live plants. This aims to visualise how plant has the ability to transport water upwards, to find possible biomimetic solutions to improve fluid flow in porous structures, and to form a better understanding of capillary effect in porous media. Reviews on biporous or bidisperse, multi-structured/composite and nanopillar wick are made, and our innovation in heat pipe integral wick structure is proposed. Mathematical modelling of wick capillary pressure and capillary speed is provided in order to characterise such new wick structure.

2 Hierarchical structure from nature

2.1 Wetting phenomena

Many biological structures at micro- and nano-scale in both plants and animals have demonstrated their interaction with water and hence the wettability. For instance, surface structure or roughness of the xylem in trees varies among species and differs with climates[22]. In hot and dry climate, xylem with small warts shows superhydrophilicity, where the contact angle of water within xylem is extremely low. The water collecting ability of the capture silk of the cribellate spider[23], in particular, gives light to surface wettability. With periodic spindle-knots and joints, continuous condensation and directional water drops collection can be achieved. The unique system of cactus[24], which is composed of well-distributed clusters of conical spines and trichomes on the cactus stem, and multi-level grooves from microgrooves to submicorgrooves on the spine, intrigues the investigation of structure-function relationship and wetting mechanism. Moreover, desert beetles[25,26] which use multi-functional elytra surface structure (hydrophilic bumps on hydrophobic base) to capture water from humid air. A systematic structure of spikes, scales and channels involved in moisture harvesting lizard's skin[27–29] indicates the level of hierarchical order influencing surface properties.

2.2 Capillary effect

A cohesion-tension theory has often been applied