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Review

Review of nature-inspired heat exchanger technology

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ABSTRACT

The enormous heat and mass transfer phenomena in nature have led engineers to seek solutions for heat transfer enhancement problems from nature. In a current study, a comprehensive review of nature-inspired heat exchanger technology is presented, with focuses on fractal geometries, heat exchanger surface wettability control and evaporative cooling. Fractal geometry, widely found in respiratory systems and vascular systems of plants and animals, has been introduced into heat transfer area because of its intrinsic advantage of minimized flow resistance and strong heat transfer capability. Plant leaves with different surface wettability inspire heat exchanger surface treatment for condensation and frosting application. Evaporation of perspiration to regulate human temperature enlightened the application of evaporative condensers. Based on a review, an outline for applying biomimicry to heat exchanger design has been developed. Promising natural phenomena for future design are discussed. This review is expected to motivate future research on nature-inspired heat transfer devices.

Étude de la technologie des échangeurs de chaleur inspirée de la nature

Mots clés : Inspiré par la nature ; Échangeur de chaleur ; Fractal ; Mouillabilité de surface ; Condenseur évaporatif ; Bio-mimétisme

1. Introduction

Nature has always been the source of inspirations for scientists and engineers to solve problems in various fields. Abundant instructive heat and mass transfer enhancement phenomena and mechanisms are observed in nature, partially imitated and applied to enhance heat and mass transfer in engineering. Heat exchanger design is of significance due to its crucial role in thermal and power systems. Hence, heat exchanger design

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Nomenclature

Symbols

AR	aspect ratio
C_p	specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
D	dimension
f	friction factor
FC	fractal channel
j_m	mass transfer Colburn factor
m	mass (kg)
m	total number of branching levels
PC	parallel channel
Re	Reynolds number
SC	serpentine channel
w_{re}	retained water ratio
θ_c	contact angle (deg)
θ_A	advancing contact angle (deg)
θ_R	receding contact angle (deg)

Subscripts

def	defrosting
re	retained

is one of the main research domains of adapting the heat and mass transfer phenomenon in the nature. Though plenty nature-inspired heat exchanger designs were proposed and studied, they are neither recognized as products of biomimicry nor systematically reviewed and studied in the past. Current study aims to give a comprehensive review of nature-inspired heat exchangers in literature.

Enormous heat exchange devices are inspired by the nature, as shown in Table 1. Heat and mass transfer phenomena that have not been applied in current technologies but are of great potential are also summarized in this table. The nature-inspired heat exchange applications reviewed in this paper include fractal heat exchange devices, heat exchanger surface wettability control and evaporative cooling. They are reviewed in details and research gaps are discussed. At the end, we outline how to apply natural mechanisms to heat exchanger designs.

2. Fractal heat exchanger devices

Fractal geometries are widely found in respiratory systems and vascular systems of plants and animals, and have been introduced into heat transfer area because of their intrinsic advantages of minimized flow resistance and strong heat transfer capability. In this section, we first review the fractal theory development, and then we discuss the model development for fractal heat exchanger devices with a focus on assumptions. We discuss our main findings and mechanisms for the phenomena as well as design parameters affecting the thermal and hydraulic performance. To close we summarize the research gaps.

2.1. *Fractal theory*

Much research has been done to develop the fractal theory (Bejan, 1997, 2002, 2003; Bejan and Lorente, 2006, 2007, 2011; Bejan et al., 2008; Mandelbrot, 1982; Murray, 1926; Sherman, 1981; West, 1997; Xu and Yu, 2006), and the major findings are summarized in Table 2.

2.2. *Model development*

Fractal theory has been applied in different kinds of heat exchange devices, but mostly in heat sinks for electronic devices,

Table 1 – Heat transfer in nature and corresponding heat exchange application.

Type	Nature phenomena	Heat exchange application inspired	Benefit
Plant	Leaf vein structure	Fractal channel (Wang et al., 2010) Micro-reactor (Chen et al., 2011) Fractal tube-in-tube heat exchanger (Azad and Amidpour, 2011) Distributor (Guo et al., 2014)	Heat transfer enhancement Pressure drop reduction
	Leaf surface wettability	Heat exchanger surface wettability control (Jhee et al., 2002)	
Animals	Sweat glands system	Evaporative condenser (Hwang et al., 2001) Artificial skin materials (Cui et al., 2014)	Heat transfer enhancement
	Lung and blood vein structure	Fractal channel (Pence, 2002) Micro-reactor (Yongping Chen, 2011) Fractal tube-in-tube heat exchanger (Azad and Amidpour, 2011) Distributor (Guo et al., 2014)	Heat transfer enhancement Pressure drop reduction
	Countercurrent blood vein in penguin feet	Preheating and cooling heat exchanger (Domanski et al., 1994)	Heat transfer enhancement
	Fish body shape	Heat exchanger with oval/airfoil/droplet shape tubes (Bacellar et al., 2016)	Pressure drop reduction
	Shark skin	Fan blade material (potential)	
	Humming bird fast-flapping wings	Fan integrated heat exchanger (Staats and Brisson, 2015)	Heat transfer enhancement
Nest structure	Termite nest; bee nest	Heat exchanger shape design to utilize natural convection (potential)	