Abstract

Fluid flowing over a solid surface and the interactive effects of surfaces structures on fluids have long been the topics of research of fluid mechanics and heat & mass transfer in many subject areas of engineering and industries; and these are particularly important when energy efficiency is concerned. Numerous efforts have been made to study how to improve the efficiency such as reducing drag, improving heat and mass transfer, etc., and this has become the major tasks of modern fluid mechanics. Can we find some useful solutions from the nature on this? This paper provides a broad overview of how nature inspired solutions help improve energy efficiency. Through reviewing the historical examples and reporting the current studies, the possible future prospects are discussed.

Introduction

In the natural world, plants and animals have evolved over time of millions of years to best adapt to the environment. They do not waste but tend to save energy; they interact effectively with the surrounding environment by exchanging heat and mass flow across their cuticles making use of specific micro/nano structures and functions to achieve a perfect energy balance. Such different functions may include the limitation of uncontrolled loss of water, protection from solar radiation, micro effect of induced turbulence on flow drag reduction, defence against pathogens, and changing surface wettability. Biomimetics, which may be interpreted as “abstraction of good design from nature”, could help find solutions for improving technological designs and providing appropriate models for efficient and sustainable engineering and technological innovations. A number of useful lessons from nature can be identified [1, 2]. As ground-breaking science subject, biomimetics or bionic engineering is increasingly focusing on studying nature phenomena and understanding how natural plants and animals rise to the best adaption to the environment. In the past decades, scientists have shown great interest in functional surfaces and done a lot of studies to explore the interactive effects of natural functional surfaces of complex topography on fluids, and the development of new applications based on microfluidic, nano technologies and complex physics have become ever more important for improving energy efficiency and sustainable development. Numerous efforts have been made to study how to improve the efficiency such as reducing drag, improving surface wettability, heat and mass transfer, etc., and this has become the major tasks of modern fluid mechanics.

This paper provides a broad overview of how nature inspired solutions help improve energy efficiency. Through reviewing the historical examples and reporting the current studies, the possible future prospects are discussed.

Energy Efficiency and Sustainable Development

Energy efficiency is a measure of “efficient use of energy”. The improvement of energy efficiency is normally aimed at reducing the amount of energy required to provide products and services. Improving energy efficiency is always related to sustainable development. The improvements of energy efficiency are generally achieved by adopting a more efficient technology in terms of the applications of commonly accepted methods to accelerate energy transfer and conversion or reduce energy loss for energy conservations. For example, insulating a dwelling or a car allows using less energy to heat and cool so as to achieve and maintain comfortable temperature or consume less amount of energy to have better effect of air-conditioning for thermal comfort. The fuel consumption of a car or an airplane is directly relevant to flow drag, etc. All these are largely related to fluids flow, heat and mass transfer through or across and interactive with its boundaries or surfaces. It should be pointed out that sustainable development is not simply equivalent to low cost or input. “Eating” disorders should be avoided in industrial and engineering projects.

Useful Lessons from Nature

Many natural phenomena become useful lessons for solutions of energy efficiency and sustainable development. Such popular stories include the “Velcro” which was inspired by the tiny hooks found on the surface of burs [3]; the story of Chinese carpenter Lu Ban inventing his saw inspired by identifying the function of particular leaves with tiny sharp tooth; and the function of macro termite mound as natural solution of effective HVAC.

The Africa macro termite mound, as shown in Fig. 1, supplies solutions of natural model of HVAC (heating, ventilation and air-conditioning). Over 2 million termites live in a mound. They work and breathe; and the oxygen consumption is considerable. Without ventilation, they would all be suffocated within 12 hours. The royal cell is in the centre; and natural ventilation is induced by the density difference between the relatively hot and cool air spaces. The walls of the termites mound made by their waste are functional; it is porous forming chimney like channel. This allows the CO2 is emitted to outside the mound and oxygen is absorbed through the functional wall [4].

Figure 1: Macro termite mound: 1) Royal cell; 2) and 3) air spaces; 4) chimney like channels.
It is well known that the fundamental interactions between an organism and its environment occur at interfaces. This is the reason why biological surfaces became optimized multifunctional interfaces over millions of years of evolution. Different functions, as shown in Fig. 2 [5], for example the limitation of uncontrolled loss of water, protection from solar radiation, micro effect of induced turbulence on flow drag reduction, defence against pathogens, etc. lead to a great variety of complex three dimensional surface structures at microscopic levels.

**Lotus Leaf Effect**

The lotus flower is considered as a symbol of purity in a few religions. Its leaves can be kept from contamination or pollution without being folded even when the lotus is around with muddy water. This phenomenon illustrates that nature can protect itself from omnipresent dirt and pathogenic organisms. Ideally, if this property is applied to functional surfaces, self-cleaning effect can be prompted in almost any materials in the open air by rain water. This phenomenon is one of the most important topics in biomimetics. Here a few useful lessons we can learn from nature, namely, the lotus leaf effect, rose petal effect, shark skin effect, earthworm effect, and plant capillary effects are discussed.

The author has recently carried out a review and summarised the theoretical models of droplets wetting on superhydrophobic surfaces with low adhesive effect and high adhesive effect, and as well as the fabricating progress of such functional surfaces [6-8].

**Rose Pedal Effect**

It has been brought into consideration that some natural surfaces with hierarchical structure and roughness can produce significant superhydrophobicity, not only from plants but also animals. It has been revealed that the leg of a water strider [Fig. 4(a)] has numerous oriented needle-shaped setae [Fig. 4(b)] with their diameters ranging from 3 µm down to several hundred nanometers [12]. Many elaborate nanoscaled grooves are noticeable on each microseta [Fig. 4(c)], forming a hierarchical structure, which origins the superhydrophobicity of the water strider's legs with assistance of the hydrophobic secreted wax.

**Materials Scientists:**

Materials scientists have long been interested in generating low adhesive and adhesive controllable surfaces, but their only approach was by generating ultra-smooth interfaces. Since 1995, the discovery of super-hydrophobic micro and nano-structured biological surfaces has led to remarkable innovation in this field. In recent years, research in biological functional surfaces has become one of the most important topics in biomimetics. Here a few useful lessons we can learn from nature, namely, the lotus leaf effect, rose petal effect, shark skin effect, earthworm effect, and plant capillary effects are discussed.

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micro- and nanoscale. In particular, the natural models that are related or similar to lotus effect have been mostly used due to their prominent features. Following this, we continue to review the recently published work that successfully manufactured superhydrophobic surfaces with typical features.

### Shark Skin Effect

For the low-drag-oriented characteristics in nature, studies have been carried out to investigate the special structures shown in the skin of marine animals such as the shark, dolphin, seal and penguin as their “talents” are believed to be due to their skin architectures. Riblet surface, inspired by the skins of fast sharks, has been seen as an effective turbulent drag reduction method which reduces flow drag by changing the position of the origin of velocity profile.

The shark skin protects its surface against biofouling and reduces drag during swimming at fast speeds. The skin of fast sharks is covered with tiny scales (dermal denticles) shaped like small riblets and aligned in the direction of fluid flow, as shown in Fig. 7, and minimal mucus secretion is probably the best. When sharks swim fast, during turbulent flow, vortices form on the surface which causes high shear stresses across entire surface.

Riblets lift the high-velocity vortices off of the surface, exposing only the riblet tips to high shear stresses. The low velocity fluid in the riblet valleys causes minimal shear stress across most of the surface. Modeling and measurements support this hypothesis of decrease in overall shear stress across surface.

Riblets have been experimented with for application to hull for boats and airplanes, providing drag reduction benefits to both. Nowadays, riblets have been applied to airplanes. 70% of surfaces of Boeing and Airbus airplane have applied riblets resulting in 3% total drag reduction. Another major commercial application is competition swimsuits.

### Earthworm Effect

Similar to other living creatures, earthworms carry bioelectricity, and an experiment measurement has shown that electric potential distribute along an earthworm body surface (shown in Table 1). The phenomenon of earthworms moving in moist soil, namely, the electric potential exists on an earthworm tissue, has been reported [15]. In general, there are two types of electric potential of all creatures including earthworms, the resting and the action potentials; the surface electric potential of the living body is a combined reflection of the two types of electric potential. The resting potential exists between inside and outside of the tissue or cell membrane when the body is stationary. When it is moving, there is an additional action potential between the excited part and the resting part of the same tissue or cells. The action potential is fluctuant with time and of short duration.

Table 1: Mean and maximum values of the surface electric potential of earthworm Michaelien body tissue [16]

<table>
<thead>
<tr>
<th>Position on body</th>
<th>Electric potential of Michaelien when creeping (mV)</th>
<th>Electric potential of Michaelien through a tube (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fore part</td>
<td>40</td>
<td>21</td>
</tr>
<tr>
<td>Middle part</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>Hind part</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

In terms of the nature of earthworms in moist soil and anti-adhesion, a few possible mechanisms, such as surface secretions, chemical compositions, and surface/body flexibilities, have been summarized [15]. The electro-osmotic flow near an earthworm body surface, as a basic electrokinetic phenomenon that takes place when the earthworm moves in moist soil, has been initially discussed in reference. The flow in a micro thin layer of water is formed in the vicinity of the earthworm’s body surface as a result of the electric double layer (EDL) interaction. Such a micro-scale electro-osmotic flow plays the role of lubrication between the earthworm’s body surface and the surrounding medium of moist soil and reduces surface adhesion, as shown in Fig. 8.

### Plant Capillary and Osmosis

Vascular system in plants is a natural structure for water transport against gravity. With the discovery of plasmodesmata, xylem, which is used for water transport upward, can be considered as an
ideal porous medium. Water transportation in plant may be concerned a few mechanisms including Cohesion-tension theory and osmosis theory, as shown in Fig. 9. Water can be transported by tension forces caused by the combination of capillary force and leaf transpiration. Surface structure or roughness of the xylem varies among species and differs with climates [17].

Conclusions
A number of solutions from natural plants and animals can be used as lessons for flow drag reduction, improving wattability, heat transfer, and energy efficiency. Natural solutions and biomimetics could help or lead to change the world to make it more efficient, more sustainable, greener, and friendlier.

References