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Nature inspired solutions of energy efficiency - the past, the current and the future

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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].

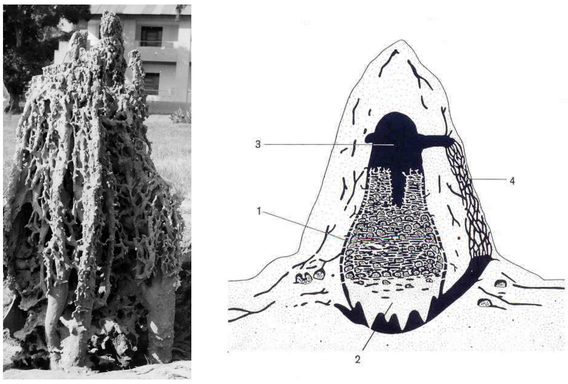

Figure 1: Macro termite mound: 1) Royal cell; 2) and 3) air spaces; 4) chimney like channels.

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 optimised 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.

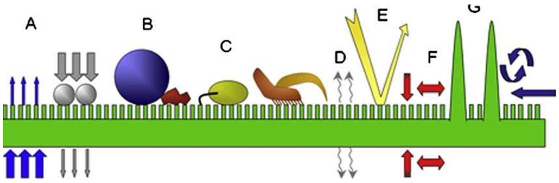

Figure 2: (A) Transport barrier: limitation of uncontrolled water loss/leaching from interior and foliar uptake, (B) Surface wettability, (C) Anti-adhesive, self-cleaning properties: reduction of contamination, pathogen attack and reduction of attachment/locomotion of insects; (D) Signalling: cues for host-pathogens/insect recognition and epidermal cell development, (E) Optical properties: protection against harmful radiation, (F) Mechanical properties: resistance against mechanical stress and maintenance of physiological integrity, (G) Reduction of surface temperature by increasing turbulent air flow over the boundary air layer.

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 pedal 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].

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. As mostly accepted, Barthlott and Neinhuis' early work has started the recent research of superhydrophobic surfaces inspired by nature [9]. Surface roughness has then been recalled to explain the surface's extreme repellence against liquid droplets, as shown in Fig. 3(a)). Subsequent and further research has indicated that the plant cuticle is technically a composite material mainly built up by a network of cutin and hydrophobic waxes, where surface structuring arises at different hierarchical levels [5]. The composite or hierarchical surface structure, formed by a combination of two (or even more) layers in different sizes, is built by convex cells and a much smaller superimposed layer of hydrophobic three-dimensional wax tubules [10], as shown in Fig. 3 (b and c) with different magnifications. It has been argued that wetting of such surfaces is minimized, because air is enclosed in the cavities of convex cell sculptures.

Along with the lotus leaves, there are other natural superhydrophobic surfaces in the plant kingdom. For example, taro (Colocasiaesculenta) leaves have been used to demonstrate the self-cleaning effect in the original paper [9]. It has been observed that the elliptic protrusions with an average diameter of about 10 μm form the microstructure on the taro leaf, and the nanoscaled pins form the hierarchical structure with the microstructure, which is however similar to the lotus leaf [11], as shown in Fig. 3(a–c).

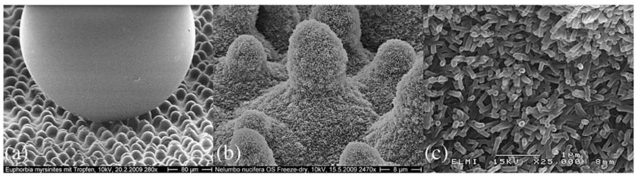

Figure 3: A glycerol drop on Euphorbia myrsinites, which is a robust specimen and well suited to show the surface's repellence against the liquid droplet. Scale bar=80 μm. (b) The upper side surface of the lotus leaf without the shrinkage artifact. Scale bar=8 μm. (c) The wax tubules from the upper side of the lotus leaf. Scale bar=1 μm.

Thus, 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.

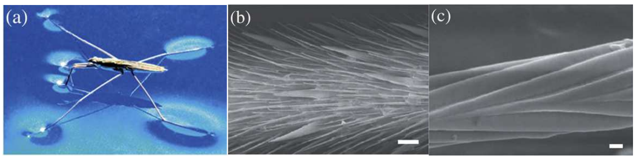

Figure 4: Natural hierarchical surfaces. (a) A water strider standing on water surface. Scanning electron microscope (SEM) images of a strider leg showing numerous oriented spindly microsetae (b) and the fine nanogrooved structures on a seta (c). Scale bars: 20 μm (b), and 200 nm (c);

On the other hand, the scales on thewing surfaces of some butterflies have regularly arranged edges which are overlapping like roof tiles [13].

Rose Pedal Effect

It is already becoming vivid from the discussions mentioned previously that the mechanisms of individual superhydrophobic surfaces are not necessarily the same with each other in every aspect. Different from the lotus effect, the so-called petal effect describes the phenomenon that a water droplet on the petal surface of a red rose (rosea Rehd) forms a spherical shape, but does not roll off even when the petal is turned upside down [14], as shown in Fig. 5. The diverse design in surface microstructure on rose petal results in different dynamic wetting from lotus leaves. When a small water drop wets the petal surface, the liquid film impregnates the textured regime. However, the liquid only wets the grooves between the projected pillars, leaving the “plateaus” dry, which form the Cassie impregnating state, as shown in Fig. 6. For the petal surfaces, the dimensions of hierarchical micro- and nanostructures both are found larger than those related to the lotus leaf. In the Cassie impregnating wetting regime, water droplets enter into the “large” grooves of the petal but not into the “small” ones. This indicates why small water drops sealed in micropapillae would be clinched to the petal's surface, showing a high contact angle hysteresis (CAH) even if the surface was turned upside down. Thus, the mechanisms for different natural superhydrophobic surfaces and their wetting states might seem vague to follow. However, the common characteristic of superhydrophobic surfaces rests on the congenially periodical structures that are hierarchically organized in 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.

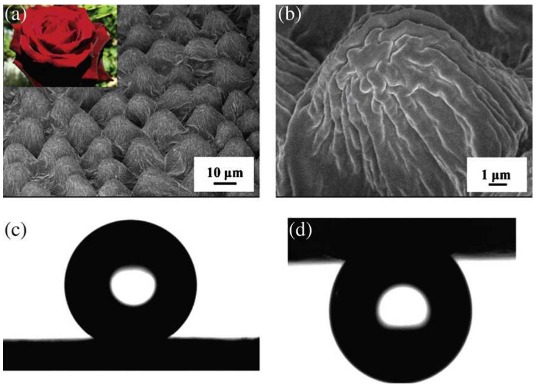

Figure 5: SEM images (a, b) of the surface of a red rose petal, showing a periodic array of micropapillae and nanofolds on each papillae top. (c) A water droplet on the petal's surface, indicating its superhydrophobicity with a contact angle of 152.4°. (d) Profile of a water droplet on the petal surface when turned upside down. [14].

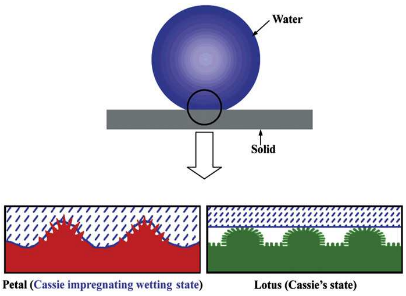

Figure 6: Schematic illustrations of a drop of water in contact with the petal of a red rose (the Cassie impregnating wetting state) and a lotus leaf (the Cassie's state). [14].

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.

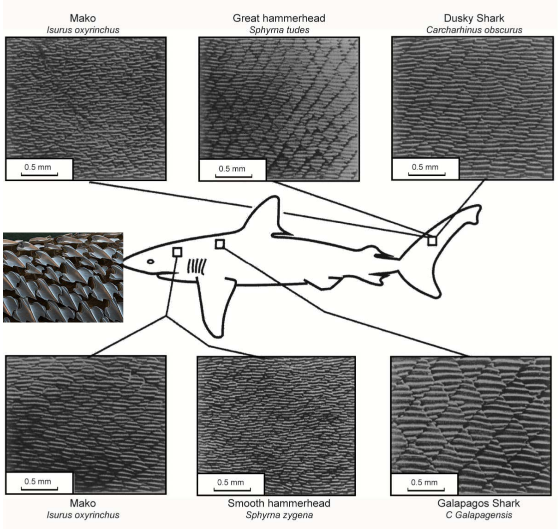

Figure 7: Natural riblets

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 Michaelsen body tissue [16]

	Electric potential of Michaelsen when creeping (mV)		Electric potential of Michaelsen through a tube (mV)	
Position on body	Maximum	Mean	Maximum	Mean
Fore part	40	21	35	20
Middle part	30	11	19	9
Hind part	18	11	18	5

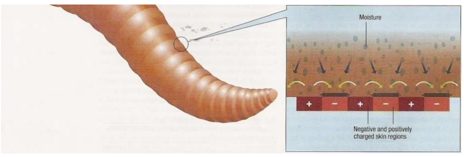

Figure 8: electroosmosis effect - earthworm

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].

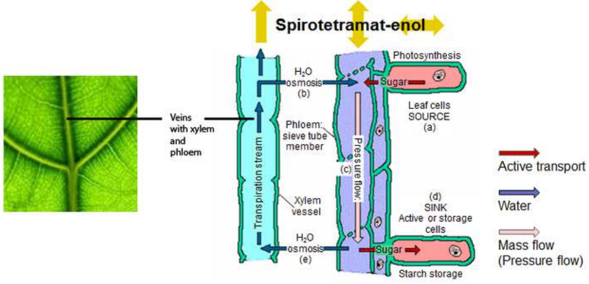

Figure 9: water flow process in plant xylem

Xylem with small warts indicates superhydrophilicity that indicates the function of improving capillarity. The water-conducting network of capillaries in vascular plants has evolved over hundreds and millions of years in order to be able to cope with bubble clogging, a problem which also affects modern microfluidic devices. It is revealed that plants growing in habitats in which the formation of bubbles, or emboli, is likely to be a frequent occurrence often have various forms of geometrical sculpturing on the internal surfaces of the xylem conduits. The wall sculpturing is reported a functional adaptation designed to increase the wettability of the walls of xylem conduits, an effect that could be described as the inverse of the well-known Lotus effect.

Current Progresses

Researches on mimicking natural functional surfaces have been intensively studied over the past decades. Major progresses have been achieved on identifying natural models, understanding the mechanisms by having micro insights of the interactions between the cuticles and droplets or fluids, and by developing coatings and fabrications based on the micro-nano technologies and using laser, plasma, and other advanced technologies. These have been reviewed by a number of researchers such as in [2, 5, 7, 10, 19, 20].

In addition to the progress of theoretical modellings in which many recent papers have been published, some of them have been reviewed in [2, 18, 20]. Numerical modellings using different methods such as CFD, meso and micro scales methods have also been approached toward simulating the interactive behaviours and optimising structure of the fabrications.

Future Prospective

Reviewing the historic development of applying nature solutions to improve efficiency of energy system involving fluids flow and heat transfer, we can see in Year-1000 or even early, people started to notice nature phenomena and solutions. In Year-2000 or now a days, people have started to have micro insights of particular functions of plants and animals cuticles and surfaces and their interactive effects on environment and fluids, and to study and understand the a number of important phenomena and effects such as the lotus effect, rose petal effect, shake skin or dolphin effect, earthworm effect, and water migration in plant and trees, etc. By understanding the mechanism of such nature solutions, the current methods of fabrications and manufacturing will be further improved.

It should be optimistic that toward to Year-3000, biomimetic or nature inspired functional surfaces will be effectively applied to fluid flow equipment, pipe lines, heat exchangers, engines, turbines and compressors, chemical processes, microchannels, building envelop, cars, and more sport facility, etc.

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.

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