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Morphological configurations inspired by nature for thermal insulation materials

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Abstract

Cooling and heating of buildings account for a significant part of the global energy consumption, where different insulation materials are applied for energy conservation. With the increasing need to reduce energy demands, developing new energy efficient services and technologies is essential. Our approach is to seek thermal solutions from strategies found in nature. Buildings, in a similar way to nature, are expected to maintain appropriate interior temperatures for occupant comfort. Living organisms maintain body temperature in very narrow ranges in order to survive, by employing a wide array of strategies that continuously balance heat gain and loss processes. In some organisms, the process is achieved through the skin functioning as a thermal medium, whereas in others, it is achieved through their built structures. Most organisms use morphological characteristics to supplement physiological and behavioral thermoregulatory strategies. It is believed that the main contributing parts in heat loss reduction are the morphology, assembly, and structure of the medium, which can analogously applied in buildings. To this end, we distinguish several morphological configurations from nature for thermoregulation, emphasize the morphological role on the thermal behaviour of natural systems, and provide recommendations for the development of new materials and systems for thermal applications.

Keywords: Biomimicry, biomimetics, morphology, form, arrangement, composition, fibers, feather, fur, insulation materials.

1. Introduction

We use a considerable amount of energy for cooling and heating our buildings. In general, buildings account for over 40% of the global energy consumption, whereas heating and cooling account for 50-70% of the total energy consumed in buildings. Thermal performance of buildings is influenced by the physical properties of materials applied in construction, where conductivity, emissivity, and absorptivity play major roles. Significant energy savings could be achieved in buildings if insulation materials are adequately designed, selected, and applied. Insulation materials differ, among others, in their composition, form, and performance. The selection of insulation materials is influenced, besides the thermal performance criteria, by its fire resistance capability, acoustics, cost, durability, and environmental impact (Al-Homoud [1]). They range from organic, inorganic/mineral, oil, to other composite materials that are available in different forms (Al-Homoud [1]). Current use of materials for insulation vary from traditional to state-of-the-art, such as mineral wool, expanded and extruded polystyrene, polyurethane, aerogels, and vacuum insulation panels (Al-Homoud [1], Jelle [25], Papadopoulos and Giama [41]), where the use of state-of-the-art materials that have higher thermal performances are limited due to high prices and fragility (Jelle [25]).

With the increasing need to reduce energy demands, proposals for the development of future thermal material solutions are having high performance requirements, such as conductivity values below 0.004 W/(mK), lifespans above 100 years, and better adaptability on construction site (Jelle *et al.* [26], Kalnæs and Jelle [28], Papadopoulos [40]). Efficient thermal solutions can be extracted from strategies found in nature. Living organisms in nature maintain body temperatures in very narrow ranges in order to survive, by employing a wide array of strategies that continuously balance heat gain and loss processes. Thermal solutions inspired by nature for application in buildings is an emerging field, where some studies have been carried out in the recent years to explore potential applications, e.g. (Badarnah [5, 6], Craig *et al.* [16], Webb *et al.* [58]). Organisms inhabiting extreme cold environments have long attracted research, and lately some studies have been revisited and new results were discussed. For example, penguins inhabiting the extreme cold Antarctic, are able to maintain a temperature gradient (between body-core and surrounding air) of about 80°C across a feather layer of roughly 2 cm (Kooyman *et al.* [30], Mccafferty *et al.* [37]). This extraordinary ability is due to a combination of special physiological, morphological, and behavioural adaptations for minimized heat loss (Du *et al.* [18], Simonis *et al.* [49], Wolf and Walsberg [59]).

This work presents an overview of basic strategies applied by nature for thermoregulation (section 2), and provides some morphological configurations (section 3) to inspire the future development of building insulation materials and systems (section 4).

2. Thermoregulation in nature

One of the fundamental characteristics of living organisms, cell, or group is their ability to maintain the internal environment within tolerable limits despite the changes in the surrounding environment (Schmidt-Nielsen [45]). They succeed to maintain this state through a constant regulation of several factors simultaneously, in particular: heat, water, and gas. Beyond generating heat metabolically, heat is transferred between animals and their environment by conduction, convection, radiation, and evaporation (Schmidt-Nielsen [45]). In some organisms, the process is achieved through the skin functioning as a thermal medium, whereas in others, it is achieved through their built structures. Different mechanisms and strategies are adapted for different climates and for different species.

In cold environments, maintaining an appropriate core body temperature is accomplished by radiation managing, conduction and convection reduction, and metabolic rate regulation. These strategies can be morphological, physiological, as well as behavioural. For example, birds use multiple strategies for retaining heat; chickadees decrease conductance in the cold by raising their feathers and withdraw head and feet into the feathers (behavioural) (Schmidt-Nielsen [45]). They trap an insulating layer of air close to the body and in doing so reduce heat losses (morphological). They also allow the peripheral tissues temperature to drop while maintaining the core temperature (physiological). These results in a decreased peripheral circulation, increased insulation thickness, and enlarged volume, which contribute to maintaining the core temperature in a very narrow range. In environments where the ambient temperature is higher than body temperature, the body receives heat by conduction, convection, and radiation. Mammals to dissipate metabolic heat and heat gained from the environment often use evaporation, and other physiological and behavioural strategies.

2.1. Conduction & convection

Conduction solutions in nature are either external (e.g. fur and feather) or internal (e.g. blubber), where morphological specializations affect thermal behaviour (Cowles [15]). Fur thickness may change throughout the seasons to accommodate temperature changes (Schmidt-Nielsen [45]). The thick subcutaneous blubber layer, in mammals inhabiting the arctic and Antarctic, provides insulation besides providing a source for energy, since fur loses most of its insulation (i.e. air-trapping) value in water (Scholander *et al.* [48]). Different body parts are not equally insulated, since animals need surfaces from which heat can be dissipated when required (Scholander *et al.* [48]). Material thickness, density, and surface area affect conduction and convection: (1) the thicker the substance the lower the conduction; (2) the denser the substance the higher the conduction; and (3) the larger the surface area the higher the chances for convection.

2.2. Radiation emission & absorption

Several adaptation strategies have evolved to manage radiation emission and absorption. Since heat loss via radiation occurs through the surface, a strong relationship exists between radiation emission and exposed surface area and its properties. Insects and reptiles use solar radiation as a source for heat gain, where colour, conductance, distance from a heat source, and orientation (relative to sun) affect their rate of absorption. Many desert organisms are primarily active at night in order to avoid the extreme heat of the day. Dark colours absorb more radiation than bright colours, and many reptiles can change their skin colour by dispersing and contracting dark pigments in their skin (Camargo *et al.* [11]). A proper posture and orientation of body parts towards sunrays, e.g. spreading legs and flattening the body, increases exposed area. Overheating is avoided by changing posture, brightening skin colour, and/or moving into a shaded area (Schmidt-Nielsen [45]).

2.1. Evaporation

When air flows over a moist surface it causes evaporation, which in turn takes a certain amount of heat from the surface. Sweating, panting, and gular fluttering are processes found in different species that increase cooling via evaporation. In gullar fluttering, the animal keeps its mouth open and increases airflow over moist vascular oral membranes by vibration; this in turn increases evaporation and results in increased dissipated heat (Weathers and Schoenbaechler [57]). Increased heat load results in increased gular fluttering (Bartholomew *et al.* [9]). Panting is also common among birds and mammals, where the rate of breathing is increased as a result of heat stress, e.g. dogs (Hill *et al.* [23]).

3. Morphological configurations for thermoregulation

Most organisms use morphological characteristics to supplement physiological and behavioural thermoregulatory strategies (Badarnah [6], Hill *et al.* [23]). Current work distinguishes three important morphological aspects for effective thermoregulation: *form*, *arrangement*, and *composition*.

3.1. Form

The form of an organism is determined by its mechanical, environmental, and behavioural patterns obeying some laws of physics (Tributsch [52]). As objects become larger in size their surface-area is proportionally reduced, see Figure 1(a). For example, the blue whale might be 10 million times larger in weight than a mouse, but only larger 10 thousands times larger in surface area (Tributsch [52]). According to Bergmann's rule (Bergmann [10]), as carefully translated by (Watt *et al.* [56]), surface-area to volume (SA:V) ratio is a significant factor for species inhabiting cold environments in order to keep body temperature above the surrounding temperature, where larger body sizes need to generate less warmth proportionally than smaller ones. Basal metabolic rate (BMR) has an exponential relation to size in most animals (Scholander *et al.* [46]), as presented in Figure 1(b). Furthermore, the tendency to have larger protruding parts (e.g. ears, limbs, tails) in individual organisms of the same species inhabiting cold and warm climates, is higher in warm environments than in cold ones (Allen [2]). Bergmann's and Allen's rules demonstrate, in most cases, an important correlation between the temperature of the environment and the size, growth, and form of an organism (Ray [44]). SA:V ratio plays a major role in dissipating or retaining heat. It is believed that the increase in size is correlated with heat conservation and the decrease in size is correlated with heat dissipation, where an optimal SA:V is applied (Mayr [35]). Small SA:V ratios can better face heat and cold stresses compared to large SA:V ratios. For example, due to high wind speeds, penguins huddle to reduce collective surface area in the harsh environment of the Antarctic (Gilbert *et al.* [20]), thus reduce heat loss, while also utilizing any ambient heat loss of neighbours, and create a micro-climate of 10°C higher than ambient temperature (Jarman [24]). The large size of whale relative to its surface, reduces excessive heat loss in the cold water (Tributsch [52]). Additionally, many animals tuck in extremities like limbs during cold events in order to help with reduced heat loss. Camels and other large volume animals inhabiting warm climates are less likely to absorb too much heat due to, among other factors, their smaller SA:V ratio.

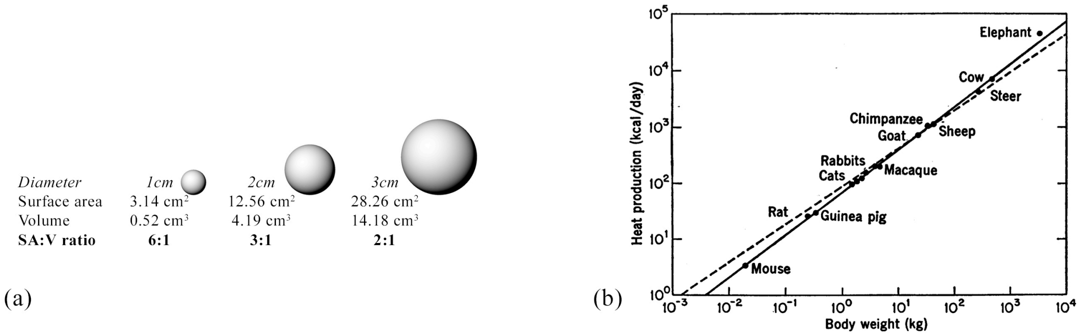

Figure 1: (a) SA:V ratio of different sizes of spheres. (b) "Metabolic heat production plotted against body weight on logarithmic scales. The solid line has slope ¾. The broken line, which does not fit the data, has slope ⅔ and represents the way surface area increases weight for geometrically similar shapes (adapted from (Kleiber [29]))", from (McMahon [38]). Reprinted with permission from AAAS.

Body orientation with respect to airflow direction also affects the rate of heat convection, where being parallel to airflow is more effective for heat transfer via convection than being perpendicular (Gebremedhin [19]). Furthermore, certain external geometrical manipulations of structures enhance air movement for heat transfer via convection (Badarnah [5]). For example, the structural features of termite mounds (see Figure 2) allow enhanced heat dissipation (Jones and Oldroyd [27]), i.e. the thin walls with numerous ridges and turrets (Korb and Linsenmair [31, 32]), where air passages close to the surface ventilate through natural convection and maintain inner thermal comfort (Korb and Linsenmair [33]).

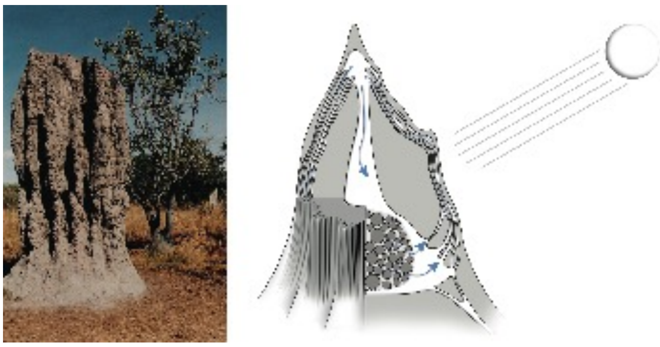

Figure 2: (left) the numerous ridges of the cathedral mound, photo by Karen Sullivan. (Right) mound cross section showing the airflow inside the mound induced by external radiation.

3.2. Arrangement

Structure arrangement is a significant factor for energy efficiency, such as counter-current systems. Bypass and counter-current systems are means for modulated flow of heat in organisms inhabiting environments with changing temperatures. Bypass systems allow a differentiated transfer of heat between two mediums, which is found in circulatory networks near the skin of some mammals (Schmidt-Nielsen [45]). They modulate heat transfer from the skin by blood flow passing the insulation layer (Kvadsheim and Folkow [34]), where they control heat dissipation or conservation according to their thermal demands (Meagher *et al.* [39]). This phenomenon is observed in seals and whales that live and swim in the arctic and Antarctic sea, since fur loses most of its insulation (i.e. air-trapping) value in water (Scholander *et al.* [46]), Figure 3(a). In humans, blood circulation is enhanced or reduced to skin surface via vasodilation or vasoconstriction (respectively), Figure 3(b). When arterio-venous anastomoses (shunts) are open, they provide a shortcut for the blood route from the arterioles to the venous plexus, which act as a warm chamber next to the skin surface, resulting in heat loss to the environment (Arens and Zhang [3]).

Counter-current circulation systems (heat exchangers) reduce thermal gradient between bodies and surrounding environment, thus retaining more heat, Figure 3(c). Heat exchangers can be found in blood vessels with special morphology, e.g. in whale flippers, where each artery is completely surrounded by veins (Scholander and Schevill [47]), Figure 3(d). This special structure arrangement results in cooling arterial blood before it reaches the periphery (losing heat to the water), and in warming returning blood (venous blood) before it enters body core (Carey and Teal [12]).

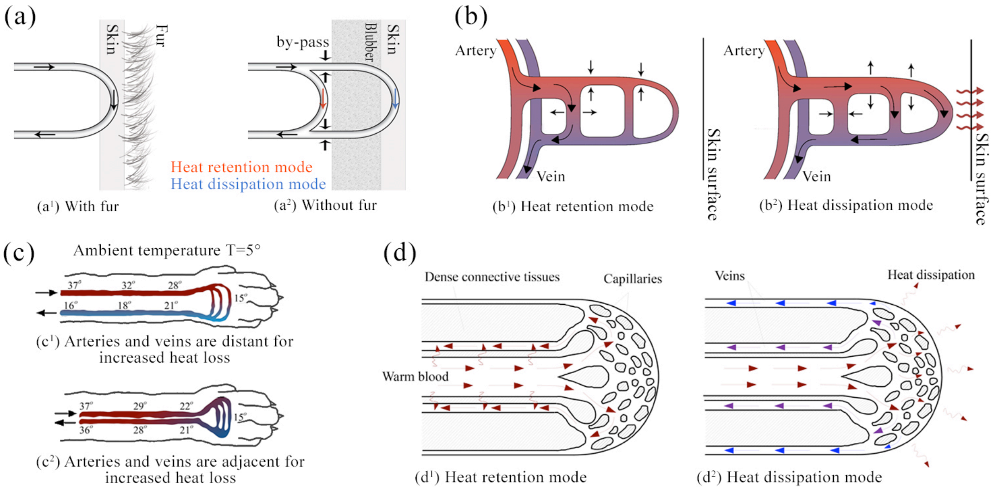

Figure 3: (a) left - fur is located outside the skin and cannot be bypassed when wet. Right – blubber bypass system for heat dissipation, after (Schmidt-Nielsen [45]) (b) left – vasoconstriction. Right – vasodilation. (c) Concurrent and counter-current blood flows in dog's feet, after (Hill *et al.* [23]). (d) Blood circulation for heat retention and heat dissipation modes in dolphin's flippers.

3.3. Composition

Some materials of the natural world are regarded as composite materials, such as wood and bone, where structural composition has a major influence on the mechanical properties of the material (Vaz *et al.* [53]). Thermal properties, similar to mechanical properties, are influenced by the geometrical configuration of composite mediums (Springer and Tsai [50]).

In normal conditions (wind speeds below 2.5m/sec), the feather layer of penguins is the principal contributing part in thermal insulation (Jarman [24]). The feather layer significantly reduces convective and radiative heat loss (Dawson *et al.* [17]). It is believed that the morphology, assembly, and structure of feathers are significant factors for minimized heat loss (Du *et al.* [18]).

Similar to penguins, polar bear's fur is highly effective in reducing heat loss. Fur structure, containing different sizes of hair with dense interfaces, provides the necessary multiple scattering of radiation to retro-diffuse heat (Simonis *et al.* [49]). Radiative heat loss occurs in the infrared wavelength range, where polar bear's fur exhibits high absorption values (~0.95) precisely for those wavelengths that are crucial for his survival (Preciado *et al.* [43]). The white colour of fur allows radiation to reach the black skin and contribute to thermal gain (Walsberg [55]).

Silkworm cocoons, a multilayer structure, maintains a stable inner temperature despite sudden thermal changes in the surrounding environment (Zhang *et al.* [60]). Cocoons are composed of silk fibroin (fibrous protein) and bound with sericin (amorphous protein polymer) for structural integrity, where differentiated structural and morphological compositions of cocoon fibres have a significant influence on different functional properties (Chen *et al.* [13, 14]). Cocoons, single or double, consist mainly of fibres composing porous layers, where each cocoon can vary from single to multilayers with different bonding properties, as shown in Figure 4(c) (Chen *et al.* [13]).

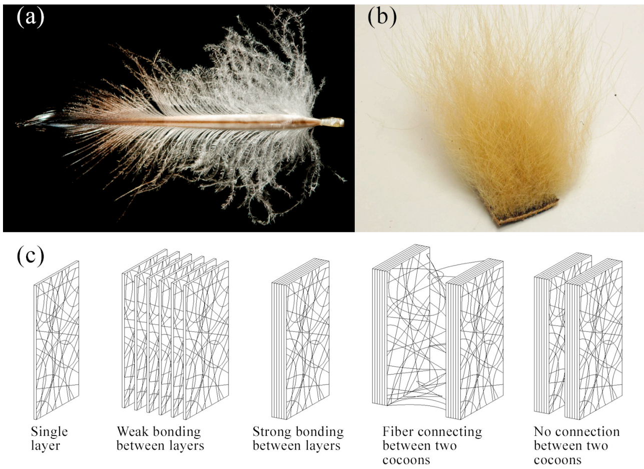

Figure 4: (a) penguin feather – large shaft and lots of down, courtesy of Featherfolio. (b) Polar bear fur patch, courtesy of Steve Gardner. (c) Different cocoon layer structures, after (Chen *et al.* [13]).

4. Conclusions & future visions

A few studies have been carried out in recent years to explore thermal strategies from nature for potential applications in buildings (Badarnah [5, 6], Badarnah *et al.* [7], Mazzoleni [36], Pawlyn [42]). Application examples are often conceptual and claim high advantages over traditional thermal solutions: a radiative cooling roofing system estimated to be cooler than a standard roof by 4.5°C (Craig *et al.* [16]); a biomimetic façade cladding material that provides higher heat retention in winter compared to a double wall facade (Aslam [4]); and a spacer textile made of translucent polymer fibres reduces heat loss by convection and radiation (Stegmaier *et al.* [51]). Several design support tools are available to facilitate design concept generation (Badarnah and Kadri [8], Goel *et al.* [21], Vincent *et al.* [54]).

In the context of thermal applications, we find it promising to select appropriate morphological configurations as the base for future biomimetic applications, see Table 1 for a summary. SA:V ratio is an important morphological factor that influences energy consumption and heat transfer between body and environment. It is not surprising that traditional villages have compact configurations, such as in Mediterranean regions, where a cluster of houses form a continuous structure with reduced external surface-area and create comfortable microclimates in their courtyards, thus reduce a great amount of heat stress taking into account other climatic and cultural aspects. There are clear benefits from applying these strategies at the building scale, such as savings in energy and reduced heat transfer to the surrounding environment. It is useful to follow some guidelines that draw a preferred volume (height and floor area) and external surface area for specific environmental conditions. We are not necessarily suggesting applying a similar ratio as in organisms, as organisms involve a complex filling network (fractal) that distributes energy and other resources optimally, which might be too complex to apply in buildings. Rather, we recommend applying optimal ratios between building envelope area and thickness as a result of the operating systems and use of building. In support of our recommendations, a recent study (Grobman and Elimelech [22]), suggests that some external geometrical manipulations of building envelopes could create microclimates near the surface for a better thermal performance, which may reduce the need for standard insulation materials. Clearly, exploring natural systems assists in finding optimized morphological configurations for building thermoregulation.

Bypass systems in nature provide inspiration for differentiated thermal transfer solutions through mediums. The arrangement and management of building systems (e.g. water pipes) can influence the thermal transfer through the building envelope, especially when warm pipes can be diverted to the inner surface in winter and outer surface in summer. Additionally, employing special arrangements that allow heat exchange between systems can enhance heat retention.

Fur and feather in birds and mammals have a significant thermal role not only for heat conservation, but also for excessive irradiation prevention (Cowles [15]). Radiation transfers heat to the surrounding environment at a higher rate than conductance in low-density fibrous materials (Simonis *et al.* [49]). This suggests that some organisms that encounter the risk of high rates of heat dissipation are better adapted for radiation loss mitigation. Most traditional insulation solutions focus on the decreased conduction of materials (as shields) instead of the reduced heat transfer through mediums to/from the environment (as interfaces). A biomimetic solution should allow a gradient heat flow to/from the environment, where heat transfer (through the biomimetic medium) changes according to temperature differences.

The present study indicates that new avenues could be explored to improve the way our systems and buildings function thermally. Several organisms and systems from nature have extraordinary abilities to withstand the harsh environmental conditions, where analogue applications in buildings are possible. The major benefit of this study is present in emphasizing the morphological role of material composition on thermal behaviour in nature for potential applications in insulation materials. Natural systems follow special morphological rules to generate interfaces rather than shields, allowing optimal flow of heat. The more extreme the environment is the more organized and distinct in form the pelage (i.e fur, hair, wool) becomes. The relatively small amount of studies on biomimetic thermal solutions for building applications has left a significant territory awaiting its grounds to be broken, and further empirical research is required to test and validate the morphological configurations for new thermal solutions applications.

	Form	***Arrangement***	***Composition***
Relevant scale	Building	System	Material
In the *Heat*	• Small • Large SA:V for dissipation • Small SA:V for prevention • Surfaces parallel to airflow and sunrays • Protruding parts	• By-pass systems • Vasodilation: enhanced circulation near surface • Fractal	• Fibrous
In the *Cold*	• Large • Small SA:V for retention • Surfaces normal to airflow and sunrays • Compact	• Counter-current systems • Vasoconstriction: restricted circulation near surface • Fractal	• Multilayer • Fibrous • Order

Table 1: Summary of morphological configurations for hot and for cold environments.

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