Intelligent thermoregulation and homeostasis: lessons from nature

Mark Worall,
The Institute of Sustainable Energy Technology, The Department of Architecture and Built Environment, The University of Nottingham
email: mark.worall@nottingham.ac.uk

Abstract

Mankind has developed sophisticated means of maintaining comfortable living conditions around the world. We use many technologies that allow us to achieve thermoregulation and homeostasis and so live, work and survive in otherwise hostile environments. Many species in nature also practice thermoregulation and homeostasis, with some of the most interesting being the social insects. Biomimetics is defined as design inspired by nature, and so a biomimetic approach to thermoregulation might enable engineers to develop novel strategies that have less of an impact on natural resources and are more responsive to the environment. The mound building termites of South America, Africa and Australasia construct sophisticated structures that enable the environment within the nest to be regulated. Wind energy is captured to exchange gases between the nest, the mound and the outside by elaborate internal galleries, tunnels, and ducts. Gas exchange and ventilation could be achieved through responsive envelopes and fabric analogous to termite homeostasis. The oriental hornet can maintain a nest temperature of 28-32°C in tropical, sub-tropical and temperate areas. It has been found that when the adult population are removed from the nest, its temperature is maintained for a number of days afterwards. The oriental hornet nest houses both the adult population and combs that contain the brood. Eggs are placed in the walls of the comb and when they hatch the pupa spin a silk weave and form a silk cap at the open entrance, sealing it from the outside. In studying the thermoregulatory properties of hornet nests, it has been shown that the silk cap and walls of the comb have thermoelectric properties that could help regulate the temperature in the comb. It was shown that as ambient temperature increases, the current intensity increases. When the ambient temperature falls the energy stored is discharged with a flow of electric current from high to low potential. The engineering materials with properties closest to the Hornet silk are the conductive polymers, although the thermoelectric properties may be more than 10,000 times lower than semiconductors used in modern devices they may be useful as heat storage and discharge systems in buildings.

Keywords: Homeostasis, thermoregulation, biomimetics, intelligent buildings, thermoelectric

1. Introduction

Human beings, like most animals on earth require stable and comfortable environments in which to live. Engineers have used their knowledge and skills to adapt the environment so that we can survive and thrive in otherwise inhospitable environments. However, we consume and waste large quantities of resources in our pursuit of comfort. Other animals have adapted to their environment in diverse and less wasteful ways. Most animals need to maintain or regulate their core temperature within certain set points. In cold blooded animals (*polikilothermic*), body temperature changes with their environment and in warm blooded animals (*homeothermic*), body temperature is maintained at high and stable temperatures. Some animals construct nests and burrows to shelter from the extremes of the environment, to avoid predators and to rear their brood. Could we learn anything about developing an intelligent building by studying how animals survive in environments perhaps more hostile than the ones we face?

Bionic engineering or biomimetics is a philosophy that takes its inspiration from nature to solve problems in engineering and design. In comparing methods of problem solving in engineering and nature, Vincent *et al* (2006) showed that only about 12% of the solutions were common to both on similar scales. Engineers have always sought knowledge to enhance their design and manufacturing skills and so the natural world can provide a vast additional resource of largely untapped potential.

Insects were the first animals to evolve social systems, flight and thermoregulation, according to Heinrich (1993). They are very vulnerable to stress due to extreme temperature changes because of their small body size and so many of them require sophisticated systems to enable them to survive. Many social insects build nests that help to regulate the environment within the nest in response to external drivers. The internal environment is not in equilibrium with the surrounding environment and so the structure acts to counteract the out-of-balance energy and mass fluxes. A study of properties and functioning of nests and burrows may enable us to design buildings that balance the disequilibrium between the interior and exterior of the building. Although bionics would not be used to copy a design for a shelter blindly, lessons may learnt in many different fields including materials use, temperature regulation, ventilation and humidity control. This paper describes some of the nest building insects and examines the application of knowledge to engineering design.

2. Thermoregulation and homeostasis

Thermoregulation and homeostasis are terms to describe the dynamic response to out-of-balance fluxes, temperature in the case thermoregulation, and a wider variety of properties that make up a habitable environment in the case of homeostasis. Here, thermoregulation is defined as “the maintenance of body temperature or temperature range independent of passive processes and the body’s metabolism during different activities”, according to Heinrich (1993) and homeostasis is defines as “a regulated dynamic disequilibrium, sustained by the active management of fluxes of matter and energy” from Turner (2008).

Most animals in nature practice thermoregulation and homeostasis. Heinrich (1993) describes in detail thermoregulatory mechanisms of many hot blooded insects, from how the physiology of individual insects enable them survive in extreme ambient conditions to how their behaviour can contribute to temperature regulation. Thermoregulation in social insects may be broadly categorised into two different types, according to Jones and Oldroyd (2007), active and passive thermoregulation. In passive thermoregulation, insects may change site location and orientation, they may move within a nest to a more suitable position, they may build structures that insulate them from the ambient conditions, or they may transport their brood to regions within a nest with superior thermal conditions. In active thermoregulation, insects may exhibit behaviour in order to moderate the temperature such as wing fanning or introducing water droplets to cause evaporative cooling.

The nest building activities of social insects are many and varied but this paper focuses on two nest builders in particular because of the possibility of applying the lessons learnt to the built environment. The mounds of the termites (*Macrotermitinae*) and the nests of the oriental hornet (*Vespa orientalis*)

2.1 Termite mounds

The fungus cultivating termites, *Macrotermitinae*, develop mounds that are among the most spectacular architectures created in nature. They are found in the tropical and sub-tropical savannahs of South America, Africa and Australasia. Termites of the order 10mm in length can build structures over a thousand times their own size according to Bölsche (1931). There are two main types of termite mounds according to Noirot (1990), open ventilation mounds in which chimneys or holes in the sides of the mounds allow air to flow into or out of the mounds due to differences in wind velocity according to Darlington (1984), and closed mounds in which no holes or chimneys exist according to Darlington (1985,1990).

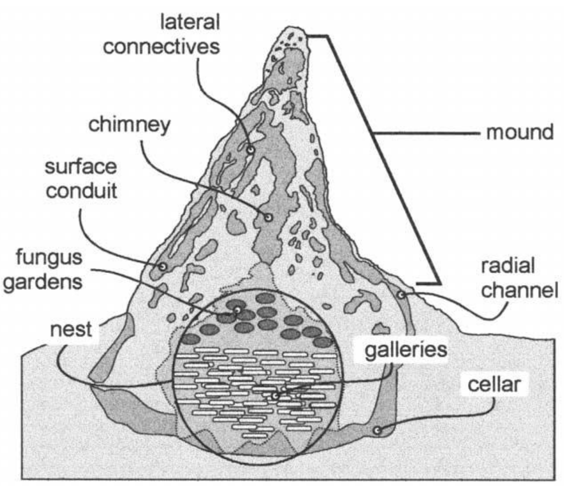

Figure 1. A termite mound that might be found in the tropical savannah. Turner (2001).

The mounds may have different forms depending on whether they are located in savannahs or gallery forests, but they have similar internal structures. Figure 1 shows a diagram of a termite mound that might be found in the tropical savannah, as described by Turner (2001). The termites do not occupy the mound but are usually located below ground. The nest consists of a central nursery with the royal cell and the fungus gardens. The termites cultivate fungi for food but the termites and fungus, *basidiomycete* fungi of the genus *Termitomyces*, have an obligate symbiotic relationship according to Wood and Thomas (1989). The nest is out of equilibrium due to the driving flux of the metabolic demand from the termites and the fungi and so homeostasis is achieved by balancing the metabolic demand with the ventilatory flux (Turner, 2008) due to complex boundary layer pressure gradients across the surface of the mound due to wind flow. The disequlibrium between the nest and the outside air is the partial pressure of O_2 below atmospheric, the partial pressure of CO_2 above atmospheric pressure and a high relative humidity close to saturation compared with a low to medium relative humidity typical of the locations where the nests are found. However, Turner (2008) has pointed out that temperature in the nest is not regulated but instead closely follows the ground temperature because of the subterranean location of the nest and the damping effect of the earth.

Various techniques have been proposed to explain the ventilation and gas exchange of termite mounds. Lusher (1961) proposed that closed mound termite nests used a thermosiphon mechanism in which the heat produced by the metabolism in the nest produced a buoyancy effect within the nest. Wier (1973) measured the ventilation in open chimney mounds of the *Macrotermes subhyalinus* and it was concluded that flow was induced by the wind passing over the open chimneys and drawing air in from openings nearer the base the mound. However, it is now thought that these simple models do not adequately describe the ventilation and gas exchange processes in a termite nest.

Turner (2008) described the process within a nest analogous to an AC circuit which is driven by an alternating current (lung tidal flow) but at high frequency. In normal respiration, air flows at high turbulent flows in the trachea to a region at almost zero flow, the alveoli, where the oxygen and carbon dioxide are exchanged by diffusion. The flow is controlled in a mixed flow region between trachea and the alveoli called the bronchi. The air volume inhaled usually exceeds the volume of the conducting airways, and is known as the dead space. But in high frequency ventilation, adequate gas exchange can be provided in which the volume inhaled is less than the volume of the conducting airways.

Slutzky and Drazen (2002) described some of the complex mechanisms that take place in the lung during high frequency ventilation. Figure 2 shows some of the mechanisms, reproduced from Slutzky and Drazen (2002). Turbulence due to low volume but high frequency tidal flow enhances mixing, turbulent flow in the bronchi enhance radial mixing, pendelluft ventilation ("asynchronous flow due to asymmetries in airflow impedance") around the branches of the bronchi enhance mixing between different branches, laminar flow and radial mixing that enhance inflow is concentrated along the inner wall and outflow is concentrated along the outer wall and collateral ventilation through non-airway connections between alveoli.

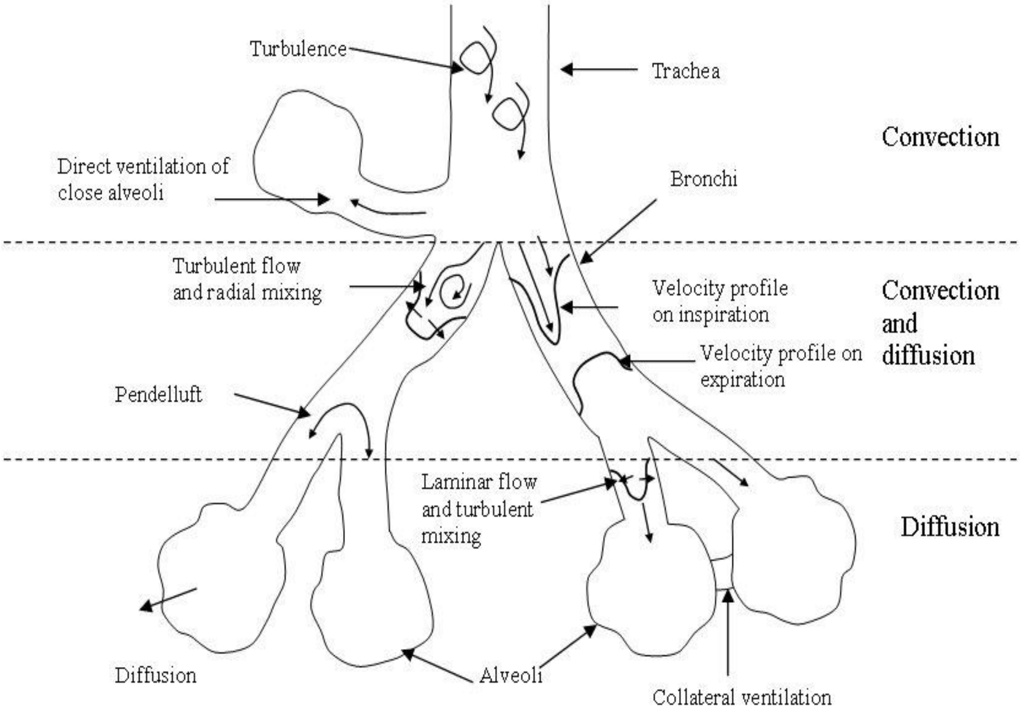

Figure 2. High frequency lung ventilation showing different gas exchange and mixing mechanisms. From Slutzky and Drazen (2002).

Turner and Soar (2008) suggested that a similar process may occur between the nest and the mound that enhances gas exchange. High frequency ventilation may match the resonant frequency of the ventilation system to enhance gas exchange and turbulent mixing in the large passages, pendelluft ventilation may enhance the mixed convection-diffusion region balance and maximise gas exchange between the branches. Soar (2008) has completed research that has been described by Turner and Soar (2008) that examined the structure of *Macrotermes Michaeleni* mounds to determine the processes involved and apply the lessons learnt in architecture and engineering design. It may be possible to design high frequency ventilation systems that require low flows but that enhance mixing and gas exchange. Wind capture systems that use boundary layer pressure gradients may be effective and reliable compared with standard turbine generator systems and be complimentary to the building form such as the envelope. Mass and energy fluxes across a surface may be developed to enhance ventilation, gas and moisture exchange in a building that is more reliable than current methods. The building forms may be constructed using and freeform manufacture methods as described by Buswell *et al* (2007) and informed by the termite mound construction.

Although termites are the most well known insects to modify their internal environment to achieve homeostasis, other insects are able to do it. Some of the most interesting insects are wasps and hornets. They can be found in most environments, from tropical rain forests, deserts, sub-tropical and temperate climates. They are able to survive in so many different conditions because they are able to thermoregulate themselves and their nests. Wasps and hornets in temperate and cold climates tend to construct paper nests projected vertically downwards and hexagonal in structure, according to Klingler *et al* (2006). The nest itself has very little thermal storage effect and there is little thermoregulation in the nest. Temperatures tend to swing in response to foraging behaviour and general energy budget. Wasps and hornets in tropical and sub-tropical climates have adapted their nest building behaviour to cope with the large temperature changes daily and seasonally. The oriental hornet has an especially interesting nest building behaviour.

2.2 Oriental hornet nest

The oriental hornet (*Vespa orientalis***)** can maintain a nest temperature of 28-32°C in tropical, sub-tropical and temperate areas according to Ishay and Ruttner (1971). This is achieved using many techniques, including building nests below ground to provide insulation from ambient temperature swings, the beating of wings to provide air flow and enhance heat and mass transfer, and the distribution of water droplets from the adult to hydroscopic materials in the nest that can be evaporated to produce a cooling effect. However, other cooling mechanisms may also be in use.

It has been found that when the adult population are removed from the nest, a temperature of 28-32°C is maintained for a number of days afterwards according to Ishay and Beranholz-Paniry (1995). It was concluded that materials in the nest were contributing to a thermoregulatory effect. The oriental hornet nest houses both the adult population and combs that contain the brood. The combs are hexagonal in structure and are formed vertically downwards as in the paper nests found in temperate climates. The combs are formed from organic building material gathered locally and masticated by saliva of the adult hornets, which quickly polymerises to form a robust structure. Eggs are placed in the walls of the comb and when they hatch the pupa spin a silk weave and form a silk cap at the open entrance, sealing it from the outside. The pupa continues to spin silk and form a layer on the comb wall, thus fully enclosing itself in a protective cocoon.

In studying the thermoregulatory properties of hornet nests, it has been shown in experiments by Ishay *et al* (2002a, 2002b), and Kirshboim and Ishay (2000) that the silk cap and walls of the comb have thermoelectric properties that could help regulate the temperature in the comb. It was shown that as ambient temperature increases, the current intensity increases. It was conjectured that a thermoelectric effect was charging the silk cap with electrical energy as the ambient temperature increased. Any excess heat was assumed to be released by the evaporation of water from the silk cap. When the ambient temperature falls, the energy stored was discharged with a flow of electric current from high to low potential, transferring heat by Joule heating and the Peltier effect. The Peltier effect is the release or absorption of a finite heat transfer rate at the junction between two constant temperature electrical conductors made of different materials.

But how can the nest provide a thermoelectric effect? The hornet nest silk cocoon consists of two types of material, a silk fibre that consists of an elastic protein called fibroin, and a surrounding protein called sericin. Each silk fibre is double stranded. Kirshboim and Ishay (2000) presented scanning electron micrographs of the structure of the silk, which can be seen in Figures 3 and 4. Figure 3 shows the construction of a silk fibre, where (a) is the surrounding sericin and (b) is the double stranded fibre made of fibroin. Each silk fibre is elliptical in shape, and varies between 1 and 5μm on the minor diameter with an aspect ratio of approximately 2 to 1. The silk cap is made of a tangle of silk fibres and sheets. Figure 4 shows a photograph of the structure of the silk. A material with good thermoelectric properties is difficult to find because on the one hand, it should have a high electrical conductivity to minimise Ohmic losses and on the other hand, it should have a low thermal conductivity to minimise conduction heat losses. The materials possessing the most desirable thermoelectric properties in engineering have been found to be semiconductors, for example Bismuth Telluride (Bi_2Te_3).

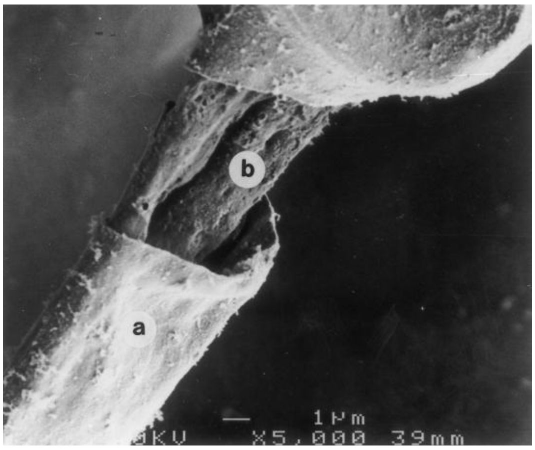

Figure 3. Photograph of silk fibre (b) with its envelope (a) Kirshhoim, Ishay (2000).

Kirshboim and Ishay (2000) proposed that the double stranded fibre was comparable with a semiconductor, where the inner fibroin strand performed the function of the *p* junction and the outer sericin envelope performed the function of the *n* junction. Thermoelectric properties are not limited to hornet silk and are known to be present in the silk spun by the silkworm *Bombyx mori* (Ishay and Barenholz-Paniry, 1995). However, comparisons of *Vespa orientalis* and *Bombyx mori* show that the hornet silk is an order of magnitude better in terms of thermoelectric properties. On the face of it, the structure of the silk does not seem to provide a good candidate for a thermoelectric device. The nearest engineering materials comparable with hornet silk are the electrically conductive polymers, such as polyaniliyne and polythiophane doped with Iodine.

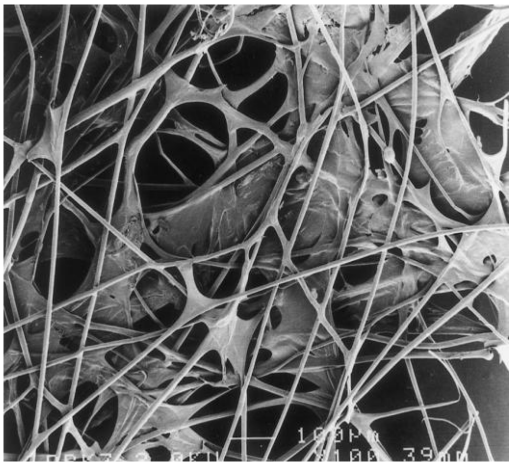

Figure 4. Micrograph of silk weave, showing fibres and sheets. Kirshhoim, Ishay (2000).

These materials were studied by Shiohari *et al* (2003) where it was shown that the Seebeck coefficient was 10,000 times less than the inorganic semiconductor Bi_2Te_3. The Seebeck effect is the creation of a potential difference due to the temperature difference maintained at junctions between two different materials and is the principle behind the thermocouple. The Seebeck coefficient is a non-linear relationship between temperature and potential difference. The papers published on the thermoelectric properties of the oriental hornet do not describe thermoelectric properties such as the Seebeck coefficient, so it is difficult to compare them with semiconductor devices or conductive polymers. However, conductive polymers are the engineering material most likely to be of use if the phenomenon of thermoregulation in hornet nests is to be developed as a technology in buildings. Although the Seebeck coefficient is much lower in a conductive polymer than an inorganic semiconductor, it can be manufactured using organic materials, at low cost, at ambient conditions, with increase in safety in manufacture and use and can be separated, recovered and recycled easily. As a thermoelectric generator or refrigerator it may impractical because it may be much larger than an equivalent device manufactured from inorganic materials and may not be able to attain the output needed, but as a heat storage device it may be applicable to air handling units in ventilation systems and coatings on the envelope of buildings, where a large surface area could be available and the low Seebeck coefficient is less relevant.

It was further proposed that the process could be compared with a heat transfer device called a heat pipe (Reay, 1982). Figure 5 shows a diagram of a heat pipe. A heat pipe consists of a closed tube filled with a fluid that can condense and evaporate at the desired working temperature of the device. One end of the device is placed in a low temperature stream, T_c, and the other end is placed in a high temperature stream, T_H. Heat transferred to the hot end, Q_{in}, causes evaporation of the fluid and sensible cooling of the stream. The vapour flows toward the low temperature end and the vapour condenses, transferring heat to the cold end stream, Q_{out}. The condensed liquid can either return by gravity to the hot end or by capillary action though a wick material connecting the hot and cold ends. The heat pipe thus exchanges heat between hot and cold streams with no moving parts and with high heat flux and high efficiency. The orientation of the individual combs lends itself to upward vertical vapour transport, evaporation from the hydroscopic silk cap at the lower end, condensation at the

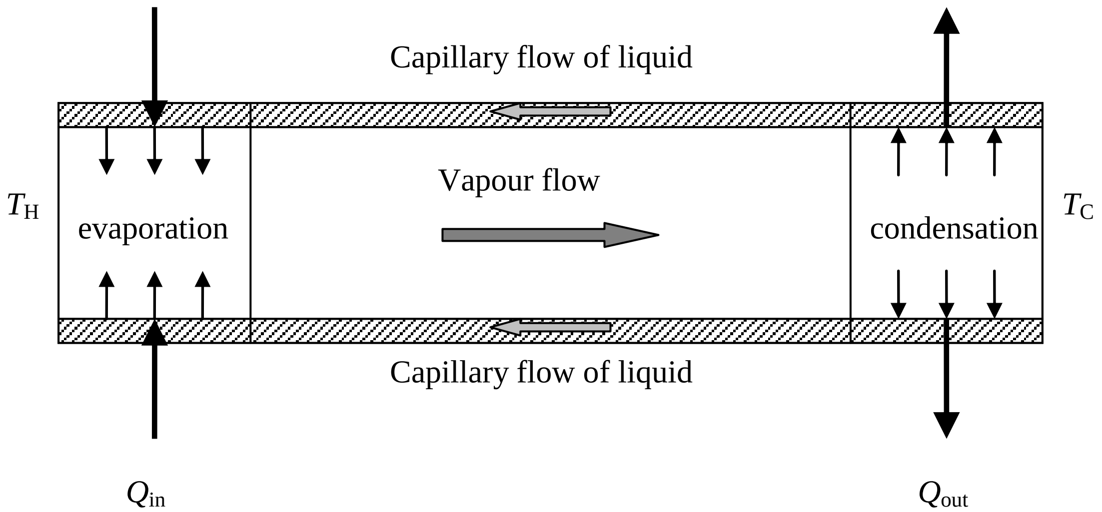

Figure 5. Schematic of a heat pipe.

comb wall near to the top end, the return of liquid through the wick like nature of the silk layer on the comb wall, and the isothermal performance of the system afforded comparison with the heat pipe. However, the process may be more analogous to a counter-current heat exchanger as shown in Figure 6. When the ambient temperature increases, a thermoelectric effect causes an electric charge to build up in the cocoon. The storage of energy reduces the heat transferred across the wall of the silk cap. Further cooling is achieved by the evaporation of water from the silk cap and reduces the temperature at the lower end of the comb. Heat is transferred across the thickness of the silk cap and cools the head of the pupa. The temperature of the comb is usually in contact with the ground and as such can be thought of as a ground source heat sink. The temperature at the roof of the comb is lower than in the silk cap end, so that heat is transferred from high temperature in the nest to a low temperature in contact with the ground. Inside the silk comb, heat transfers from the upper extremity of the pupa to the head through the haemolymph. Thus, a countercurrent is set up between the comb wall and the pupa, and therefore acts as an insulator in an end-to-end direction. When ambient

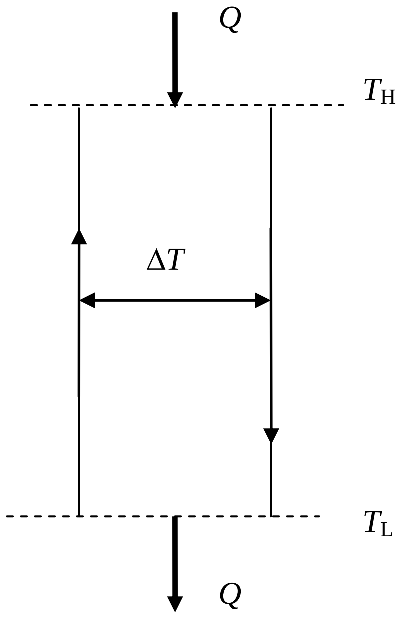

Figure 6. Countercurrent heat exchanger as thermal insulation system, Bejan (1982).

temperature decreases, the electric energy stored in the silk cocoon is discharged, transferring heat by the Peltier effect to the pupa and the nest. The flow of an electric current also produces a Joule heating effect. The flow of electric current between discrete *p* and *n* junctions in the silk cocoon can also be thought of as work transfer to the system and therefore a thermal insulator in an end-to-end direction.

3. Conclusions

This paper has described some of the nest building activities of a number of social insects, such as the termite *Macrotermitinae* and the hornet *(Vespa orientalis***)**. The termite mounds of the African, South American and Australasian continents used a variety of methods to moderate the environment in a nest, including siting the nest below ground, building mounds to intercept the winds flowing across the region and exchanging gases between the nest, mound and the exterior. The ventilation mechanism may be complex and involve many different mixing mechanisms but it may be possible to devise systems that could exploit the low and fluctuating energy of the wind to exchange gases between the interior and exterior of a building. The oriental hornet uses a number of strategies to regulate the temperature in a nest, including building the nests below ground to damp the temperature changes and reduce the maximum temperature experienced in the nest, fanning wings to enhance convective heat transfer, using moisture to promote evaporative cooling, and using the silk cocoon of the pupa that has thermoelectric properties to store excess heat as an electric charge and release the change to produce Joule heating and the Peltier effect. Although the thermoelectric properties of the silk may be over 10,000 times less than that of an inorganic semiconductor, it may be possible to use a conductive polymer that is doped to give it thermoelectric properties and use it as a heat storage device for buildings.

References

Bejan, A, (1982). *Entropy generation through heat and fluid flow*, p. 248. New York: Wiley.

Bejan, A, (2006), *Heat Transfer, Ch 3*, New York: Wiley.

Bölsche, W, (1931). *Der Termitenstaat*. Kosmos Gesellschaft der Naturfreunde: Stuttgart.

Buswell, R. A, Soar, R. C, Gibb, A. G. F, Thorpe, A, (2007). Freeform construction: Mega-scale Rapid Manufacturing for construction. *Automation in Construction*, V 16, pp. 224-231.

Clements-Croome, D. J, (2004). *Intelligent Buildings: Design, Management and Operation*. London: Thomas Telford.

Darlington, JPEC, (1984). Two types of mounds built by Macrotermes subhyalinus in Kenya. *Insect Science Applications*, V 5, pp.481-492.

Darlington, JPEC, (1985). The structure of the mature mounds of the termite Macrotermes michaelseni in Kenya. *Insect Science Applications*, V 6, pp.149-156.

Darlington, JPEC, (1990). Ventilation systems in termite nests in Kenya. *Sociobiology*, V 15, pp. 262-264.

Heinrich, J, (1993). *The hot blooded insects: Strategies and mechanisms of thermoregulation*, Harvard: Harvard University Press, p 600.

Ishay, J., Ruttner, F, (1971). Die thermoregulation im hornissennest. *Z. Physiol*.V 72, pp.423–434.

Ishay, J, Barenholz-paniry, V, (1995). Thermoelectric effect in hornet (*Vespa orientalis)* silk and thermoregulation in a hornet's nest, *J. Insect Physics 4*, Vol. 41, No. 9, pp.753-759.

Ishaya. J.S, Litinetsky, L, Pertsis, V, Linsky, D, Lusternik, V, Voronel, A, (2002a). Thermoelectric conversion and specific heat of hornet combs, *Journal of Optoelectronics and Advanced Materials*, V. 4, No. 1, pp.135-145.

Ishaya. J.S, Litinetsky, L, Pertsis, V, Linsky, D, Lusternik, V, Voronel, A, (2002b). Hornet silk: thermophysical properties, *Journal of Thermal Biology*. V 27, pp.7–15.

Jones, J, C, Holdroyd, B, P, (2007). Nest thermoregulation in social insects, *Advances in insect physiology*, V 33, pp. 133-191.

Kirshboim, S, Ishay, J, S, (2000). Silk produced by hornets: thermophotovoltaic properties- a review, *Comparative Biochemistry and Physiology*. Part A 127, pp.1-20.

Klingler, R, Richter, K, Schmolz, E, (2006). Strategies for social wasps for thermal homeostasis in light paper nests, *Journal of Thermal Biology*, V 31, pp.599-604.

Lüscher, M, (1961). Air conditioned termite nests, *Scientific American*, V 238, pp.138-145.

Noirot, C, (1990). Evolution of the aeration systems in some higher termites, *Social insects and environment*, New Delhi, Oxford, pp.680-681.

Reay, D. A, (1982). *Advances in Heat Pipe Technology*. Oxford: Pergamon Press.

Slutzkey, A. S, Drazen, J. M, (2002). Ventilation with low volume flows, *New England Journal of Medicine*, V 347, No 9, August, pp. 630-631.

Shiohari, Y, Ohara, K, Imai, Y, Isoda, Y, Nagashi, H, (2003). Problems of conductive polymers as thermoelectric materials. *22nd Conference on thermoelectrics.* La Grande Motte, France.

Soar, R, (2008). *3D-Mapping of Macrotermes Michaelseni Mounds and Simulation of their Homeostatic Functions*, EPSRC grant Ref GR/T05875/01.

Turner, J,S, (2001). On the Mound of Macrotermes michaelseni as an Organ of Respiratory Gas Exchange, *Physiological and Biochemical Zoology*, V 74, No 6, pp.798–822.

Turner, J, S, (2008). Homeostasis, Complexity, and the problem of biological design, *Emergence: Complexity and Organization*, V 10 No2, pp. 76–89

Vincent, J. F. V, Bogatyreva, Bowyer, A, Pahl, A, (2006). Biomimetics: its practice and theory, *Journal of Royal Society*, pp.1-12.

Weir, J. S, (1973). Air flow, evaporation and mineral accumulation in mounds of Macrotermes subhyalinus, *Journal of Animal Ecology*, V42, pp.509-520.

Wood, T,G, Thomas, R,J, (1989). *The mutualistic association between Macrotermitinae and Termitomyces*. Insect–fungus interactions. London: Academic Press, pp 69–92.