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Ant mound as an optimal shape in constructal design: Solar irradiation and circadian brood/fungi-warming sorties

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HIGHLIGHTS

- Geometry, ambient and in-dome temperature, solar radiation and illumination are measured.
- Insolation of a right cone by direct-beam, descending and ascending reflected radiation is modeled.
- "Cozy trapezium" where the insects-brood are exposed to "morning" sunbathing sessions are demarcated.
- Mound optimization criteria involve pure solar energy gained by the dome penalized by losses for locomotion.
- Optimal cone angle is explicitly expressed through the zenith angle of the Sun and meteorological constants.

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ABSTRACT

Sizes, shapes, ambient and in-dome temperature, incoming solar radiation and illumination are measured on a *Formica rufa* anthill in a mixed forest of the Volga-Kama National Reserve in Russia. These data are used in a conceptual model of insolation of a right conical surface by direct-beam, descending atmospheric and ascending ground-reflected radiation. Unlike a standard calculation of the energy flux intercepted by a solar panel, the anthill is a 3-D structure and double-integration of the cosine of the angle between the solar beams and normal to the surface is carried out for a "cozy trapezium", where the insects expose themselves and the brood to "morning" sunbathing pulses (Jones and Oldroyd, 2007). Several constructal design problems are formulated with the criteria involving either a pure solar energy gained by the dome or this energy, as a mathematical criterion, penalized by additive terms of mechanical energy (potential and friction) lost by the ants in their diurnal forays from a "heartland" of the nest to the sun-basking zone on the surface. The unique and global optima are analytically found, with the optimal tilt angle of the cone explicitly expressed through the zenith angle of the Sun and meteorological constants for the isotropic sky model.

"… *This golden optimum of Solar radiation, which is tiding us, was, apparently, the best and most important quantitative cause, which forced an organic cell to ascend in its evolution to a human being… Solar energy is, most probably, the main factor determining evolution of plants and animals, a constant factor with respect to the geological time and geographical position of the site*". Chizhevsky (2004).

1. Introduction

The ant hills (hereafter AH) are remarkable structures constructed by social insects (Wilson, 1971; Oster and Wilson, 1978), with several colony-protecting functions similar to dwellings of the human race. Andrews (1926) stated: *"The mound is not only adobe of the adults but preeminently the incubator for the young and thus the means of securing the perpetuation of the race… one of the*

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most enduring architectural results of insect communism". Since then myrmecologists acquired lot of experimental and modeling data/results confirming that in AH intricate juxtaposition of the following bio-physical factors take place:

(a) The composite texture of the AH thatch ("smart" thermophysical properties in the parlance of material scientists), with a low-thermal conductivity, specific gravity, zonal hydrophobicity of a highly permeable and bi-porous aggregates of the forest litter, collected, reworked and assembled by the insects, who use these "environmentally friendly" construction materials.
(b) Ability of AH to intercept the incident solar radiation ("passive heating" of the structure, in the vernacular of building engineers, for whom "active heating" implies electricity/fuel burning), similar to solar panels-collectors.
(c) Generation and smart conduction – convection – re-radiation of the in-nest produced (metabolic) heat, with maintaining ideal (about 25–30 °C) thermal conditions in the brood chamber ("heartland") of the nest, as well as in the interior zones of AH where agro-fungi are nurtured (cultivated) by the colony.
(d) "Smart" cyclo-stationary mass transfer, with a continuous counter-rotten circulation of the solid elements of the nest matrix that facilitates ventilation of AH, gas exchange and – when necessary – cooling of the nest interior, among others. No wonder that AH, as well as similar termite domes, inspire modern architectural designers and thermal engineers (see, e.g. http://www.dezeen.com/2009/09/05/the-termite-pavilion-at-pestival/). For example, Kasimova and Obnosov (2012), driven by biomimetics (bionics) principles, illustrated, both experimentally and mathematically, that a common urban litter (used carton boxes) is efficient in passive thermal insulation of building roofs for the hot climate of Oman.

In cold and moderate climatic conditions, the average daily air temperature and the amplitudes of daily temperature swings of 15–20 °C even in summer are beyond the comfort (and even survival) limit of the redwood ants (Baksht, 2011a; Dlussky, 1967). To adapt to these harsh ambient conditions, insects construct nests of a "right" (Camazine et al., 2001) architecture, in particular, erecting structures of "right" sizes and shapes. For example, forest ants *Formica rufa* and *Formica polyctena* construct mounds one side of which (most insolated) has a milder lee slope, as compared to other, stoss slopes. Termite cones (see the photo-gallery attached) have similar insolation-controlled shapes. Adaptive shaping of the nest depends on shading by the forest canopy (if any around) and other microclimatological conditions in the nest vicinity.

In early-, -mid-, mornings, when the ambient air temperature is at its minimum, ants are engaged in periodic motion: they collect the brood and cultivated fungi from the interior of the nest and hoist them to a certain zone of the AH surface exposed to early sun rays, i.e. the colony gains energy from sunbathing (see e.g. Jones and Oldroyd, 2007, their Fig. 3). Later, the ambient radiation vanishes but the nest interior warms owing to the heat wave propagated into the AH interior from the insolated-warmed dome surface. Radiation on the surface of the AH may become too caustic for the exposed insects. Therefore, as Jones and Oldroyd (2007) observed, the sun-basking on the AH surface stops about the noon time and the brood is vacated back to the interior.

In hot climates, the heated walls (external surface) of the nest dissipate excessive heat back into the atmosphere. Simultaneously, a certain amount of heat is irradiated into the interior of the nest that facilitates comfort conditions in the night brood-chambers, queen's premises and nest's fungi garden.

The in-nest thermal-humidity- atmospheric conditions and their control by different colony activities (dome sizing-shaping and geographical location, regular translocation of the brood within the nest, sealing and opening of ventilation channels, continuous processing of the material making the thatch, hoisting soil particles from deep horizons to the dome, etc.) has been studied by Anderson and Munger (2003); Bachem and Lamprecht (1983); Baksht (2011a, 2011b); Bluthgen and Feldhaar (2010); Bollazzi and Roces (2002, 2010); Bucy and Breed (2006); Coenen-Stab et al. (1980); Cokendolpher and Francke (1985); Dlussky (1967, 1975); Dreyer and Park (1932); Frouz (2000); Frouz and Finér (2007); Green et al. (1999); Hubbard and Cunningham (1977); Korb (2003); Korb and Linsenmair (1998a); Penick and Tschinkel (2008); Roces and Núñez (1995); Rosengren et al. (1987); Thomas (2002); Turner (2005) and Turner et al. (2006). From the viewpoint of global energy balances and fluxes (see e.g. Kooijman, 2010; Sousa et al., 2010; Volk, 2009) social insects, like human beings, utilize the solar radiation in the Gause-Chigevsky (1934) sense (see the epigraph), i.e. through three main paths:

1. Tertiary (e.g. by consuming other living/dead species as vegetarians and carnivores that is mechanically provided by common foraging-scavenging sorties to the AH vicinity).
2. Secondary (e.g. by licking the oozed substances of in-nest cultivated species).
3. Primary (direct interception of radiation by the dome or insects themselves).

Clearly, insects hoisting themselves and the brood/fungi from the nest interior to the sun-basking segment of the AH slope, as Jones and Oldroyd (2007) described, spent the mechanical energy to overcome gravity and friction against locomotion. Overall, the colony trades-off between the gains of solar energy and energy outflows for laboring against gravity and friction (partially re-utilized as a nest-heating metabolic heat). Consequently, Bejan's principle (see, e.g. Bejan et al., 2008; Bejan and Lorente, 2011; Reis, 2006) can be used, i.e. an optimization task to select the best AH architecture can be mathematically formulated.

In this paper we present experimental data (thermography, solar energy fluxes and illumination) for a *Formica rufa* AH, analytical modeling of solar irradiation of AH as a 3-D dome and analytical optimization of its size. A general idea and research question come from Dreyer and Park (1932) who wrote: "*Also, the mounds themselves are so constructed that the maximal surface area is exposed to the sun rays while the perpetually shaded north side of the mound becomes, in many instances, a steep slope from the apex of the nest to the ground. This suggestion of light as a factor is further substantiated by the fact that wherever nests appear within the forest, rather than along the margins, they are located within an actual clearing, which permits practically the same amount of light to fall upon the mounds as does on the marginally located nests and those of the open territory*." So, we will try to explain the "so constructed" of Dreyer and Park, by using a recently developed Bejan's theory, standard (calculus-differential geometry) mathematical techniques and the paradigm of physical (thermal) bioengineering (Gutiérrez and Jones, 2006, Wright and Jones, 2006), as applied to the ant race.

We also take into account the Jones and Oldroyd (2007) sun-basking zonation of the AH surface, which captures solar radiation during a fixed period of a Solar day, when the insects spread out over a certain segment of the dome surface facing the Sun. We mathematically formulate and analyze what Jones and Oldroyd (2007) described as: "*At dry sites, the ants utilize solar radiation to heat their nests. In addition to orient the mound to maximize incident solar radiation, the workers maximize this effect by basking on outside of the mound… Other species orientate the nest so that it offers the smallest possible profile to incident solar radiation during the middle of the day*". Similarly, Lange (1959) and Dlussky (1967,