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Simulation of a biomimetic façade using TRNSYS

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HIGHLIGHTS

- Biomimicry was employed to improve thermal performance of building facades.
- Animal fur and blood perfusion were selected as biological models.
- Fur parameters were optimised to maximise thermal performance.
- Biomimetic initiatives were integrated in a conventional building facade design.
- Biomimetic designs could reduce 17% energy consumption to a conventional approach.

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ABSTRACT

Biomimicry – innovation inspired by nature – is a creative methodology that translates characteristics from the biological world to the domain of human technology. Functional biomimicry offers opportunities to advance the development of flexible building facades. Following biomimetic principles, external fur and bioheat transfer (blood perfusion) and were combined into a mathematical model of a commercial office building façade for a west-facing wall of an office building situated in Melbourne, Australia. TRaNsient SYstem Simulation (TRNSYS) software tool was used to determine temperatures and heat transfer of this biomimetic façade in summer design conditions compared to a reference. The biomimetic façade was simulated to provide cooling of greater than 50 W m^{-2} and reduced mean surface temperatures in the occupied zone by 2.8 °C, compared with the reference.

1. Introduction and purpose of the study

With the increasing concern over greenhouse gas (GHG) emissions and global warming, there is currently an increasing focus on building energy efficiency and the operational energy consumption. Since the construction of the first solid stone walls and nomadic tents [1], humanity has, with some exceptions, perceived facades as static building structures. Only relatively recently (in the past half-century or so) have façade-integrated systems been recognised as important factors in reducing building operational energy consumption [2]. Ihara et al. [3] illustrated that U-value, solar reflectance and solar heat gain coefficient (SHGC) of glazing all have substantial influence on operational energy consumption.

Equally, building occupants expect high levels of thermal comfort and meeting thermal comfort requirements often requires energy-intensive heating ventilation and air conditioning (HVAC) systems. This creates a design conflict: a trade-off between the desire to reduce building operational energy consumption (and thus reduce GHG emissions) but also achieve high levels of thermal comfort. One approach to resolve this conflict is to reduce the energy consumption while maintaining thermal comfort. Improving the thermal performance of building envelopes is one method to reduce building operational energy consumption without compromising comfort [4]. Santamouris [5] notes that due to global warming, population growth and potential economic growth, demands for cooling in buildings to meet comfort requirements could significantly increase in the next half century. Improvements in building energy performance as well as the development of alternative strategies and technologies are required to mitigate cooling energy growth.

With concerns over GHG emissions and a desire to maintain thermal comfort, multiple initiatives have been developed to passively and actively improve façade performance. Alternative passive and active systems have been considered [4,6,7]. Examples of active and passive façade systems are described and Schittich et al. [8], while Wigginton and Harris [9] focus on active systems. Lee et al. [10] provide guidance on technological approaches for building facades while also presenting several case studies. Chan et al. [11] reviewed passive solar heating and cooling techniques, while Santamouris and Kolokotsa [12] reviewed

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Nomenclature

Symbols – Latin

A	area [$\mathrm{m^2}$]
c_p	specific heat at constant pressure [$\mathrm{kJ\,kg^{-1}\,K^{-1}}$]
d_f	hair diameter [m]
$d_{h,p}$	equivalent spherical diameter of particles [m]
d_p	pressure differential [Pa]
d_t	simulation timestep [s]
d_x	simulation spatial step [m]
F_s	characteristic describing interaction of fur with radiation [–]
h	height [m]
h	heat transfer coefficient [$\mathrm{W\,m^2\,K^{-1}}$]
k	thermal conductivity [$\mathrm{W\,m^{-1}\,K^{-1}}$]
k_{eff}	overall effective thermal conductivity of fur [$\mathrm{W\,m^{-1}\,K^{-1}}$]
k_p	thermal conductivity of fur orthogonal to hair [$\mathrm{W\,m^{-1}\,K^{-1}}$]
$\mathrm{L_f}$	fur layer thickness [m]
l	path length of fluid flow in Ergun equation [m]
$\dot{m}$	mass flow rate [$\mathrm{kg\,s^{-1}}$]
n_f	number of hairs per $\mathrm{m^2}$ [$\mathrm{m^{-2}}$]
$N_{f,s}$	non-dimensional parameter (apparent ‘optical thickness’ of fur in the solar spectrum) [–]
P	power delivered [W]
Q, q	heat transfer [$\mathrm{W\,m^{-2}}$]
q'''	volumetric heat generation [$\mathrm{W\,m^{-3}}$]
q_f	heat transfer through fur [$\mathrm{W\,m^{-2}}$]
$q_{e,S}$	solar radiation absorbed by skin/façade [$\mathrm{W\,m^{-2}}$]
R	thermal resistance [$\mathrm{m^2\,K\,W^{-1}}$]
S	solar radiation [$\mathrm{W\,m^{-2}}$]
T	temperature [K]
t	time [s]
T_{a0}	inlet water temperature to perfusion façade [K]
v	velocity [$\mathrm{ms^{-1}}$]
$\dot{V}$	volumetric flow rate [$\mathrm{m^3\,s^{-1}}$]
w	width [m]
$\dot{w}_b$	‘blood’ perfusion rate [$\mathrm{m^3\,m^{-3}\,s^{-1}}$]
x	horizontal dimension through façade (external surface = 0) [m]

Symbols – Greek

α	thermal diffusivity ($k/\rho c_p$) [$\mathrm{m^{-2}\,s^{-1}}$]
α	material absorptivity [–]
β_h	extinction coefficient for fur (infrared spectrum) [–]
$\beta_{h,S}$	extinction coefficient for fur (solar spectrum) [–]
ε	material emissivity [–]
ϕ_f	maximum azimuthal variation of hair from grain direction [°]
η	non-dimensional distance through fur [–]
η_{TOT}	total efficiency [–]
κ	façade porosity [–]
μ	fluid viscosity [$\mathrm{kg\,m^{-1}\,s^{-1}}$]
ρ	density [$\mathrm{kg\,m^{-3}}$]
ρ_f	hair mass density [$\mathrm{kg\,m^{-3}}$]
θ_f	angle between normal to skin surface and hair [°]
θ_S	angle between normal to the skin and solar direction [°]

Subscripts

1, 2, 3, 4	finite difference node positions
a	air
amb	ambient
avg	average
b	‘blood’ (biomimetic façade cooling/heating fluid)
B	beam
cond	conduction
conv	convection
d	diffuse
e	external
eff	effective
env	environmental
f	fur
g	ground
i	internal
i, j, n	summation indices
lw	long wave
rad	radiation
RC	combined radiation and conduction
s	surface
S	solar
skin	skin
sky	sky
surf	surf
T	total
t	‘tissue’ (biomimetic façade material)
u	unitised façade element
w	wall

Superscripts

n	current finite difference timestep

passive cooling techniques, in particular earth air heat exchangers, evaporative cooling and passive ventilation cooling. Active, integrated unitised facades have been constructed, for example, in the Debitel Headquarters in Stuttgart, Germany [1]. Double skin facades have become widespread and tailored to different climates [13–15]. Naturally ventilated double skins have been developed (e.g. [16]). The KfW Westarkade building in Frankfurt am Main actively operates louvres in its double skin façade to regulate temperature [17]. Innovation continues in this space, with experiments conducted on passive approaches such as hybrid passive cooling that incorporates dehumidification, evaporative cooling and low pressure heat recovery Grosso et al. [18]. Other researchers have developed a passive cooling strategy using porous ceramic materials [19]. However, there is still a large gap between existing levels of performance and what could be possible with more adaptable and flexible facades. The purpose of this study was to exemplify the opportunities for innovation that biomimicry could bring to the built environment, and non-residential building facades in particular. Biomimicry – innovation through natural inspiration – offers humanity vast scope to develop more functional and sustainable technology. By studying natural adaptions, from an ever-growing body of biological knowledge, innovators can extract functional characteristics and translate these characteristics into innovative adaptive, flexible and more efficient designs. Several methods have been proposed to incorporate biomimicry into design. Two examples are the Biomimicry Design Lens [20] and “BioTRIZ” [21,22], which is based on *Teoriya Resheniya Izobretatelskikh Zadatch* (TRIZ), interpreted as a “Theory of Inventive Problem Solving” [23].

In the built environment, biological inspiration has influenced architectural design throughout history [24,25]. In modern technology, biomimicry has been shown to be a successful method to engender