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MODELLING AND OPTIMISATION OF A BIOMIMETIC FAÇADE BASED ON ANIMAL FUR

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ABSTRACT

Biomimicry offers opportunities to advance the development of flexible, adaptive facades. This paper focuses on fur heat transfer and translates the distinctive performance characteristics of animal fur to building envelopes. A time-dependent mathematical model is developed to describe the application of fur to a façade.

An optimised 'fur' layer was shown to have a thermal conductivity of 0.055 W/mK, compared with deer fur at 0.091 W/mK.

When an optimised, fur-lined façade was compared with a conventional lightweight façade under sunny summer conditions, heat gains reduced by up to 50%. During a winter scenario, heat losses to the external environment were reduced by at least 50%.

INTRODUCTION

Sustainability and energy consumption

There is currently a strong focus on energy sustainability in the built environment. Energy and sustainability are irrevocably intertwined as humanity continues to generate much of its energy from non-renewable resources, contributing significantly to global warming.

Building facades and energy consumption

The relationship between building energy consumption and facades is illustrated by Werner Lang (in Schittich (Ed.) et al. 2006). Along with three vital questions to ask when designing a façade, relating to "Function", "Construction" and "Form", Lang adds a fourth, "Ecology": "What is the energy consumption of the building/the building skin during construction, use and demolition?" (Schittich (Ed.) et al. 2006, p. 29). Lang outlines the importance of a façade to operational energy: in office buildings, nearly 40% of total energy is devoted to heating, with a further 40% consumed by air-conditioning and ventilation (20% is consumed by artificial lighting). Thus "components that protect against excessive heat gain in summer and unwanted transmission and ventilation losses in winter are therefore especially important" (Schittich (Ed.) et al. 2006, p. 33).

Since the construction of the first solid stone walls and nomadic tents (Knaack et al. 2007), humanity has, with some exceptions, perceived facades as static building structures. Only recently have dynamic façade elements gained credence, e.g. the Debitel Headquarters in Stuttgart, Germany (RKW trchitektur + Städtebau, 2002 – Knaack et al 2007) incorporates an 'alternating façade'.

Biomimicry and the built environment

This paper examines Biomimicry as a strategy to design facades that boost thermal performance in order to decrease building operational energy consumption.

Architecture has long been inspired by biology. Aldersey-Williams (2003) writes "…we find that it is not entirely by chance that animals and buildings share some of their most basic characteristics". George Hersey (1999) finds architectural inspiration in all natural forms. The development of loadbearing frameworks enclosed by curtain walls altered the approach, as it was no longer the aesthetic form of nature being mimicked, but animal structure – an internal skeleton (Aldersey-Williams 2003) .

Janine Benyus explores the modern philosophy of biomimicry (1997). Benyus' thesis involves three axioms "Nature as model", "Nature as measure" and "Nature as mentor" (1997). Pedesen Zari identifies two fundamental approaches in the built environment – "design looking to biology" and "biology influencing design" (2007, p. 2).

A systematic approach (Vincent & Mann 2002) has been proposed to combine biomimicry with TRIZ, interpreted from Russian as a "Theory of Inventive Problem Solving". By investigating patent databases (quoted as 3,000,000), researchers have established a predictable set of engineering problem-solving tools. TRIZ converts a specific problem into a general problem, leading to a general solution (Domb 1997). The conversion involves inherent "contradictions" (i.e. trade offs) within the design problem, which can be resolved via "40 Principles of Invention" (Domb 1997, p. 3).

In later research, Vincent (2006) proposes that the TRIZ technological contradiction matrix be recreated with biological rather than technological phenomena. The result – termed "BioTRIZ" – is a 6x6 matrix summarising how biology "solves" contradictory objectives, and offers biological "inventive principles" for designers to try to resolve these contradictions (Vincent et al. 2006, p. 477).

Craig et. al. (2008) use biomimicy classified by BioTRIZ to design a radiative roof cooling system, deciding upon a structural change to the insulation (2008, p. 61). Modelling of the resulting honeycomb structure, with a convection guard, indicated that the "new" design improved roof cooling performance (Craig et al. 2008, p. 65).

Therefore, biomimicry offers architects and façade engineers opportunities to advance the development of flexible, adaptive façades to further reduce energy consumption. In particular, heat transfer in mammal fur has been studied in detail and the thermal performance indicates potential advantages for insulating building skins and scattering solar radiation.

GOALS OF THE STUDY

This study aims to translate biological systems knowledge into initiatives for building facades. Specifically, this paper draws upon the physics of fur heat transfer to translate the distinctive characteristics of animal fur to building envelopes. Using a fur heat transfer model, the performance of fur as a component of a building skin is tested and key parameters are optimised.

The study aims to illustrate how the adaption and integration of biological characteristics, such as fur, can augment and improve building facades. Thus the "biomimetic" façade is compared against a conventional façade system to understand the implications for heat transfer.

FUR HEAT ENERGY TRANSFER

The thermodynamic properties of fur have been the subject of several studies since 1950. Scholander et al. (1950) used a hotplate of known power output with fur and measured heat loss, resulting in fur insulation estimates between ~1.3 m^{2}K/W (shrew) and ~0.18 m^{2}K/W (white fox). In contrast, Hammel (1955) experimentally determined insulation values between 0.45 m^{2}K/W (red fox) and 1.09 m^{2}K/W (coyote, tanned pelt).

Cena and Monteith (1975a) develop a fur heat transfer model by adapting models for vegetation created by Cowan (1968, 1971). Three papers consider effects of direct beam radiation, conduction and convection, and vapour diffusion. The effects of diffuse radiation are combined with conduction and convection in the second paper (Cena, K. & Monteith, J. L. 1975).

While the homogeneous variables used by Cena and Monteith are effective in describing thermal properties of fur to compare with biological samples, their equations are not amenable to design for the built environment.

Kowalkski and Mitchell (1979) provide a detailed mapping of fur heat transfer utilising non-dimensional variables and optical thickness. Their model does not consider direct beam or short wave radiation and also relies on a random orientation of fur fibres to derive an average absorption coefficient. Assuming a random fibre orientation limits the design possibilities for fur (as described below).

The methodology of Davis and Birkebak (1974) is similar – it uses a combined method for conduction, radiation and convection that depends on a suite of variables defined by the structure and thermodynamic properties of the animal fur. Parts of this model are compatible with Kowalski and Mitchell (1979). The Davis and Birkebak model was selected for detailed translation due to the geometric detail, the ability to manipulate a significant number of variables, and the inclusion of short wave radiation.

The basis for the selected model relates the energy flux from the skin surface, q_f, to a temperature gradient, ΔT, and fur thickness layer, L, via an effective fur thermal conductivity, k_{eff}:

$$q_f = k_{eff} \frac{\Delta T}{L_f} \qquad (1)$$

Equation (1) accounts for conductive and diffuse radiative heat transfer through fur in the absence of direct solar radiation – short wave radiation is considered below.

Overall, heat transfer is calculated in a direction perpendicular to the skin, while individual hairs are oriented at an angle θ_f. A definition of ρ_{eff}/ρ_f is also given to describe effective hair mass density:

$$\frac{\rho_{eff}}{\rho_f} = \frac{n_f \pi d_f^2}{4\cos\theta_f} \qquad (2)$$

where:

- n_f = no. of hairs per sq. m,
- d_f = hair diameter (assumed circular),
- ρ_f = fur (hair) mass density,
- ρ_{eff} = effective fur coat mass density.

Geometric variables are illustrated in Figure 1.

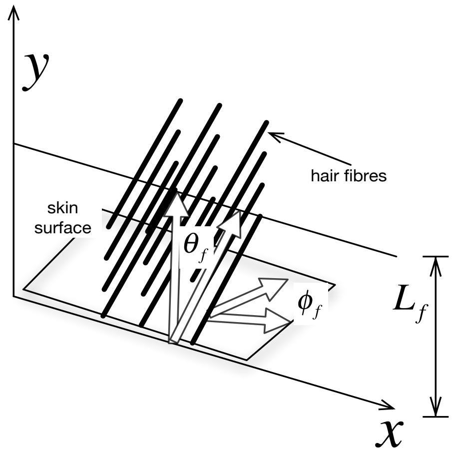

Figure 1 – Basic geometry of fur model

Conduction is calculated in principal directions parallel and perpendicular to the hairs, with thermal conductivities k_f (hair), k_a (air) and k_p (orthogonal):

$$k_y = \left\{ \left(\rho_{eff} / \rho_f \right) k_f + \left[1 - \left(\rho_{eff} / \rho_f \right) k_a \right] \right\} \cos^2 \theta_f$$
$$+ k_p \sin^2 \theta_f \qquad (3)$$

Davis and Birkebak (1974) account for radiation by first modelling the fur material to determine an extinction coefficient and add a further step to define energy relationships.The radiative component of the thermal conductivity for the fur coat (k_{rad}) is as follows:

$$k_{rad} = k_{r-y} \left[1 + \frac{F_1 N_f}{4F_2} \frac{T_{sk}^4 - T_{\infty,r}^4}{T^3 \Delta T} \right]_{\eta = 1/2} \qquad (4)$$

where:

- F_1 and F_2 are hemispherical double integrals, describing, respectively, the radiation emitted from the skin and the amount of radiation passing through the y plane due to emission and scattering,
- η (non-dimensional length) describes the point at which k_{rad} is evaluated.
- T_{sk} = skin temperature,
- $T_{\infty,r}$ = temperature of radiation sink,
- T = temperature at evaluation point in the fur (i.e. eta $\eta = ½$) and
- ΔT = the temperature difference between skin surface and external fur surface.

Note that:

$$k_{r-y} = \left(8 \sigma T^3 L F_2 \right) \pi N_f \qquad (5)$$

Here also:

$$N_f = 4 \left(\rho_{eff} / \rho_f \right) \varepsilon_f L / \pi d_f \qquad (6)$$

N_f is non-dimensional and effectively describes the optical thickness of the fur. Accordingly, a value of $N_f > 10$ constitutes an 'optically thick' fur coat (Davis and Birkebak, 1974, p 256).

Using the preceding analysis, the effective thermal conductivity can be calculated as:

$$k_{eff} = k_y + k_{rad} \qquad (7)$$

Heat transfer to/from the skin surface can then be calculated as per Equation (1).

The calculation of k_{eff} is predicated on the evaluation of radiation at η = ½ with a linear temperature profile. Studies described in Birkebak (1966), Birkebak and Warner (1964) and Hammel (1955) suggest a this is a valid assumption.

Davis and Birkebak (1974, p. 260) establish a basis for heat transfer to/from a fur coat in the presence of direct solar radiation using the following equation:

$$q_f = \frac{k_{eff}}{L} \left(T_{s,e} - T_{f,e} \right) +$$
$$\left(1 - \left[\cos \theta_s / N_{f_s} F_s \right] \right) q_{f,w} \qquad (8)$$
$$- \left(\alpha_{f,s} S \cos^2 \theta_s / N_{f_s} F_s \right)$$

MODELS

Reference Plane Wall

The analysis is completed using a simplified model of the heat transfer on a plane wall. A time-dependent model is developed based on the generalised 1-D heat equation without sources/sinks (Holman 2001, p. 140):

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \qquad (9)$$

Here α_w is the thermal diffusivity of the wall, or $k_w / \rho_w C_{pw}$. A generalised plane wall is assumed; the layer and overall properties are shown in the Table 1.

To derive the initial and boundary conditions, the physical situation is represented in Figure 2.

Table 1 – Plane wall properties

Layer (outside to inside)	**Thickness [m]**	***k* [W/mK]**	**ρ [kg/m^3]**	***C_p* [kJ/kg.K]**
1. Cladding	0.02	0.1	506	2090
2. Insulation	0.05	0.04	12	880
3. Air gap	0.02	0.026	1.2	1.01
4. Gypsum	0.01	0.17	880	1050
Wall total	0.1	0.06	109	963
α [m^2/s]	5.7×10^{-7}			

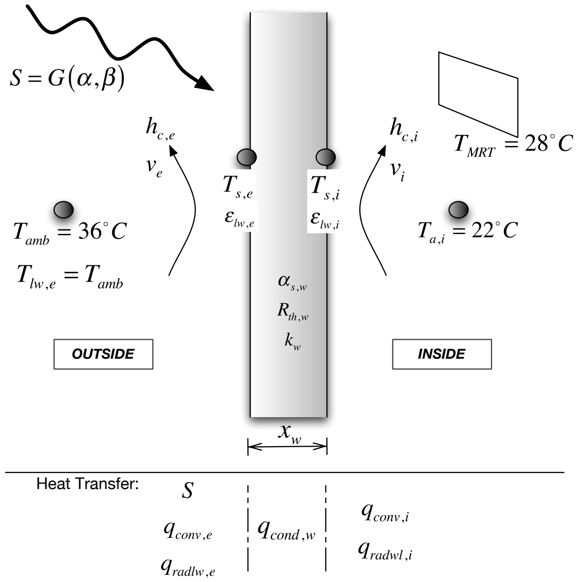

Figure 2 – Heat transfer variables associated with plane reference wall

To determine the heat transfer from the external environment to the internal occupied space, a heat balance is required. For the external surface:

$$S + q_{radlw,e} = q_{conv,e} + q_{cond,w} \quad (10)$$

For the internal surfaces:

$$q_{cond,w} = q_{conv,i} + q_{radlw,i} \quad (11)$$

Using the scheme for external radiation to built surfaces presented in CIBSE Guide J (Butcher 2002), equation 9 can be rewritten as:

$$\alpha_{s,w} G(\theta,\beta) + L^*(\beta) = h_{c,e}\left(T_{s,e} - T_{amb}\right) \quad (12)$$

To determine the heat transfer from the external environment to the internal occupied space, a heat balance is required. For the external surface:

$$S + q_{radlw,e} + q_{conv,e} = q_{cond,w} = -k_{wall} \left.\frac{\partial T}{\partial x}\right|_{x=0} \quad (13)$$

For the internal surfaces:

$$q_{radlw,i} + q_{conv,i} = q_{cond,w} = -k_{wall} \left.\frac{\partial T}{\partial x}\right|_{x=0.1} \quad (14)$$

Using the scheme for external radiation to built surfaces presented in CIBSE Guide J (Butcher 2002), equation 10 can be rewritten as:

$$\alpha_{s,w} G(\theta,\beta) + L^*(\beta) + h_{c,e}\left(T_{amb} - T_{s,e}\right) = -k_{wall} \left.\frac{\partial T}{\partial x}\right|_{x=0} \quad (15)$$

Here:

$$G(\theta,\beta) = B(\theta,\beta) + D(\theta,\beta) + R_g(\theta,\beta) \quad (16)$$

$$L^*(\beta) = \varepsilon_{lw,e}\left[L_{sky}(\beta) + L_g(\beta) - \sigma T_{s,e}^4\right] \quad (17)$$

(Refer to CIBSE Guide J (Butcher 2002) for the full formulation.)

Using the standard Fourier equation for conduction and the method presented in Appendix 3.A3 of CIBSE Guide A (Butcher 1999) for internal long wave radiation exchange, equation 10 can be reformulated as:

$$h_{c,i}\left(T_{s,i} - T_{a,i}\right) + \left(\tfrac{6}{5}\right) 4\sigma T_{s,i}^3 E\left(T_{s,i} - T_{MRT}\right) = -k_{wall} \left.\frac{\partial T}{\partial x}\right|_{x=0.1} \quad (18)$$

The factor E is the Emissivity Factor (Butcher 1999, pp. 3-37) for the occupied space, accounting for all emissivities of internal surfaces and view factors. In the simple case where the internal surfaces can be approximated by a cube (i.e. 6 internal surfaces of approximately the same area and emissivity):

$$E = \varepsilon_{lw,i}\left[1 + \varepsilon_{lw,i}\left(1 - \varepsilon_{2,lw}\right) / 5\varepsilon_{2,lw}\right]^{-1} \quad (19)$$

Initially (at *t=0*) a linear temperature profile was assumed:

$$T(x,0) = 35 + \tfrac{27-35}{0.1} x \quad (20)$$

Using the boundary conditions (equations 15 and 18) plus the initial condition (equation 20), the time dependent heat transfer given in equation 9 could be solved numerically using a Matlab function.

Biomimetic Fur Wall

The model for the biomimetic wall follows the reference model and adds a layer of fur lining on the external surface. Figure 3 depicts this situation.

The heat transfer through the fur may be given by Equation 8 and this relationship can be incorporated into a heat balance on the fur surface:

$$S + q_{radlw,e} + q_{conv,e} = q_f \quad (21)$$

Following the convention above, we can write:

$$\alpha_{s,w} G(\theta,\beta) + L^*(\beta) = q_f \quad (22)$$

Noting that heat q_f flows through the fur to the external wall surface (i.e. underneath the fur layer):

$$q_f = -k_{wall} \left.\frac{\partial T}{\partial x}\right|_{x=0} \quad (23)$$

Furthermore we have a three-term expression for q_f in terms of the fur variables (equation 8). By combining equations 8, 22 and 23, it is possible to derive a viable set of boundary conditions to numerically solve equation 9. The internal surface boundary condition and initial condition are equivalent to the reference (no-fur) case.

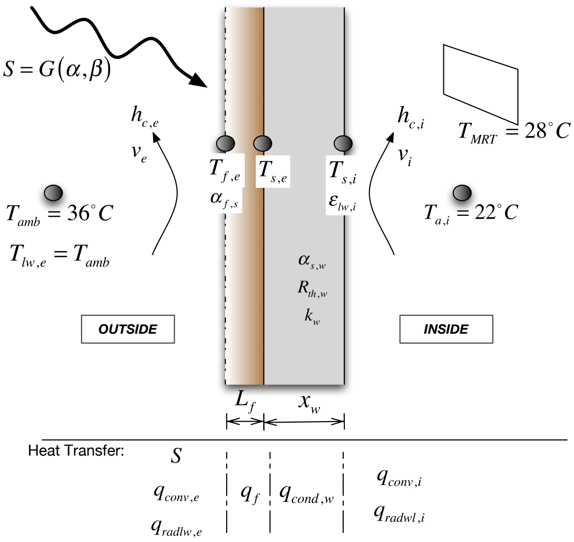

Figure 3 – Heat transfer variables associated with fur-lined plane wall

SELECTING PARAMETERS FOR FUR LAYER

Davis and Birkebak (1974), along with the research of Cena and Monteith (1975a; 1975; 1975b), Hammel (1955) and Scholander et al. (1950) present findings of the thermal properties of fur found in nature. Several examples are shown in Table 2.

Table 2
Thermal Conductivities of Fur

SPECIMEN	APPROX. FUR THERMAL CONDUCTIVITY [W/MK]	REFERENCE
Tanned Deer	0.091	Davis and Birkebak (1974)
Red Fox	0.040	Hammel (1955)
Reindeer	0.033	Scholander et al. (1950)
Wolf	0.061	Scholander et al. (1950)
Rabbit	0.095	Cena and Monteith (1975)

The model of Davis and Birkebak (1974) allows the physical dimensions of the fur to be varied to control the effective conductivity (k_{eff}) of a fur layer. If a 'fur' layer applied to the exterior of a building, it would be beneficial to select physical characteristics that optimise heat transfer through the wall.

Initially excepting the impact of solar radiation, the goal of optimisation was to minimise k_{eff} to maximise the insulative value. (By maximising insulation, natural ventilation and passive cooling options may become important to ensure internal loads do not increase.)

Given the number of physical variables available, the analysis was restricted to the optimisation of the following 4 controllable variables:

- L_f – fur layer thickness (m)
- d_f – fur fibre diameter (m)
- θ_f – fur angle from surface normal (°)
- n_f – number of fur fibres per unit area (m^{-2})

To be practically applicable, the 4 variables were subject to the constraints listed in Table 3.

Table 3
Constraints for Optimisation Variables

VARIABLE	MINIMUM VALUE	MAXIMUM VALUE
L_f	0.01	0.1
d_f	0.0001	0.01
θ_f	20	60
ρ_{eff}/ρ_f (to determine n_f)	0.2	0.8

Note: as n_f, d_f and θ_f are physically linked (Equation 2), n_f was constrained by restricting the effective density ratio, ρ_{eff}.

With these constraints, an optimisation analysis was conducted to minimise the value of k_{eff} and maximise the overall insulative value of an external fur layer. Matlab's Optimisation Toolbox was employed to achieve this, using the function **fmincon**. The **fmincon** function finds a minimum of a constrained non-linear multivariable function (*Matlab & Simulink* 2010).

Additional physical parameters required to calculate k_{eff} – as identified through Equations 1-8 – were input as follows:

- $k_{air} = 0.026$ W/mK,
- $k_p = 0.039$ W/mK,
- $k_f = 0.26$ W/mK,
- $\varphi_f = 10°$,
- $T_{f,e} = T_{lw,e} = 309.15$ K,
- $T_{s,e} = 316.85$ K, and
- $\varepsilon_f = 0.76$.

Given the equation input for k_{eff}, the 4 optimisation variables, the constraints from Table 3, parameter values for additional physical characteristics, and random starting values, optimal values for each variable were calculated for an external wall application. Table 4 displays the results.

As an adaption characteristic for winter conditions, the thermal properties were also calculated where hair fibres were extended (equivalent to animals' fur standing up during piloerection). These values are also shown in Table 4.

Table 4
Results of Optimisation – summer and winter

VARIABLE	SUMMER VALUE	WINTER VALUE
L_f	$L_{f,\,summer} = 0.1$	$L_{f,\,winter} = 0.19$
d_f	0.0001	0.0001
θ_f	60	20
n_f	12732395	12732395
ρ_{eff}/ρ_f	0.2	0.2
k_{eff}	0.055	0.065
$R_{TH,f}$	1.8	2.9

COMPARISON OF HEAT TRANSFER

Heat transfer for a plane wall installed with the optimised 'fur' layer was compared with two reference cases:

1. A plane wall of equal thickness to that lined with the fur layer, and
2. A plane wall of equal thickness to that lined with fur *plus* the fur thickness (i.e. L_f).

Reference conditions were taken as approximate summer and winter design days for Melbourne, Australia. These are shown in Table 5.

Internal conditions were set as follows:

- $T_{a,i} = 22°C$, $h_{c,i} = 6$ W/m^{2}K, and
- $T_{MRT} = 28°C$.

For the fur layer wall, the following parameters were also set (refer to Equation 8):

- $\theta_{f,s} = 60°$, $\alpha_{f,s} = 0.8$, $N_{f,s} = 124.3$, $F_s = 0.44$.

Table 5
Design test conditions

PARAMETER	SUMMER VALUE	WINTER VALUE
T_{amb} (°C)	36	4
v (wind velocity, m/s)	2	5
Global irradiance (G, W/m^2)	800	0
Diffuse irradiance, (D, W/m^2)	400	0
Solar azimuth, α_s	45°	n/a
Solar altitude, $\gamma_s = 60°$	60°	n/a
Wall title angle, β	90°	90°

Having defined the inputs, equation 9 was solved numerically for the two reference cases and the wall with a fur layer, all subject to solar radiation and over a time period of 2 hours. The resulting temperatures and heat transfer are shown in Table 6.

Table 6
Temperatures and Heat Transfer for Fur Layer Wall and Reference Cases

WALL	WALL THICKNESS (m)	HEAT FLOW at 2 hrs (W/m^2)	*Ts,e* (°C)	*Ts,i* (°C)
Summer				
Fur Layer	0.1 (wall) + 0.1 (fur)	8.5	40.0	25.7
Ref. Case 1.	0.1	16.2	53.3	26.4
Ref Case 2.	0.2	8.4	53.5	25.3
Winter				
Fur Layer	0.1 (wall) + 0.19 (fur)	-5.4	12.5	21.5
Ref. Case 1.	0.1	-11.0	2.8	21.1
Ref Case 2.	0.2	-5.8	2.7	21.9

The following plots the temperature profile for all three test cases against non-dimensional wall distance (x/x_w) at the end of the simulation, i.e. t = 7200s for both the summer and winter scenarios.

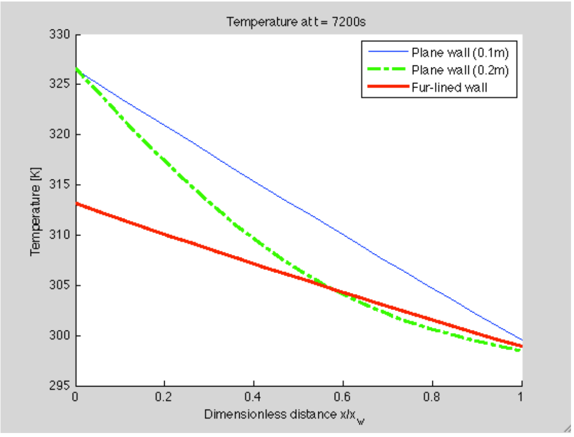

Figure 4 – T [K] profile through wall models at t = 7200s – Summer scenario

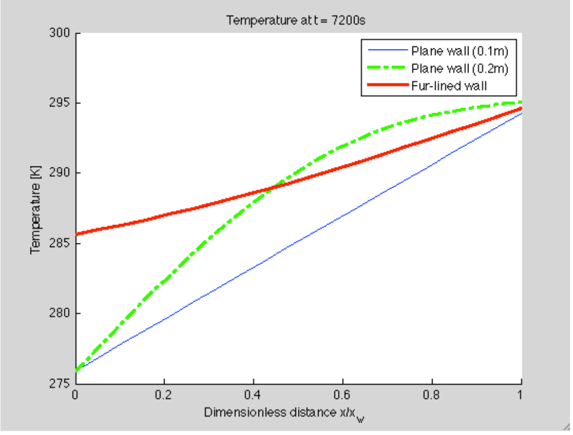

Figure 5 – T [K] profile through wall models at t = 7200s – Winter scenario

DISCUSSION

The calculated fur thermal conductivity (Table 4) concurs with an intuitive assessment of the conductive heat transfer process through a fur layer. Thicker fur creates greater insulation, narrow-diameter, low-density fibres allow for a large number of small air pockets to develop, while flatter fibres (i.e. larger θ_f) create a better barrier to heat transfer. The calculations are of similar magnitude to previous research (Table 2). The values of fibre thermal conductivity (k_p and k_f) were significant in lowering overall thermal conductivity below other animal examples (Hammel 1955; Scholander et al. 1950). Hence lower-conductivity materials would significantly improve the resultant thermal performance. Furthermore, Kowalksi and Mitchell (1979) also offer a means to calculate k_p based on air and fur thermal conductivity, fur geometry and fibre spacing.

The comparative results in Table 6 illustrate the relative impact that external opaque fabric loads have on an already-insulated building. Given a basic level of thermal insulation (~1.7 m^{2}K/W), external loads are estimated at about the same magnitude as internal gains, i.e. 10-20W/m^2. Under Australian design conditions, cooling loads may exceed 170W/m^2 in perimeter office zones. Thus, external wall gains contribute perhaps 5-20% of the total cooling load. When related back to the estimate of Lang (Schittich (Ed.) et al. 2006), the cooling energy consumption attributable to opaque fabric loads would then be in the order of 4-8%.

With reference to the calculated heat transfer in Table 6, the fur-lined wall performed significantly better than both Reference cases 1 and 2, reducing heat transfer by 40% and 60% respectively. The fur layer provides both an added insulation component due to low thermal conductivity, and in addition it dissipates and scatters incoming solar radiation.

However, when considering the overall heat loads in a thermal zone on a summer design day in Melbourne, we can observe that a 40-60% reduction in external fabric load equates to an overall cooling load reduction of, optimistically, 4-10% (~8-12W/m^2).

Considering the winter scenario, the fur-lined wall provides a 75% and 53% reduction in heat loss over reference cases 1 and 2, respectively. The appreciable reductions in heat loss are attributable to the low thermal conductivity of the fur layer. Also, as the hairs are raised to $\theta_f = 20°$, the 'fur' layer roughly doubles in thickness due to 'piloerection'. This provides an adaptable characteristic that increases the thermal resistance.

Given the limited benefit in these two scenarios, the addition of a fur layer would need to be critically examined in each design context to ensure a useful benefit. Significant advantages exist with large differences between internal and external temperatures, and when the external fabric is subject to extensive sun exposure. In the southern hemisphere, northern and western walls and roofs would be the most appropriate locations for 'fur cladding'. Angular orientation (i.e. selection and possible adaptability of θ_f and $\theta_{f,s}$) would be important to minimise solar heat gains.

A further consideration is the effect of convection. Davis and Birkebak (1974) and Cena and Monteith (1975a) assess consequences for heat transfer when fur is exposed to a free stream velocity. Cena and Monteith (1975a) contend that natural convection away from the skin is important when a homeothermic animal is exposed to a cooling environment. However, other researchers, including Hammel (1955), indicate that natural convection is not as significant. Also, the thermal conductivities calculated by Cena and Monteith tend to be lower than the calculations of Davis and Birkeback (1974) and require an additional natural convection component to equate them with field measurements.

Both Davis and Birkebak (1974) and Cena and Monteith (1975a) consider the effects of a free stream velocity. Heat transfer increases appreciably when buffeted by the wind velocity, reaches a threshold value, v_p, found to be 3-5m/s (Davis & Birkebak 1974). Therefore a fur-lined wall would be expected to perform well in winds up to v_p. Mechanically stiffer fibres (artificial or natural) may be an alternative to improved wind resistance.

MATERIAL CONSIDERATIONS

New fabrication technologies and processing techniques enable the creation of a new generation of materials that rewrite existing conventions. Brownell (2008, p. 8) describes seven materials trends that categorise the "current material transformations". Four trends can assist in manufacturing new biomimetic building materials: 'ultraperforming', 'recombinant', 'intelligent' and 'transformational' materials (Brownell 2008, pp. 9-10). Indeed, Brownell mentions both materials that take inspiration from biology and materials that "undergo a physical metamorphosis based on environmental stimuli" (Brownell 2008, p. 10).

Several manufacturers have developed fabrics that provide desired characteristics for an external fur layer. LAMA Concept (*LAMA* 2011) offer an alternative fabrication technique with their innovative wool-felt carpet press. LAMA Concept have also developed a special cutting technique to create "Furore" (*LAMA* 2011), a customisable synthetic fur fabric. Finally, Kuraray America Inc. have created "Vectran", a "high-performance multifilament yarn spun from liquid crystal polymer (LCP (*Vectran - Liquid Crystal Polymer Fiber* 2010). While developed for industrial purposes in aerospace, marine exploration and ropes and cables, the product nonetheless indicates that the current revolution in materials science offers opportunities for biomimetic applications.

CONCLUSIONS AND FURTHER WORK

The modelling of fur on an external building façade has illustrated that an artificial 'fur' layer can provide an effective insulative and radiative barrier to heat transfer, boosting the thermal performance of a lightweight façade.

By optimising four controllable variables – fur layer thickness, fur fibre, angular orientation of fur fibres and the number of fibres per unit area – it was shown that the effective thermal conductivity could be reduced to $k_{eff} = 0.055$ W/mK. This contrasts to value of $k_{eff} = 0.091$ W/mK for a layer of deer fur with the same thermal characteristics, a reduction of 40%.

When applied to an example of a lightweight external façade under sunny summer conditions, time-varying heat transfer model indicated that a fur-lined façade could reduce heat loads to an occupied space by up to 50% when compared to an equivalent wall using standard insulation. However, it was noted that this would result, optimistically, in a heat load reduction of 8-12% to an occupied zone conditioned to 22°C. Under a winter scenario, heat loss from the internal environment was reduced by 50% for a fur-lined façade over an equivalent opaque plane façade.

Further work can initially test various geometric configurations, including variable and controllable values of θ_f and $\theta_{f,s}$, to minimise heat gain in summer and maximise solar heat gain in winter. The fur-lined external wall can be tested with alternate materials – both natural and artificial fibres. The work of Cena and Monteith (1975a; 1975) can be investigated to explore the opportunities with various radiation characteristics. Cena and Monteith (1975b) also offer a means to integrate vapour diffusion characteristics, although this process is less significant (in temperate regions) for artificial walls than biological fur.

Furthermore, the thermal model may be moulded to respond dynamically to external climate conditions. For example, the model may offer an hourly dynamic simulation of the fur-lined biomimetic façade over the course of a summer/winter design day, eventually extending this across an entire year of weather data. Additionally, the thermal model can be extended to enable the selection and testing of the fur layer's physical parameters.

The results of the modelling on the fur-lined façade begin to demonstrate the potential of biomimicry to reduce the impact of buildings on global warming by decreasing operational energy consumption.

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