Convective Energy Transfer in Fur

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Introduction

Motion of the surrounding air increases the transfer of energy from an animal. To apply thermal modeling techniques, one has to know of the importance of convection within the fur relative to conduction and radiation (see Birkebak, 1966; Birkebak et al., 1966; Gates and Porter, 1969).

To find the amount of energy exchanged between the skin and the environment, equate the energy transfer through the fur with that lost from the surface to the surroundings:

\[
q_f = h_f(T_s - T_f) = h(T_f - T_\infty) + \varepsilon_f \sigma(T_f^4 - T_\infty^4)
\]

where

- \(q_f\) = rate of energy transfer per unit area of skin (W m\(^{-2}\))
- \(T_s, T_f, T_\infty, T_\infty, r\) = temperature (°K) of the skin, the outer surface of the fur, the ambient air, and the external radiation sink
- \(\sigma\) = Stefan–Boltzmann constant, \(5.67 \times 10^{-8}\) Wm\(^{-2}\)K\(^{-4}\)
- \(\varepsilon_f\) = emittance of the fur surface, which has been found to be very close to unity (see Birkebak et al., 1966; Hammel, 1956; Davis, 1972)

The heat-transfer coefficient \(h\) (W m\(^{-2}\)K\(^{-1}\)) applies to convection from the outer surface of the fur, while \(h_f\) (W m\(^{-2}\)K\(^{-1}\)) is a heat-transfer coefficient within the fur and arises from motion of air in the fur layer. The coefficient \(h_f\) is the subject of this paper. Radiation and conduction are treated in detail by Davis (1972) and Davis and Birkebak (1974, 1971).

Before discussing the energy transfer within the fur, we shall briefly review the pertinent ideas about convective heat transfer for a common basis of discussion. The third part of this paper reviews the pertinent experimental results available, and the final two parts present the analytical treatment of the results.
Convective Heat Transfer

When a fluid of temperature $T_\infty$ moves over a surface of temperature $T_s$, the rate of energy transfer per unit area of surface, $q$, can be calculated from the relation

$$q = h(T_s - T_\infty) \quad (2)$$

Equation 2 is sometimes called Newton's law of cooling. In the present usage, rather than being regarded as a law, it is simply considered the definition of the heat-transfer coefficient. The fundamental problem of convection is to determine the value of $h$ using analytical or experimental methods.

The heat-transfer coefficient is a function of the type of flow field over the surface, fluid properties, shape of the surface, boundary conditions along the surface, and time.

Flow fields are laminar, turbulent, or both. Laminar flow is characterized by smooth, ordered stream lines and is the kind of flow occurring within fur. In turbulent flow, macroscopic "chunks" of fluid move in a rapid and irregular fashion. Unless velocities are small, the motion of air or water in natural systems is turbulent.

Since there is no relative motion of the fluid and the surface just at the boundary, all energy transferred from the surface must be removed by conduction. The use of Fourier's law gives

$$q = -k \left( \frac{\partial T}{\partial y} \right)_{y=0} \quad (3)$$

where $k = \text{thermal conductivity of the fluid}$

$y$ is measured normal to the surface at the point of interest

$\frac{\partial T}{\partial y}_{y=0} = \text{fluid temperature gradient at the surface}$

The definition of the heat-transfer coefficient can then be written

$$h = \frac{-k \left( \frac{\partial T}{\partial y} \right)_{y=0}}{T_s - T_\infty} \quad (4)$$

If $D$ is a characteristic dimension of the body, Eq. 4 can be rewritten in dimensionless form

$$\text{Nu} \equiv \frac{hD}{k} = -\left( \frac{\partial T'}{\partial \eta} \right)_{\eta=0} \quad (5)$$

where Nu is the Nusselt number, the dimensionless temperature $T'$ is defined as

$$T' = \frac{T - T_\infty}{T_s - T_\infty} \quad (6)$$

and the dimensionless coordinate $\eta$ is given by

$$\eta = \frac{y}{D} \quad (7)$$