A REVIEW OVER THE INFLUENCE OF PHYSICAL AND MORPHOLOGICAL CHARACTERISTICS ON ANIMAL HEAT TRANSFER

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Abstract. *The present work consists on an overview about heat exchange mechanisms involved in the interaction between an animal and its respective environment. Influence of physical and morphological factors, such as body parts geometry, skin and fur thickness, exposed surface area were specified. Mechanisms utilized by the animals for manipulating heat flux and controlling surface temperature were discussed and simple mathematical models for representing energy balance were developed.*

Keywords*: heat transfer, energy balance, endothermic animals, heat transfer coefficient*

1. INTRODUCTION

The energy balance of an endothermic animal is predominantly defined by equilibrium between the metabolic generated energy and the heat exchanges involving the body and its surroundings. Animal and biologic tissues heat transfer basically involves all the exchange mechanisms in nature. Radiative emissions, convective flux between the animal and the air (or water), latent heat loss (sweat), conduction in the tissues (fat layers, fur), all these mechanisms interact and constitute an animal energy balance.

Animals present different physical, morphological and behavioral characteristics according to their environment. These characteristics regulate the metabolic rate and the energy spent and loss. For instance, animals surviving to harsh winters have the skin covered with insulate fur, besides their fat reserves under the skin, and spend more inactive time.

Heat exchanges depend on environment characteristics and how they interact with the animals. Large temperature differential produces more intense heat flux. The existence of winds and air turbulences, or humidity will define convective flux and evaporative heat loss.

A review over all heat exchange methods was developed and then correlated with several animal characteristics. This procedure made possible the comprehension of some methods of controlling heat flux and surface temperature and to glimpse the transposition to engineering of the principles found.

2. HEAT EXCHANGE MECHANISMS

2.1. Radiative heat exchanges

A random body on Earth surface will experiment radiative heat exchanges. An animal is subjected to solar radiation, atmospheric emission, the surrounding bodies' emission and emits its own radiation. The heat absorbed by an animal will depend on its absortance (α) to solar radiation, sky (atmospheric emission) and other bodies' radiation and the liberated heat will depend on its emissivity (ε).

The radiative heat exchanges in an animal body can then be mathematically expressed.

$$Q_{rad} = \alpha_s G_s + \alpha_{sky} G_{sky} + \alpha_{sr} G_{sr} - \varepsilon_a \sigma T_a^4 \quad (1)$$

where α_s is the animal absortance to solar irradiation (G_s); α_{sky} is the animal absortance to sky irradiation (G_{sky}); α_{sr} is the animal absortance to other surrounding bodies irradiation (G_{sr});ε_a is the animal emissivity; σ is the Stefan-Boltzmann constant and T_a is the animal surface temperature.

Irradiation due to atmospheric emission is given by

$$G_{sky} = \sigma T_{sky}^4 \quad (2)$$

where T_{sky} is the sky temperature, that depends on atmospheric conditions and vary from 230 K in a cold and cloudless day to 285 K in hot and cloudy day.

An animal on Earth surface can be approximated as a small body in a black body socket. Thus, according to subject literature, it can be stated that its absortance to sky radiation is equal to its own emissivity. Equation (1) can then be rewritten.

$$Q_{rad} = \alpha_s G_s + \varepsilon_a \sigma T_{sky}^4 + \alpha_{sr} G_{sr} - \varepsilon_a \sigma T_a^4 \quad (3)$$

2.2. Convective flux

Any animal will present convective heat exchange. This exchange will occur, for a terrestrial animal, between its body and the air, while it occurs between the body and the water for an aquatic animal. In the case of a terrestrial creature, it will be loosing energy trough the winds (forced convection) or, when involved by quiescent air, trough free convection. The convective heat transfer rate is defined by the Newton's law:

$$Q'' = h(T_S - T_\infty) \quad (4)$$

where h is the convection coefficient, T_S is the animal surface temperature and T_∞ is the air temperature.

The convection coefficient depends on fluid and flow characteristics (velocity, laminar or turbulent flow, natural or free convection) and geometric surface parameters, as much as it depends on the animal body orientation relative to the winds. The Nusselt number is usually presented as a dimensionless convective coefficient, since it is given by

$$Nu_L = \frac{hL}{k} \quad (5)$$

The determination of Nusselt number is basically empirical. The empirical relation is different for distinct shapes, and usually follows this format:

$$Nu_l = C_l Re_l^n \quad (6)$$

when it comes to forced convection and

$$Nu_l = C_l Ra_l^n \quad (7)$$

when it comes to free convection. C_l and n are constants to be experimentally determined.

2.3. Evaporative heat loss (sweat)

Sweating is a physiological mechanism with the aim of raising heat flux leaving the animal body, avoiding high temperatures in the organism. The physical principle governing this mechanism is the evaporation of fluid, an endothermic process (consuming energy process) that makes use of heat produced by the organism to happen.

The heat consumed in the evaporative process is the latent heat. In fact, heat exchanging processes involving latent heat are much more efficient than the ones involving only the sensitive heat. Yan and Soong analyzed the evaporative heat transfer in a system consisted by an inclined heated plate over which water at room temperature flowed. They observed that magnitude of the evaporative latent heat flux may be six times greater than that of the sensible heat.

Evaporation is a mass transfer process that can be modeled similar to the heat convective flux:

$$n'' = h_m(\rho_{A,s} - \rho_{A,\infty}) \quad (8)$$

where n''_A (kg/s m^2) is the mass flux of water, h_m (m/s) is the mass convective transfer coefficient, $\rho_{A,s}$ (kg/m^3) is the water mass density in the surface and $\rho_{A,\infty}$ (kmol/m^3) is the water mass density in the air, proportional to the air humidity.

Inspection of Eq. (8) makes clear that sweating is only an efficient mechanism when the ambient air humidity is not very high, so there will be a concentration gradient to maintain the water mass flux. The evaporative heat flux can be expressed as the product of the evaporative mass flux and the vaporizing latent heat.

$$Q''_{evap} = n''_A h_{fg} \tag{9}$$

2.4. Heat conduction in the tissues

Tissues such as skin, fur and fat layers actually act as thermal resistances to the heat flux between the animal and the environment. Thick skin and fat layers are isolators, and can be found in creatures living in the coldest places. If we consider the animal as a body with internal energy generation (metabolic rate), these tissues act as restraints to the release of the energy produced to the external surrounding, hindering a significant drop of the body temperature.

The conduction thermal resistance can be expressed as following.

$$R = \frac{1}{Sk} \tag{10}$$

and the heat flux trough this resistance is given by

$$Q = \frac{\Delta \mathrm{T}}{\mathrm{R}} \tag{11}$$

where S is the conduction form factor. The form factor will be different for each animal, and the smaller it is, the greater will be the isolative properties of the skin, fur and fat layers.

2.5. Energy balance

An animal body exposed to a natural environment is subjected to all types of heat transfer. There is probably heat loss by convection, heat gain trough the incident solar radiation, gain or loss by conduction (depending on the temperature of the ground surface). If the body is in equilibrium, the heat transfer mechanisms described will be balanced with the metabolic energy production of the animal. Thus, the energy balance for an animal body in steady state conditions can be established.

$$M \pm Q_{conv} \pm Q_{rad} \pm Q_{cond} = 0 \tag{12}$$

where M is the energy produced by the metabolic rate; Q_{conv} is the convective heat loss, Q_{rad} is radiative heat exchange and Q_{cond} is the conductive heat exchange. It should be noted that the signs before Q_{conv}, Q_{rad} and Q_{cond} in the equation are determined by environmental conditions, that defines whether heat is loosen or gained. When it comes to an animal capable to sweat in a hot environment:

$$M \pm Q_{conv} \pm Q_{rad} \pm Q_{cond} - Q_{evap} = 0 \tag{13}$$

If we consider that, as a result of all types of heat exchange, the animal loses heat to the environment, we have:

$$M = Q_{lost} \tag{14}$$

Jofré and Caviedes-Vidal (2003) stated that the rate of energy flow between an animal living in a cold season and its surroundings is determined by environmental factors and animal-dependent variables like metabolic rate; evaporative water loss rate; thermal conductance of fat, fur of feathers; absorptivity to radiation; size and shape of the body and body orientation. “A simple expression may be used to characterize relationship between heat production and the difference between body and air temperature of a mammal.” Hence, for a steady state condition, Jofré and Caviedes-Vidal (2003) defined:

$$M = C(T_b - T_a) \tag{15}$$

where the metabolic rate or rate of heat loss, is directly proportional to the whole body thermal conductance, C, and to the difference between the body (T_b) and air (T_a) temperatures. The overall thermal conductance includes the effects of convection, thermal radiation, evaporation, fur or feather layer conductance and surface tissue conductance.

Grémillet and Wilson (1999) defined an expression for the heat losses of a species of diving bird, the great cormorant (*Phalacrocorax carbo*) to the water. It was considered a featherless swimming cormorant, isolated by an air layer. The following expression was obtained.

$$Q = kA\,\Delta\mathrm{T} \tag{16}$$

where Q is the heat flux from the cormorant body to the water (W), k is the coefficient of heat transmission ($Wm^{-2}K^{-1}$), A is the skin surface area (m^2), and ΔT is the temperature difference between the body temperature (ºC) and the water temperature (ºC). The coefficient of heat transmission, k , can be calculated by:

$$k = \frac{1}{\left(\frac{1}{\alpha}\right)+\Sigma\frac{\delta}{\lambda}} \tag{17}$$

where α is the coefficient of heat transfer (W/m^2 K), λ is the coefficient of steady-state heat conduction of a particular insulating layer (here either a fat or air layer), and δ is the thickness of this layer (m).

Similarity of Eqs. (15) and (16) can be easily perceived. The difference is that Eq. (15) uses a unique constant, "C", to represent the product of the global heat transfer coefficient and the heat exchange surface area.

2.6. Attainment of heat transfer coefficient

All heat exchange mechanisms between an animal and its surroundings can be agglutinated into a global heat exchange coefficient. A model for this global coefficient is already demonstrated in Eq. (17) defined by Grémillet and Wilson (1999). However, they do not present methods for attainment of convection coefficient and conductivity. The conductivity can only be obtained through experimental procedures. The major problem is the definition of the convection coefficient, since experimental procedures for such end is complicated, and it depends on environmental, surface and geometrical factors. Equations (6) and (7) give the format of empirical relation for Nusselt number. Convection coefficient is then determined trough Eq. (5).

Gates (1962) and Porter and Gates (1969) recommend the use of convection relations for circular cylinders or spheres using the animal diameter as the characteristic dimension. But since Mitchell (1976) this approach has not been extensively verified, and may not be applicable to animals of quite different shapes.

Mitchell (1976) proposes a method for obtaining a generalized relation for use in modeling of the convective heat flow for an animal. The relation proposed is based on convection relations for a sphere, and employs a readily obtainable characteristic dimension for the animal based on mass. He defines a general characteristic dimension as:

$$L = V^{\frac{1}{3}} \tag{18}$$

where V is the volume.

Based on this characteristic dimension the following dimensionless numbers are defined:

$$Nu_L = \frac{hL}{k} \tag{19}$$

$$Re_L = \frac{vL}{\upsilon} \tag{20}$$

where υ is the fluid velocity and v is the fluid cinematic viscosity. Hence, the convective relation becomes:

$$Nu_L = C_L Re_L^n \tag{21}$$

Mitchell (1976) obtained values for C_L and n for several animal and geometric forms. According to him, all the results fall about ±20% of the sphere relation. Therefore, using the appropriate characteristic dimension, the sphere relation gives a satisfactory estimate of the convection coefficient for a large range of geometries. The geometries tested by Mitchell (1976) are shown at Tab. 1, extracted from his article.

Table 1. Convective heat transfer relations for animal shapes

Animal/geometry	**C_l**	**n**	**l (characteristic dimension)**	**Notes**	**References**
Sphere	0,37	0,6	Diameter	40<Re<4000	Kreith (1958)
Cylinder	0,615 0,174	0,466 0,618	Diameter	4000<Re<40000	Kreith (1958)
Cow	0,65	0,53	Trunk diameter		Wiersma e Nelson (1967)
Man	1,30	0,53	Average diameter	Adult man walking, l = 0,2 m	Nishi e Gagge (1970) Rapp (1973)
Ship	0,50	0,55	Trunk diameter		Bennet e Hutchinson (1964)
Frog	0,258	0,667	Snout-vent length		Joyce et al. (1966)
Lizard	0,35	0,6	Snout-vent length		Tracy (1972)
Lizard	0,1	0,74	Snout-vent length		Porter et al. (1973)
Lizard	1,36	0,39	Snout-vent length		Porter et al. (1973)
Lizard	1,91	0,45	Snout-vent length		Muth (1975)
Flying insects	0,0749	0,78	Snout-vent length		Church (1960)
Spiders	0,47	0,5	Diameter		Reichart and Tracy (1975)

3. INFLUENCE OF ANIMAL CHARACTERISTICS IN THE HEAT TRANSFER

3.1. Physical characteristics (fur, plumage, skin, etc.)

As already mentioned the major function of layers of fur, skin and fat is acting as isolators. They are necessary when temperature differential between the body and the environment is high. The effect of these kinds of isolative structures is very important to endothermic diving animals, as it is pointed out by Grémillet *et al.* (2005), since they tend to loose thirty times more heat to their surrounding (water) in comparison with strict terrestrial animals.

Another situation is the one of the aquatic polar mammals. They are efficient predators, wich is guaranteed by the fact they are big and cumulate thick subcutaneous fat layers. Marine birds of the artic and antartic regions are protected by their impermeable plumage.

Since Jofré and Caviedes-Vidal (2003), the nature and thickness of insulative layers in an animal body are important factors that determine the amount of heat exchanged. The efficiency of these layers is determined by the presence of a static air sheet that minimizes convective flux. Piloerection is a common mechanism to extend this effect.

Dawson *et al.* (1999) stated that the isolation in the penguin body is strongly connected to the morphology of their feathers and the different arrangement they can form according to environment conditions. The feathers constitute a thick layer filled with air for isolation means, eliminating convection and reducing radiative losses. However, they constitute a thin, smooth and impermeable cover when the penguin is immersed in the water.

3.2. Morphologic characteristics

Morphology is an important factor when it comes to heat transfer. It is easily observed that animal bodies or member sizes or shapes significantly differ accordingly to the region they live at. Since Jofré and Caviedes-Vidal (2003), creatures living at extremely adverse conditions, such as permanent cold seasons, exhibit some morphological adaptations.

When analyzing two immersed bodies in the same fluid, under the same physical conditions, the possible differences in the amount of heat transferred are fundamentally related to geometric parameters. Mitchell (1976) makes clear the influence of such parameters in the convective exchanges. He worked using the convective relation given by Eq. (7). The physical characteristics of the flow, such as velocity, are related to the Reynolds number (for the case of free convection, the Rayleigh number). The geometric parameters are then strictly connected to C and n constants. Therefore, he tabulated values of C and n for different animal and simple geometric forms. Table 1 evidences the influence of geometry.

3.3. Physiological characteristics and metabolic rate

Endothermic animals maintain their body temperature approximately constant, independently of the environment condition. That occurs due to changes in the metabolic rate. When the environment temperature is low, the metabolic rate increases in order to keep the body temperature high, compensating the heat losses. If the outside temperature is high, the metabolic rate is lower. The organisms make use of other strategies, like sweating, to low the body temperature down. This mechanism is efficient since the latent heat loss for sweat to evaporate is extracted of the body surface, pushing its temperature down.

Metabolic rate variations are thought to be of extreme importance for small mammals from artic and north zones, as defended by Jofré and Caviedes-Vidal (2003). Since them, isolative changes are thought to be of limited value for these creatures, so they present the greatest metabolic response to temperature exchanges. “Unless they can escape exposure to winter cold, seasonal acclimatation must largely lie in their ability to change heat production.”

3.4. Area /volume relationship

According to Hainsworth, the changes in the area/volume relationship affect the most effective ways of heat transfer. Several animals make use of mechanisms that modify their exposed surface area, controlling the surface temperature and the heat exchange. Since Jofré and Caviedes-Vidal (2003), animals can adopt a curled posture in order to reduce the exposed body surface area.

Besides these temporally adaptations, it is possible to perceive differences in the exposed area between animals that live in warm areas and the ones that live at low temperature condition. Elephants, for instance, live in warm areas and present large ears in order to dissipate heat more easily, throughout the big exchange area proportioned. Or, another example, the *Ammospermophilus leucurus*, a desert antelope ground squirrel that possess a large tail. On the other hand, animals of cold regions have characteristics that tend to minimize the heat transfer area, so they will not have large ears or big tails.

4. CONCLUSIONS

Animals experiment all kinds of heat transfer mechanisms. A review was made with the objective of describing how animal characteristics change in order to manipulate heat exchanges and to adapt to environmental conditions. The research can have some appliances in the engineering field.

Morphologic characteristics of animals can be analyzed in the heat transfer field trough the constants C and n found in the convection relation. The higher these constants are the most effective is the convective heat flux for a given Reynolds or Rayleigh number. The reproduction of a geometry strongly favorable to convective transfer can be made through the approximation of its C and n constants to the constants of an animal living under high temperatures, that depends on convective heat losses to maintain a relative low body temperature. This principle should be applied as a passive cooling solution.

Controlling exposed surface area is a method used by several creatures to reduce or amplify heat flux and then manage the body surface temperature. This principle can be applied, for instance, to solar collectors, that would amplify the exposed area during the day time (when the heat is absorbed by the collector) and minimize it during dim time (when the heat is loosened from the collector). This could be achieved through the use of foldable surfaces.

The research showed a remarkable value as a step toward a better interaction between engineering and other science research areas. This interaction should make possible the appearance of more creative and innovative solutions to engineering problems.

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