Effective thermal conductivity of the hair coat of Holstein cows in a tropical environment[1]

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ABSTRACT - The objective of the present study was to assess the effective thermal conductivity of the hair coat (k_{ef}, $mW.m^{-1}.K^{-1}$) of Holstein cows in a tropical environment, as related to conduction and radiation in the absence of free convection. The average k_{ef} was 49.72 $mW.m^{-1}.K^{-1}$, about twice the conductivity of the air (26 $mW.m^{-1}.K^{-1}$) and much less than that of the hair fibres (260 $mW.m^{-1}.K^{-1}$). The low k_{ef} values were attributed mainly to the small cross area of individual hairs, ρ_{ef}/ρ_f (17.2% and 21.3% for black and white hairs, respectively). White coats were denser, with longer hairs and significantly higher k_{ef} (53.15 $mW.m^{-1}.K^{-1}$) than that of the black hairs (49.25 $mW.m^{-1}.K^{-1}$). The heritability coefficient of the effective thermal conductivity was calculated as $h^2=0.18$ the possibility was discussed of selecting cattle for increased heat transfer through the hair coat.

Key Words: hair coat, Holstein cows, thermal conductivity

Condutividade térmica efetiva da capa de pelame de vacas Holandesas em ambiente tropical

RESUMO - O objetivo neste trabalho foi estudar a condutividade térmica efetiva do pelame (k_{ef}, $mW.m^{-1}.K^{-1}$) atribuída à condução e radiação na ausência de convecção livre no pelame de vacas Holandesas manejadas em ambiente tropical. A média para condutividade térmica efetiva do pelame foi 49,72 $mW.m^{-1}.K^{-1}$, quase o dobro da condutividade térmica do ar (26 $mW.m^{-1}.K^{-1}$) e bem inferior à do pelo (260 $mW.m^{-1}.K^{-1}$). O baixo valor observado para condutividade térmica efetiva do pelame deve-se principalmente à pequena área ocupada por pelos (ρ_{ef}/ρ_f), que foi somente 17,2% e 21,3% nos pelames preto e branco, respectivamente. O pelame branco foi mais denso e formado por pelos mais compridos, logo sua condutividade térmica efetiva (53,15 $mW.m^{-1}.K^{-1}$) foi significativamente maior que a do pelame preto (49,25 $mW.m^{-1}.K^{-1}$). A herdabilidade para a condutividade térmica efetiva é de 0,18, o que indica a possibilidade de se fazer seleção para elevar a transferência de calor através da capa.

Palavras-chave: condutividade térmica, pelame, vacas Holandesas

Introduction

The thermal conductivity of hair coat is related to the structure of a non-homogeneous system (Davis & Birkebak, 1974; Cena & Monteith, 1975ab) constituted by the hairs and the air trapped among them. The metabolic heat generated in the inner body regions is conducted through the hair coat to the atmosphere (a) by free convection in the air among the hairs, and (b) by molecular conduction along the hairs (Davis & Birkebak, 1974).

Evaluation of the thermal conductivity of hair coats is difficult because of the complexity of the energy transfer mechanism, as a result of the interacting convection, conduction and radiation processes within the hair coat (Kowalski, 1978). In order to understand the thermal conductivity in the non-homogeneous system constituted by hairs and air, Davis & Birkebak, (1974) studied some coat characteristics that affect conductivity and observed that the coat thickness and position, size, diameter and number of hairs are mutually related traits

which directly affect the thermal conductivity of the coat.

Based on the studies by Davis & Birkebak (1974) and Cena & Monteith (1975b) several models were developed to describe the effective thermal conductivity of the hair coat as a function of the coat characteristics (Kowalski, 1978). However, such models have been used to obtain thermal conductivity estimates based on the physical characteristics of reduced hair samples (Gebremedhin et al., 1983; 1997; Jiang et al., 2005), most of them taken from dead animals.

The objective of the present study was to estimate the effective thermal conductivity of the hair coat of Holstein cows in a tropical environment, using the models by Davis & Birkebak (1974), Cena & Monteith (1975b) and Kowalski (1978), taking into consideration the conduction and radiation processes in the absence of free convection. In addition, the genetic parameters of this trait were estimated, in order to assess the possibility of genetic improvement of the animals for tolerance to the tropical conditions.

Material and Methods

Hair samples were taken from the flank area about 20 cm below the spinal column, by means of adapted pliers, according to the method described by Silva (2000); 973 Holstein heifers and cows were sampled in a commercial herd in Descalvado, São Paulo (22º01' latitude, 47º53' longitude, 856 m altitude); these animals were aged from 2 to 13 years and were offspring of 793 dams and 205 sires.

Coat thickness (*E*, cm) was measured *in situ* by means of a metal ruler. Average hair length (*C*, cm) was given as the mean length of the longest ten hairs of each sample, as chosen visually and measured with a digital calliper, according to the method by Udo (1978). The same ten hairs were measured for their diameters (*D*, cm) with a digital micrometer (Mitutoyo). The number of hairs per unit area (*N*, hairs per cm^2) was estimated by counting all the hairs of each sample and relating them to a skin area of 0.14 cm^2; the estimate was later adjusted for 1 cm^2.

The effective thermal conductivity of the coat (k_{ef}, mW.m^{-1}.K^{-1}) was calculated by assuming absence of air movements, according the system of Cartesian coordinates illustrated in Figure 1 (Davis & Birkebak, 1974). The x axis is parallel to the skin and oriented to the predominant hair direction, while the y axis is normal to the skin. The z axis is normal to both x and y; θ is the angle between y and the hair axis; θ_f is the angle of the hair in relation to the normal to the skin; ϕ is the angle between x and the hair dominant
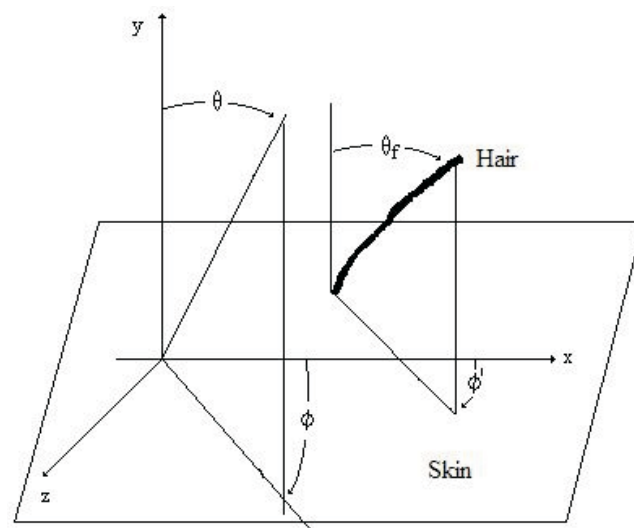

Figure 1 - Hair geometry: θ_f = angle of the hair in relation to the normal to the skin; ϕ' = angle between the hair projection on the sin and the hair dominant direction. Adapted from Davis & Birkebak (1974).

direction; ϕ' is the angle between the hair projection on the skin and the hair dominant direction.

According to Davis & Birkebak, (1974) one needs only to calculate the energy flux in the y direction, in order to obtain k_{ef} by means of the equation:

$$k_{ef} = k_1 \cos^2 \theta_f + k_p \mathrm{sen}^2 \theta_f \qquad [1]$$

For convenience,

$$k_1 = \left\{ \left[\frac{\rho_{ef}}{\rho_p} \right] k_f + \left[1 - \left(\frac{\rho_{ef}}{\rho_f} \right) k_a \right] \right\} \qquad [2]$$

where k_f and k_a were thermal conductivities of the hairs and the air, respectively. According to Davis & Birkebak (1974): $k_f = 0.26$ W.m^{-1}.K^{-1} and $k_a = 0.025$ W.m^{-1}.K^{-1}.

Equation 1 demands knowledge of the fraction area parallel to the skin and the fraction volume of the coat that is effectively occupied by hair mass, at a given distance from the skin. Such a relation is:

$$\frac{\rho_{ef}}{\rho_f} = \left(\frac{0,25 N\pi D^2}{\cos\theta_f} \right) \qquad [3]$$

where θ_f (decimal degrees) is the angle of the hairs in relation to the normal to the skin,

$$\theta_f = \arccos\left(\frac{E}{C} \right) \qquad [4]$$

Thus,

$$\frac{\rho_{ef}}{\rho_f} = \frac{0,25 CN\pi D^2}{E} \qquad [5]$$

Thermal conductivity in a direction perpendicular to the hair axis (k_p mW.m^{-1}.K^{-1}) can be estimated according to Kowalski (1978) and Gebremedhin et al. (1997) in the following form:

$$k_p = \left(\frac{k_a (l_c - D)}{l_c} \right) + \left(\frac{D k_a k_f}{D k_a + (l_c - D) k_f} \right) \qquad [6]$$

where $l_c = \dfrac{1}{\sqrt{N}}$.

Equation 1 gives the conductivity in the direction y within a hair layer formed by hairs oriented to the θ direction, but as the hairs of an actual hair coat were randomly oriented (Kowalski, 1978) an average k_{ef} value (from values obtained with equation 1 for all directions) can be given by:

$$k_{ef} = 0.5 (k_1 + k_p) \qquad [7]$$

However, radiative transfer through the coat (k_r, mW.m^{-1}.K^{-1}) is not considered in equation 7, because k_r can be estimated by theoretical calculations (Cena & Monteith, 1975ab) in which the thermal conductivity of the coat due to the radiation is defined as:

$$k_r = \frac{4b}{3P} \qquad [8]$$

where $b = 4\sigma \overline{T}_c^3$; σ is the Stefan-Boltzman constant (5.67051×10^{-8} W.m^{-2}.K^{-1}) and $\overline{T}_c$ is the temperature within the hair layer. Cena & Monteith (1975b) demonstrated that the b value increases from 5.7 W.m^{-2}.K^{-1} for $\overline{T}_c = 293$ K to 7.0 W.m^{-2}.K^{-1} for $\overline{T}_c = 313$ K. Of course, if the maximum temperature difference through the hair coat is less than 20 K, then b can have a value defined by a mean temperature $\overline{T}_c$. Then, a value $\overline{T}_c = 303$ K was assumed and consequently $b = 6.3097$ W.m^{-2}.K^{-1}.

Cena & Monteith (1975a) defined P as the fraction of the radiant energy that is intercepted by a unit hair thickness:

P = ND (tan θf)   [9]

Consequently, k_r can be determined by:

$$k_r = \frac{8.4129}{ND(\tan \theta_f)} \qquad [10]$$

Finally, by combining equations 6 and 9 the thermal conductivity of the coat due to the conduction and the radiation through the hair layer can be estimated as:

$k_{ef} = 0.5 (k_1 + k_p) + k_r$ [11]

The data were analysed by the least squares method (Harvey, 1960) using the Statistical Analysis System (SAS, version 6.1). The model used for the thermal conductivity of the coat was:

$$y_{ijklm} = \mu + m_i + i_j + s_k + c_l + \varepsilon_{ijklm} \qquad [12]$$

where y_{ijklm} is the effective thermal conductivity of the hair coat of the m-th cow of the j-th age class, sired by the sire of k-th origin, considering the l-th coat colour, measured in the i-th month; m is the fixed effect of the i-th month of observation; i is the fixed effect of the j-th age class; s is the random effect of the k-th origin sire origin; c is the fixed effect of the l-th coat colour; μ is the overall mean and ε is the random error.

The Restricted Maximum Likelihood (REML) method was used for the univariate analyses to estimate variance components and genetic parameters in an animal model, by means of the MTDFREML package.

The matrix model was:

y = Xb + Za + e   [13]

where y is the n_i x 1 vector of de n_i observations in the cows; X is the n_i x p incidence matrix of the p levels of fixed effects; b is the p x 1 vector of fixed effects and covariates; Z is the n_i x n_i block diagonal incidence matrix of the genetic values, with dimensions n x q for random effects per animal; a is the q x 1 vector of animal random effects; e is the n x 1 vector of random errors, in which q is the number of random effect levels and p is the number of levels of fixed effects and covariates.

Assumptions for model 13 were E(y)=Xb and E(a)=E(e)=0, in which the effect of the error (including genetic, environmental and non-additive genetic effects) is independently distributed with variance σ^2. Therefore, var(e) = Iσ_e^2= R; var(a) = Aσ^2=A$_a$ and cov(a,e)=0, where A is the relationship matrix of the animals; I is the identity matrix; σ_a^2 ia the direct additive variance of the traits; σ_e^2 residual variance of the traits. As cov(a,e)=0, then ZAZ`.

The mixed model (12) can be represented as:

$$\begin{bmatrix} \mathbf{X'X} & \mathbf{X'Z} \\ \mathbf{Z'X} & \mathbf{Z'Z + A_a^{-1}} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{b}} \\ \hat{\mathbf{a}} \end{bmatrix} = \begin{bmatrix} \mathbf{X'Y} \\ \mathbf{Z'Y} \end{bmatrix}$$

where a= σ_e^2 / σ_a^2 or $(1-h^2)/h^2$, in which heritability coefficient is $\hat{h}^2 = (\sigma_a^2 / \sigma_f^2)$. Other terms were defined previously.

Results and Discussion

The coat morphological characteristics and the characteristics of the black and white coats were different

(Maia et al. 2005) (Table 1). The white coat was denser with long, thin hairs, while the black coat was less dense with short, thick hairs. The average thermal conductivity of the hair coat was 49.72 mW.m^{-1}.K^{-1} (Table 2), a value lower than the range of 76 to 147 mW.m^{-1}.K^{-1} recorded by Bennett (1964) and Davis & Birkebak (1974). On the other hand, Cena & Monteith (1974b) suggested that expected values for the thermal conductivity of hair coats in the absence of free convection were between 30 and 45 mW.m^{-1}.K^{-1}. The value k_{ef}=49.72 mW.m^{-1}.K^{-1}

observed in the present study would be attributed mainly to the area occupied by the hairs, which was ρ_{ef}/ρ_f =17.8% only. This implies a variation between 25 and 29 mW.m^{-1}.K^{-1}, close to the thermal conductivity of the air (26 mW.m^{-1}.K^{-1}); in other words, about 71% of k_{ef} were due to k_l.

The fraction of the surface area that was effectively occupied by the hairs at a given distance from the skin (ρ_{ef}/ρ_f) was significantly higher (P<0.05) in the white than in the black coat (Table 2). This result was related to the number of hairs per unit area, greater in the white coat

Table 1 - Four hair coat characteristics in Holstein cows bred in a tropical environment. Values adjusted for coat colour

Item	Coat colour		Mean
	Black	White	
Number of observations	973	973	1946
Hair coat thickness (cm)	0.24b ± 0.0024	0.28a ± 0.0024	0.255 ± 0.0011
Hair length (cm)	12.97b ± 0.16	15.13a ± 0.16	1.31 ± 0.008
Number (hairs/cm^2)	921b ± 21	1,296a ± 21	1,112 ± 10
Hair diameter (cm)	0.0062a ± 0.000028	0.0059b ± 0.000028	0.00620 ± 0.000013

Means with the letter, for the same effect and between black or white column, do not differ (P>0.05) by the Tukey test.
Source: Maia et al. (2005).

Table 2 - Coat characteristics and hair coat thermal conductivity in Holstein cows bred in a tropical environment. Values adjusted for coat colour

Item	Coat colour		Mean
	Black	White	
Number of observations	973	973	1946
Fraction of the surface area that is occupied by hairs at a given distance from the skin (ρ_{ef}/ρ_f)	0.172b ± 0.0045	0.213a ± 0.0045	0.178 ± 0.0021
Thermal conductivity in a direction perpendicular to the hair axis, k_P (mW.m^{-1}.K^{-1})	26.07b ± 0.029	26.37a ± 0.029	26.21 ± 0.013
Thermal conductivity in a direction parallel to the hair axis, k_l (mW.m^{-1}.K^{-1})	65.47b ± 1.05	75.16a ± 1.05	66.99 ± 0.50
Thermal conductivity due to the radiation within the coat, k_r (mW.m^{-1}.K^{-1})	3.43a ± 0.11	2.35b ± 0.11	3.11 ± 0.045
Effective thermal conductivity, k_{ef} (mW.m^{-1}.K^{-1})k_{ef}	49.25b ± 0.048	53.15a ± 0.048	49.72 ± 0.022

Means with the letter, for the same effect and between black or white column, do not differ (P>0.05) by the Tukey test.
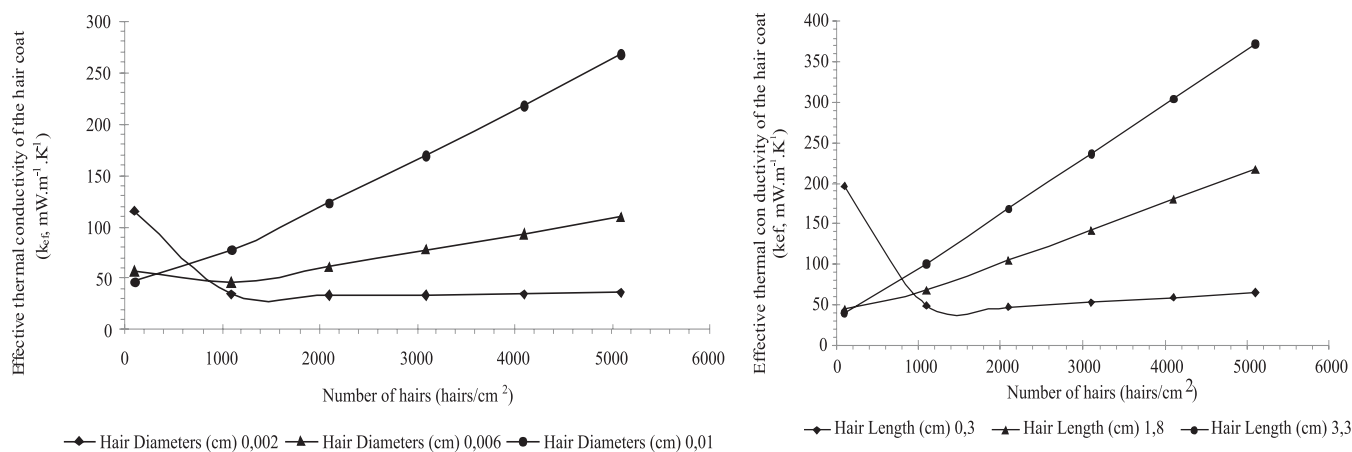

Figure 2 - Effective thermal conductivity of the hair coat in Holstein cows in relation to the number of hairs and associated to three hair diameters, hair length.

(1,296 hairs/cm^2); these hairs are also longer (Table 1). The fact that the denser coat had the longest hairs explained why the thermal conductivity of the white coat was greater (P<0.05) than that of the black coat (Table 2).

The number of hairs (Figure 2) increased together with the hair diameter (above 0.006 cm) there was a significant increase in the effective thermal conductivity of the hair coat. In fact, k_{ef} reached a value of 270 mW.m^{-1}.K^{-1} when N=5,000 hairs/cm^2 and D=0.01 cm. The result was reversed when Dd≤0.002 cm.

The increase in the number of hairs when associated to increased hair length (C>1.8 cm) favoured the increase in k_{ef}. The value of k_{ef} is 370 mW.m^{-1}.K^{-1} for N=5,000 and C=3.3 cm; however, if C≤0.5 cm, the effective thermal conductivity has an inverse relationship with the number of hairs. The increase in the hair diameter in association with hair lengths over 1.8 cm caused increase in k_{ef} (Figure 3), but opposite results occurred when C=0.3 cm.

It is possible to increase the k_{ef} value in two ways (Figure 2). In the first case, N>1,000, C>2.0 cm and D>0.05 cm and we have a dense coat consisting of long, thick hairs. The results of Maia et al. (2002) showed a high positive genetic correlation of the hair length and hair diameter with coat thickness. The conclusion was that the selection of animals in that direction would increase the thermal resistance of the hair coat – because the resistance is proportional to the coat thickness.

However, if such a result is advantageous in a cold environment, it is detrimental in a tropical climate. In the second case a reverse selection would be applied; i.e., for

less dense coats (<500 hairs/cm^2) with short (<1 cm), thin (<0.003 cm) hairs. The results of Maia et al. (2005) showed an inverse relationship of hair number with the effective transmittance of the coat. In other words, the smaller the N value, the greater the probability a photon would run through the hair coat and strike the skin. In such a case the animals must present a highly pigmented skin for protection against ultraviolet radiation.

The heritability coefficient of k_{ef} was h^2=0.18 (Table 3), by which it is possible to select the animals for greater values of heat transfer through the hair coat. The model used to calculate k_{ef} (Kowalski 1978) was also used by other authors (Gebremedhin et al., 1981; 1997; Jiang et al., 2005), but does not take into consideration the heat transfer by convection within the hair coat. However, the effect of that fact is hitherto unknown on the final value of k_{ef}. New models must be developed in order to calculate k_{ef} by taking convection transfer into consideration.

The selection direction is also questioned: (a) for denser coats with longer, thicker hairs or (b) less dense coats with short, thin hairs. Based on the k_{ef} values obtained by the model by Kowalski (1978) and Cena & Monteith (1975) under the assumption of high solar radiation levels, selection would be made for animals with less dense coats with short, thin hairs over a highly pigmented skin. On the other hand, non-pigmented skins must be covered by a dense coat with long, thick hairs.

Table 3 - Genetic parameters estimated for the effective thermal conductivity (k_{ef}) of the hair coat in Holstein cows

Parameter	k_{ef}
σ_a^2 Additive genetic variance	13.14
σ_e^2 Environmental and non-additive genetic variance	59.90
σ_f^2 Phenotypic variance	73.04
h^2 Heritability coefficient	0.18 ± 0.033

Conclusions

The value of the effective thermal conductivity of the hair coat was low, but greater for white coats because of its greater density. The heritability coefficient of the effective thermal conductivity showed a moderate value and pointed to the possibility of selection for increased heat transfer through the hair coat. More efficient models are needed to estimate the effective thermal conductivity of hair coats, by taking into consideration the heat transfer by convection within the hair coat.
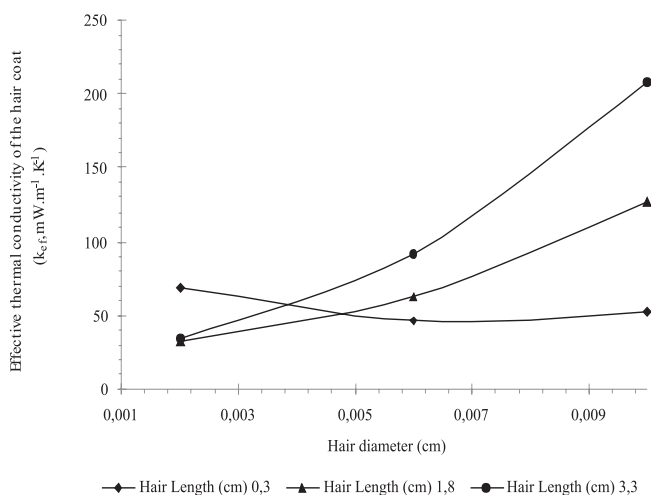

Figure 3 - Effective thermal conductivity of the hair coat in Holstein cows in relation to the diameters of hair and associated to three values of hair length.

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