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Latent heat loss of Holstein cows in a tropical environment: a prediction model

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ABSTRACT - Nine lactating Holstein cows with average 526 ± 5 kg of BW, five predominantly black and four predominantly white, bred in a tropical region and managed in open pasture were observed to measure cutaneous and respiratory evaporation rates under different environmental conditions. Cows were separated in three weight class: 1 (≤450 kg), 2 (450-500 kg) and 3 (>500 kg). Latent heat loss from cutaneous surface was measured using a ventilated capsule; evaporation in the respiratory system was measured using a facial mask. The results showed that heaviest cows (2 and 3 classes) presented the least evaporation rates. When air temperature increased from 10 to 36ºC the relative humidity decreased from 90 to 30%. In these conditions the heat loss by respiratory evaporation increased from 5 to 57 Wm^{-2}, while the heat loss by cutaneous evaporation increased from 30 to 350 Wm^{-2}. The results confirm that latent heat loss was the main way of thermal energy elimination under high air temperatures (>30ºC); cutaneous evaporation was the main mechanism of heat loss, responding for about 85% of the heat loss. A model was presented for the prediction of the latent heat loss that was based on physiological and environmental variables and could be used to estimate the contribution of evaporation to thermoregulation; a second, based on air temperature only, should be used to make a simple characterization of the evaporation process.

Key Words: evaporation rate, Holstein cows, tropical environment

Perda de calor latente em vacas Holandesas em ambiente tropical: um modelo de predição

RESUMO - Nove vacas Holandesas lactantes com 526 ± 5 kg de peso corporal (cinco predominantemente pretas e quatro predominantemente brancas), criadas em região tropical e manejadas em pastagens, foram observadas com os objetivos de determinar simultaneamente as taxas de evaporação cutânea e respiratória em ambiente tropical e desenvolver modelos de predição. Para a medição da perda de calor latente pela superfície corporal, utilizou-se uma cápsula ventilada e, para a perda por respiração, utilizou-se uma máscara facial. Os resultados mostraram que as vacas que tinham maior peso corporal (classe 2 e 3) apresentaram maiores taxas evaporativas. Quando a temperatura do ar aumentou de 10 para 36ºC e a umidade relativa do ar caiu de 90 para 30%, a eliminação de calor por evaporação respiratória aumentou de aproximadamente 5 para 57 $W\ m^{-2}$ e a evaporação na superfície corporal passou de 30 para 350 $W\ m^{-2}$. Esses resultados confirmam que a eliminação de calor latente é o principal mecanismo de perda de energia térmica sob altas temperaturas (>30ºC); a evaporação cutânea é a maior via e corresponde a aproximadamente 85% da perda total de calor, enquanto o restante é eliminado pelo sistema respiratório. O modelo para predizer o fluxo de perda de calor latente baseado em variáveis fisiológicas e ambientais pode ser utilizado para estimar a contribuição da evaporação na termorregulação, enquanto o modelo baseado somente na temperatura do ar deve ser usado apenas para a simples caracterização do processo evaporativo.

Palavras-chave: ambiente tropical, taxa de evaporação, vacas Holandesas

Introduction

Thermal equilibrium is achieved by cattle when the amount of heat produced by metabolic reactions equals the heat gained by the body from the environment. However, under too high environmental temperatures the thermal equilibrium can hardly be attained and in these circumstances the heat excess can be stored in the body tissues (Finch, 1985; McLean et al., 1983), thus increasing body temperature.

Under low ambient temperatures thermal energy is lost mainly as sensible heat due to the large temperature

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difference between the body surface and the environment (McLean 1963). In contrast, under high temperatures the body can gain heat by convection (Gebremedhin & Binxin, 2001); if the environment is characterized by intense solar radiation the body gains large amounts of heat by radiation (Curtis, 1982). In those conditions the ability of the animal to withstand its environment is proportional to its ability to dissipate heat by evaporation from the skin surface as a result of sweating (Finch et al., 1982; McLean, 1963; Maia et al., 2005a) or from the respiratory system by panting (Stevens 1981; Maia et al., 2005b).

Knowledge about the latent heat flow from Holstein cows managed under natural conditions in a tropical environment would contribute to genetic improvement programmes of dairy cattle in the tropics, by including fitness characteristics that are more favourable to the heat balance of animals. In addition, knowledge about latent heat loss mechanisms can be used to develop mathematical and physical models as those proposed by Stevens (1981), McLean (1963), Gebremedhin et al. (1981), Turnpenny et al. (2000) and McGovern & Bruce (2000) to explain thermal interaction between livestock and their environment.

These models have become valuable tools to determine how climatic events, mainly due to the improvement of shelter and management practices, affect the animal. The present investigation aims to measure the latent heat loss from the body surface and from the respiratory tract of Holstein cows managed under natural conditions in a tropical environment, with the objective of establish predicting models based on simple physiological and environmental measurements.

Material and Methods

Nine lactating Holstein cows were used, five predominantly black and four predominantly white, with average 526 ± 5 kg pf BW. Cows were separated in three weight class: 1 (≤ 450 kg), 2 (450 - 500 kg) and 3 (> 500 kg). The cows were observed under the environmental conditions of (21º15'22" South, 48º18'58" West, 595 m altitude) during the period of July-September 2004. The observations were made 1 or 2 days per week in the time period from 01:00 a.m. to 06:00 p.m. The cows were managed in open pasture and received silage ad libitum twice a day, always after milking (05:00 a.m. and 01:00 p.m. respectively). Their average milk yield was 15 kg per day. The animals were observed after milking inside the milk parlour, where one cow at a time was kept standing inside an enclosure (1.2 x 3.0 m), while the other cows remained outside the milking parlour in a pen where they were exposed to direct sunlight. Black globe, dry and wet-bulb temperatures and air velocity were taken near the animals inside the milking parlour (approximately 1.0 m from each animal, 3.5 m from the roof and 1.0 m from the floor).

Dry and wet-bulb temperatures were measured with a portable sling psychrometer; air velocity was determined by a thermo-anemometer (Alnor APM-360); for the black-globe temperature there was used a standard 0.15 m diameter hollow copper painted matt black. The black-globe temperature was used to estimate the mean radiant temperature (T_{RM}, K) according to DaSilva (2000). All these recordings were made as each cow was sampled.

The latent heat flow from the respiratory system and that from the cutaneous surface were determined at the same time, by using a facial mask and a ventilated capsule respectively. The heat loss by respiratory evaporation (E_R, W m^{-2}) was given by:

$$E_R = \frac{lVF(\Psi_E - \Psi_A)}{60A} \qquad [1]$$

while the heat loss by cutaneous evaporation (E_S, W m^{-2}) was given by:

$$E_S = \frac{lf_c(\Psi_C - \Psi_A)}{A_C} \qquad [2]$$

where $\lambda = 2500.7879 - 2.3737t_A$ is the latent heat of vaporisation (J g^{-1}), A is the body surface area ($A = 0.13w^{0.556}$, m^2), w is the body weight (kg), A_C the area of skin covered by the capsule (0.00724 m^2) and Ψ_A, Ψ_E e Ψ_C (g m^{-3}) are absolute air humidity of the atmosphere, of the expired air and of the air outgoing the capsule; they are given respectively by:

$$\Psi_A = \frac{2166.87 P_P\{t_A\}}{273.15 + t_A} \qquad [3]$$

$$\Psi_E = \frac{2166.87 P_P\{t_E\}}{273.15 + t_E} \qquad [4]$$

$$\Psi_C = \frac{2166.87 P_P\{t_C\}}{273.15 + t_C} \qquad [5]$$

where $P_P\{t_A\}$, $P_P\{t_E\}$ and $P_P\{t_C\}$ are the partial vapour pressures (kPa) of the air ambient, air expired and air from the capsule, respectively; t_A, t_E and t_C are the temperatures (Celsius degree) of atmosphere, expired air and the air from the capsule respectively. A CO_2/H_2O gas analyzer (Li-Cor, mod. LI-6262) was connected by tubing to the mask's outlet valve and to the capsule outlet tube, in order to determine Ψ_E and Ψ_C.

Air flow rate (f_C, m^3 s^{-1}) over the hair coat surface within the capsule was obtained by multiplying the cross-section area (0.0003630 m^2) at the air outlet tube of the capsule by the velocity (U_C, m s^{-1}) of the air passing over the hair coat surface; U_C was measured by a precision thermo-anemometer (Alnor APM-360) set at the air outlet tube of the capsule (for more details see Maia et al., 2005a). Tidal volume (V, m^3 breath^{-1}) was determined as follows: the probe of a precision thermo-anemometer (Alnor APM-360) was set at the mask air inlet, in order to measure the speed of the air entering the mask during the respiration process; as the inspiration-expiration wave was known to be approximately a square wave, the air speed measured as above described was assumed to be the mean air velocity, U_M (m.s^{-1}). The radius (r) of the air inlet was 0.023 m, the volume of air entering the mask was $\pi r^2 U_M = 0.0016619 U_M$ m^{3}s^{-1}, thus the tidal volume can be given by:

$$V = 0.0997141 UF^{-1} \qquad [6]$$

where F is the respiratory rate (breaths min^{-1}). It was determined by counting the movements of the air inlet valve of the mask (for more details see Maia et al., 2005b). The total heat flux by evaporation (E_T, W m^{-2}) was $E_T = E_R + E_C$.

Data were initially analysed by the least-squares method (Harvey 1960) using the Statistical Analysis System (SAS, 2001), according to Littell et al., (1991). The statistical model used to describe the total heat loss by evaporation was:

$$Y_{ijkl} = \alpha + w_i + r_j + c_{ik} + b_1 t_A + b_2 t_A^2 + b_3 U_R + b_4 U_R^2 + \varepsilon_{ijkl} \qquad [7]$$

where Y_{ijkl} is the total heat loss by evaporation (E_T) in the lth cow; w_i is the fixed effect of the ith weight class ($i = 1,...,3$); r_j is the fixed effect of the jth repetition ($j = 1,...,9$); c_{jk} is the random effect of the kth cow within weight class ($k = 1,...,3$ for $i = 1$; $k = 1,...,3$ for $i = 2$; $k = 1,...,3$ for $i = 3$); b_1, b_2, b_3 and b_4 are the linear and quadratic regression coefficients on air temperature and air relative humidity; ε_{ijkl} is the residual term, inclusive the random error; and α is the intercept.

Non-linear regression methods were used to estimate E_R, E_C, E_T and t_C, as function of air temperature and humidity, using Origin-5 software (Microcal Software Inc., Northampton, Mass. USA).

Results and Discussion

Heaviest cows (2 and 3 classes) presented the least evaporation rates (Table 1). In fact, lighter animals have larger body surface areas in relation to the volume. Cutaneous evaporation losses increase as the environmental temperature rises (especially above 24ºC), becoming the main way of latent heat dissipation (Figure 1). In such a condition the larger relative surface area of class 1 cows would certainly favours a greater potential for total heat flow by evaporation.

Table 1 - Total evaporative heat loss in Holstein cows, according to the body weight

Item	Total latent heat loss (W m^{-2})
Overall mean	72.54 ± 9.87
Weight class	
1 (≤450 kg)	123.01 ± 9.22a
2 (450-500 kg)	98.70 ± 8.70b
3 (>500 kg)	96.11 ± 7.14b

Means within a column with different superscript differ (P<0.05) by Tukey test.

Latent heat loss (Figure 1) increases with air temperature in almost a linear fashion until 25ºC and then becomes increasingly high as the ambient temperature rises above 27ºC. The same was observed by Finch (1985) and Kibler & Brody (1954). This increase in the evaporative heat loss was presumably a direct consequence of the decreased thermal gradient between the coat surface temperature and that of the surrounding air. When t_A was 10ºC, t_C was about 27ºC; but when t_A reaches 35ºC, t_C increases to near 37ºC (Figure 1 and 2). Consequently the thermal gradient decreases from 17ºC to only 2ºC, thus weakening the convection heat flux and causing the thermal radiation exchange to become a way of heat gain (Maia et al., 2005a; Gebremedhin & Binxin, 2001).

Total heat flux by evaporation (Figure 1) averaged 17.40 ± 0.92 Wm^{-2} when the air temperature was >20ºC and the air humidity approached 80%; from this total, an amount of 4.66 ± 0.34 Wm^{-2} was lost in the respiratory tract and 12.81 ± 0.99 Wm^{-2} through the cutaneous surface. These values agree with those found by Kibler & Brody (1954). However, when the air temperature reached 35ºC and the air humidity decreased to <30% the total evaporation was 264.67±37 Wm^{-2} on the average, being 216.88±33 Wm^{-2} lost by cutaneous evaporation while the rest was lost by respiratory evaporation.

Heat loss by evaporation was highly correlated with air relative humidity and this correlation was negative, while the contrary was observed for the air temperature (Figure 3). On the other hand, there was a high correlation between air relative humidity and air temperature, near 0.86; therefore, during the realization of the present study there were occurred low levels of air relative humidity in association to high environmental temperatures; a fact to be expected,

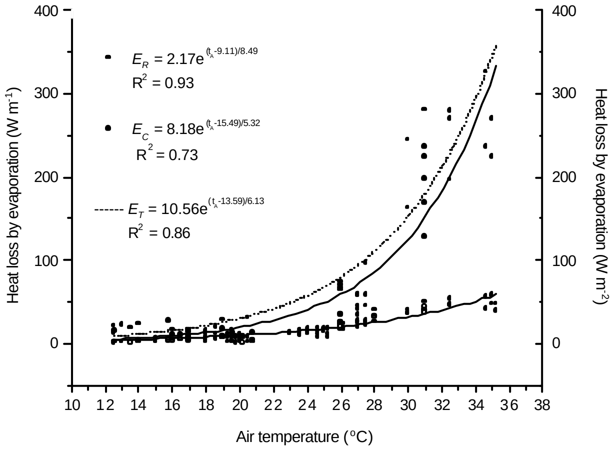

Figure 1 - Heat loss flux by respiratory (E_R; o) and cutaneous (E_C; •) evaporation of Holstein cows as functions of the air temperature. $E_T = E_R + E_C$.

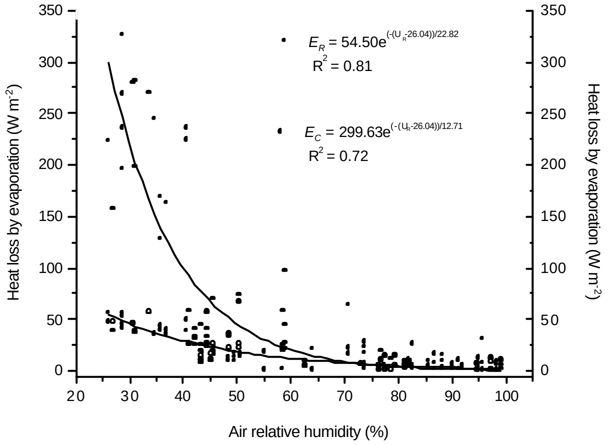

Figure 3 - Heat loss flux by respiratory (E_R; o) and cutaneous (E_C; •) evaporation of Holstein cows as functions of the air relative humidity.

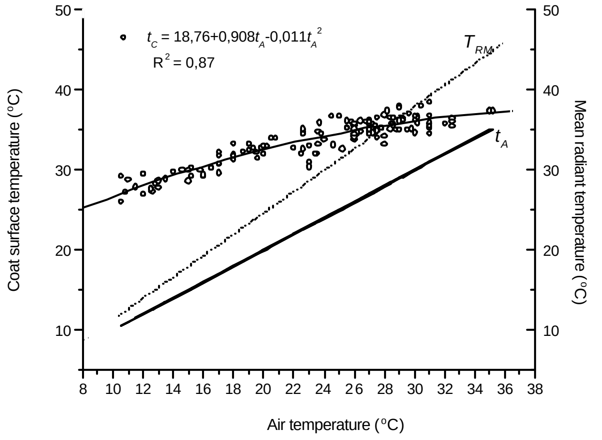

Figure 2 - Coat surface temperature (t_C; o) of Holstein cows as function of air temperature (— t_A).

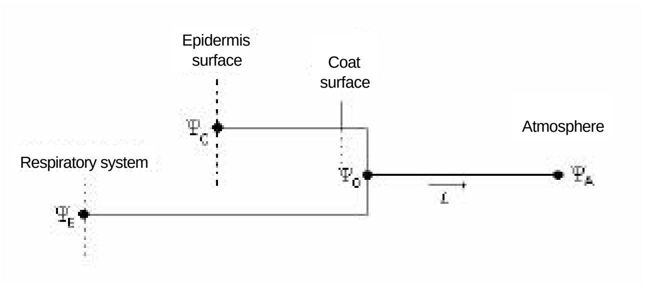

Figure 4 - Heat total flow by evaporation between animal and environment. Ψ_A, Ψ_E, Ψ_S are the absolute humidity of atmosphere, expired air, and cutaneous surface; Ψ_O was the operative absolute humidity.

as in most Brazilian country the summer was the rainy season. Such a correlation could explain why the inclusion of the air relative humidity in the prediction model for evaporative heat loss did not markedly increase the R^2 value.

Two models were used to predict the total heat flux by evaporation. Model 1 was based on the linear function of t_A given by log*ET* = $(0.86+t_A)613^{-1}$. For example, a Holstein cow observed under 35°C air temperature dissipated about 347.2 Wm^{-2} of latent heat, as estimated by this model.

In the model 2 the total heat flux by evaporation can be described by Figure 4.

In Figure 4, Ψ_A e Ψ_E were combines in the operative humidity Ψ_O (g m^{-3}), thus:

$$\frac{lVF(\Psi_O-\Psi_A)}{60A}+\frac{lf_C(\Psi_O-\Psi_A)}{A_C}=\frac{lVF(\Psi_E-\Psi_A)}{60A}+\frac{lf_C(\Psi_C-\Psi_A)}{A_C} \qquad [8]$$

and solving for Ψ_O (g m^{-3}) the result was:

$$\Psi_O=\frac{60Af_C\Psi_C+A_CVF\Psi_E}{60Af_C+A_CVF} \qquad [9]$$

knowing that A_C = 0.00724 m^2; the air flow rate through the capsule (f_C) was set at 1.74 -2.05 L min^{-1}, considering the mean value to f_C = 1.90 L min^{-1} or 3.17x10-5 m^3 s^{-1}. Thus

$$\Psi_O=\frac{114A\Psi_C+0.00724VF\Psi_E}{114A+0.00724VF} \qquad [10]$$

There Ψ_O depends on Ψ_E and Ψ_C that are given by equations 5 and 6 respectively and that depends on $P_P\{t_C\}$; t_E was estimated according to Maia et al. (2005b) and Maia (2005), as:

$$t_E = 9.47 + t_A(1.18 - 0.01278t_A) \qquad [11]$$

$$P_P\{t_C\} = -25.40 - 0.896t_A + 2.17t_C - 0.0096t_A^2 - 0.046t_S^2 + 0.043t_A t_S$$
[12]

while V was estimated from the respiration rate, according to Maia et al. (2005b) by:

$$V = \frac{F-2}{-755.32 + 161.93(F-2) + 1.97(F-2)^2} \qquad [13]$$

Together with the equations 5, 6, 11 and 13, Ψ_O was estimated in function of t_A, t_C, F and body weight, without the use of facial mask and ventilated capsule. Thus

$$\Psi_O = \frac{\left\{\dfrac{14.82w^{0.556}2166.87P_P\{t_C\}}{273.15+t_C}\right\} + \left\{\dfrac{[F(0.00724F-0.01448)]}{F[-7.756+F(1.115+0.0143F)]}\dfrac{e^{\frac{1938.72+t_A(28.85-0.313t_A)}{246.97+t_A(1.18-0.01278t_A)}}}{[282.62+t_A(1.18-0.01278t_A)]}\right\}}{\left\{\dfrac{w^{0.556}[-15876.67+F(2283.02+29.19F)]+F(0.00724-0.01448F)}{-1071.3+F(154.05+1.97F)}\right\}}$$

[14]

Finally, the total latent heat flow from animal (E_T, W m^{-2}) was given by:

$$E_T = \frac{[l(\Psi_O - \Psi_A)(60Af_C + A_C VF)]}{60AA_C} \qquad [15]$$

$$E_T = \frac{l(\Psi_O - \Psi_A)\{w^{0.556}[-0.2646 + F(0.038 + 0.000486F)] + F(0.00724F - 0.01448)\}}{0.0565w^{0.556}[-1071.3 + F(154.05 + 1.97F)]}$$

[16]

In order to test the model, we can consider a 570 kg Holstein cow standing inside the milk parlour under 35ºC air temperature and 1.60 kPa partial pressure. The cow has a respiratory rate of 57 breaths per minute and a coat surface temperature of 37ºC. In this environmental condition the latent heat of vaporisation was λ =2417.71 Jg^{-1}. We can calculate:

$$P_P\{t_C\} = -25.40 - 0.896(35) + 2.17(37) - 0.0096(35^2) - 0.046(37^2) + 0.043(35)(37)$$
$$= 4.47 \text{ kPa}$$

$$\Psi_O = \frac{\left\{\dfrac{14.82(570)^{0.556}\,2166.87(4.47)}{273.5+37}\right\} + \left\{\dfrac{[57(0.00724(57)-0.01448)]}{57[-7.756+57(1.115+0.0143(57))]}\dfrac{e^{\frac{1938.72+35(28.85-0.313(35))}{246.97+35(1.18-0.01278(35))}}}{[282.62+35(1.18-0.01278(35))]}\right\}}{\left\{\dfrac{570^{0.556}[-15876.67+57(2283.02+29.19(57))]+57(0.00724-0.01448(57))}{-1071.3+57(154.05+1.97(57))}\right\}}$$
$$= 31.33 \text{ g m}^{-3}$$

$$\Psi_A = \frac{2166.87(1.60)}{273.15+35} = 11.25 \text{ g m}^{-3}$$

$$E_T = \frac{2417.71(31.33-11.25)\{570^{0.556}[-0.2646+57(0.038+0.000486(57))]+57(0.00724(57)-0.01448)\}}{0.05659(570)^{0.556}[-1071.3+57(154.05+1.97(57))]}$$
$$= 252.77 \text{ W m}^{-2}$$

Therefore, in the specified conditions the contribution of the latent heat to the cow's thermoregulation was 252.77 W m^{-2}, as based in model 2.

For test power prediction of these models was comparing simulated (E_{S1} and E_{S2}) and measured (E_M) values using mean squared deviation (*MSD*) and its components, according to Kobayashi & Salam (2000):

$$MSD = \frac{1}{n}\sum_{i=1}^{n}(E_{S_i} - E_{M_i}) = SB + SDSD + LCS \qquad [17]$$

Table 2 - Total evaporation (E_T) in a Holstein cow measured with facial mask and ventilated capsule and values of evaporation simulated by model 1 (E_{S1}) and model 2 (E_{S2})

Item	^{1}Fbreath. min^{-1}	$^{2}t_A$ºC	$^{3}t_U$ºC	$^{4}t_S$ºC	^{5}wkg	EW m^{-2}	E_{S1} W m^{-2}	E_{S2} W m^{-2}
01	15	12	10.5	26.8	600	18.07	8.15	15.36
02	21	12	10.5	27.7	540	44.96	8.15	29.26
03	22	13	9.5	27.9	540	51.93	9.59	56.82
04	21	15	14.2	28.7	540	24.38	13.29	22.48
05	17	16	15	30.3	570	34.89	15.65	38.32
06	22	16	15	29.4	550	38.05	15.65	30.72
07	19	17	15	31.9	450	38.45	18.42	57.61
08	26	18	16	32.4	590	69.11	21.68	58.97
09	25	20	19	33.0	570	37.99	30.05	43.64
10	36	20	20.0	33.0	590	22.87	30.05	25.81
11	52	21	20.2	33.9	560	47.64	35.38	40.09
12	23	23	18	31.0	540	51.90	49.02	73.25
13	55	25	22	32.6	590	55.91	67.94	53.30
14	42	26	22	34.5	540	123.58	79.97	92.49
15	60	26	18	34.2	500	183.97	79.97	171.58
16	56	27	21	35.3	500	114.96	94.15	137.67
17	41	27	21	35.2	570	116.55	94.15	132.08
18	38	27	23	35.2	600	114.24	94.15	90.71
19	30	28	19	33.2	500	161.60	110.83	144.23
20	52	31	21	36.9	550	218.88	180.80	208.34
21	31	32	20.0	36.2	780	213.05	212.84	217.27
22	35	35	21	37.5	570	270.46	347.21	257.20
23	56	35	21	38.0	600	339.97	347.21	273.59

^{1}Respiration rate, ^{2}air temperature, ^{3}water bulb temperature, ^{4}body surface temperature and ^{5}weight.

$$SB = (\overline{E}_{S_i} - \overline{E}_{M_i})^2 \quad [18]$$

$$SDSD = (SD_S - SD_M)^2 \quad [19]$$

$$LCS = 2SD_S SD_M (1 - r) \quad [20]$$

where *SB* represent the bias of simulation from measurements, *SDSD* was the difference in the magnitude of fluctuation between the simulation and measurement, while *LCS* was the lack of positive correlation weighted by standard deviation, *r* was the correlation coefficient, SD_S and SD_M are standard deviation of simulation and measurement values, respectively and are the means of simulation and measurement values, respectively.

The value of *MSD* for model 2 was smaller than model 1 (Figure 5). The same result occurred for *SB*, *SDSD* and mainly for *LCS*. The bigger value of *LCS* for model 1 indicated that this model failed to simulate the pattern of fluctuation across the n measurements. This fact occurred due its higher SD_S (96.63 W m^{-2}) than the SD_S (77.25 W m^{-2}) for model 2. The lower the value of *MSD* for model 2 showed that the closer the simulation was to the measurement, obliviously indicating that this model was better than the model 1 for predicted value of heat loss by evaporation. This result indicated that the inclusion of physiological variables like respiration rate and body surface temperature in combination with environmental variables as air temperature and air humidity can improve the prediction power of the model.

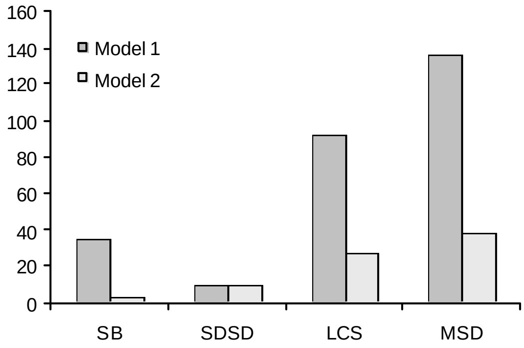

Figure 5 - Comparison of the mean squared deviation (*MSD*) and its components, lack of correlation weighted by the standard deviation (*LCS*), squared difference between standard deviation (*SDSD*) and squared bias (*SB*) for model 1 and 2. The values must be multiplicity by 100.

Conclusions

In Holstein cows managed in tropical environment the dissipation of latent heat by evaporation is the main way of elimination of excess thermal energy, when air temperature exceeds 30ºC. Cutaneous evaporation is responsible by 80% of total latent heat loss, while the rest is eliminated by respiratory evaporation. The prediction model for latent heat loss based on physiological and environmental variables can be used to estimate the contribution of evaporation for thermoregulation, while the model based on air temperature only must be used solely to make simple characterization of the evaporation process.

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