J. Trop. Agric. and Fd. Sc. 31(1)(2003): 119–127

Diurnal heat balance cycle model of a lactating cow in the tropics

(Model kitaran imbangan haba diurnal lembu tenusu di iklim tropika)

A.J. Md. Eusof*

Key words: dairy cattle, diurnal heat balance cycle, thermal stress

Abstrak

Satu model kitaran imbangan haba diurnal lembu tenusu telah dibangunkan untuk mengenal pasti punca tekanan haba dan tempoh waktu berlakunya tekanan haba pada ternakan tersebut. Model ini telah dibangunkan dengan menggunakan kaedah analisis sistem. Sumber pengeluaran haba mengambil kira haba metabolik yang dikeluarkan dan sinaran matahari yang diserap oleh lembu tersebut. Pembuangan haba pula mengambil kira kehilangan haba secara penyejatan dan bukan penyejatan serta melalui air yang diminum.

Lembu tenusu kacukan Friesian yang mengeluarkan 12.8 kg susu sehari telah mengeluarkan haba sebanyak 15.10 MJ/m^2/hari. Jumlah haba yang dikeluarkan untuk penyelenggaraan badan, penghadaman makanan, sintesis susu, berjalan dan berdiri, dan penyerapan sinaran matahari masing-masing ialah 8.62, 0.88, 4.27, 0.82 and 0.51 MJ/m^2/hari. Pembuangan haba secara bukan penyejatan, peluh, pernafasan dan melalui air minuman pula masing-masing ialah 4.67, 6.38, 2.03 and 2.13 MJ/m^2/hari. Kitaran imbangan haba diurnal menunjukkan kacukan ini berada dalam keadaan yang selesa antara pukul 2300 hingga 0600. Manakala, tekanan haba paling tinggi antara pukul 1200 hingga 1900.

Kajian mendapati tekanan haba berpunca daripada penimbunan haba di dalam ternakan tersebut yang tidak dapat dikeluarkan. Antara cadangan untuk mengurangkan tekanan haba ini adalah dengan memberi makanan foraj dan memerah susu 5–6 jam sebelum atau beberapa jam selepas berlakunya tekanan haba.

Abstract

Diurnal heat balance cycle model of a lactating cow was developed to quantify the sources of heat production and heat loss, and to assess the causes and period of thermal stress in the animal. The analysis was conducted using the system analysis technique and the values represent an average half-bred Friesian cow in Malaysia. Heat production was calculated from the metabolic heat generated and the radiant heat absorbed by the animal; whereas heat loss was computed from sensible or non-evaporative, evaporative and losses through drinking water.

Heat produced by a half-bred Friesian cow at peak lactation producing 12.8 kg milk per day was about 15.10 MJ/m^2/d. The amount of heat produced by body maintenance, feed ingestion, milk synthesis, walking and standing, and the amount of radiant heat absorbed by the animal were 8.62, 0.88, 4.27, 0.82 and 0.51 MJ/m^2/d, respectively. Heat loss through sensible, sweating, respiration, and

*Strategic Livestock Research Centre, MARDI Headquarters, Serdang, P.O. Box 12301, 50774 Kuala Lumpur, Malaysia
Author's full name: Md. Eusof Abdul Jamak
E-mail: eusof@mardi.my

drinking water, on the other hand, were 4.67, 6.38, 2.03 and 2.13 MJ/m^2/d, respectively. The diurnal heat balance cycle showed that the comfortable period for the cow is between 2300 h and 0600 h.

The most stressful period appears to be between 1200 h and 1900 h. The study also showed that stress was largely caused by the accumulation of heat stored by the animal and thus to reduce these stresses, the study suggested that the feeding of roughage and milking are to be carried out 5–6 hours before or a couple of hours after the stressful period.

Introduction

The introduction of European breed of dairy cattle into the tropics, by direct transfer of the animals or by artificial breeding, did not normally achieve the expected results. The animals' genetic potential is generally suppressed mainly due to stresses produced by the high environmental temperature and very fibrous feed. Apart from reduced performance, fertility and feed intake are also affected. The reasons for these reduced performances are not fully understood. One way that can be used to explain the decline, is to analyse the diurnal heat balance cycle and temperature regulation of the animal. With the analysis, the rate of heat production and heat dissipated by the animal throughout the day can be quantified. The information will also provide a better understanding of how the animal's response in a given environment and what can be done to elevate their performance.

Body temperature of an animal has been used to assess thermal stress and to measure thermal relief (Fuquay et al. 1979). According to Bligh (1973) when the body temperature of the animal is maintained within 1 °C of its normal level, it does not suffer severe heat stress. To examine the control of body temperature in cattle under heat load, Finch (1986) suggested that the relationship must come from an approach in which the animal is viewed in relation to both its thermal and nutritive environments. As there are many biological environments affecting lactation, this study will analyse these interactions by evaluating the diurnal heat balance cycle of the animal using the system analysis technique.

The objective of this study, therefore, was to construct a diurnal heat balance cycle model of a high-grade Friesian cow to quantify the sources of heat production and heat loss, and to assess the causes and period of thermal stress.

General concept

The general concept of this model has been reported previously (Md. Eusof 1995). The model is made up of two sub-models: the heat production and the heat loss. The heat production sub-model is the sum of the metabolic heat generated and the radiant heat absorbed by the animal. The heat loss sub-model, on the other hand, was computed from the sensible, evaporative and losses through drinking water.

The model is dynamic and deterministic. It is designed to provide information on the heat exchange between the animal and its environment during the 24-hour period at peak lactation *(Figure 1)*. The model runs in a loop and for each hour, heat produced and heat loss is calculated. Heat that is not expelled is stored in the animal. The body temperature of the animal is calculated based on the amount of heat stored and sweating rate. In the model, it is assumed that the body temperature, through heat exchange, regulates the total metabolic heat produced by the animal. This is done by not allowing the temperature to exceed or fall below its limits of between 38.0 °C and 39.5 °C. The amount of feed consumed by the animal is triggered by the amount of heat the animal is able to expel. The consumed feed is then used to calculate milk yield at peak lactation, after deducting those

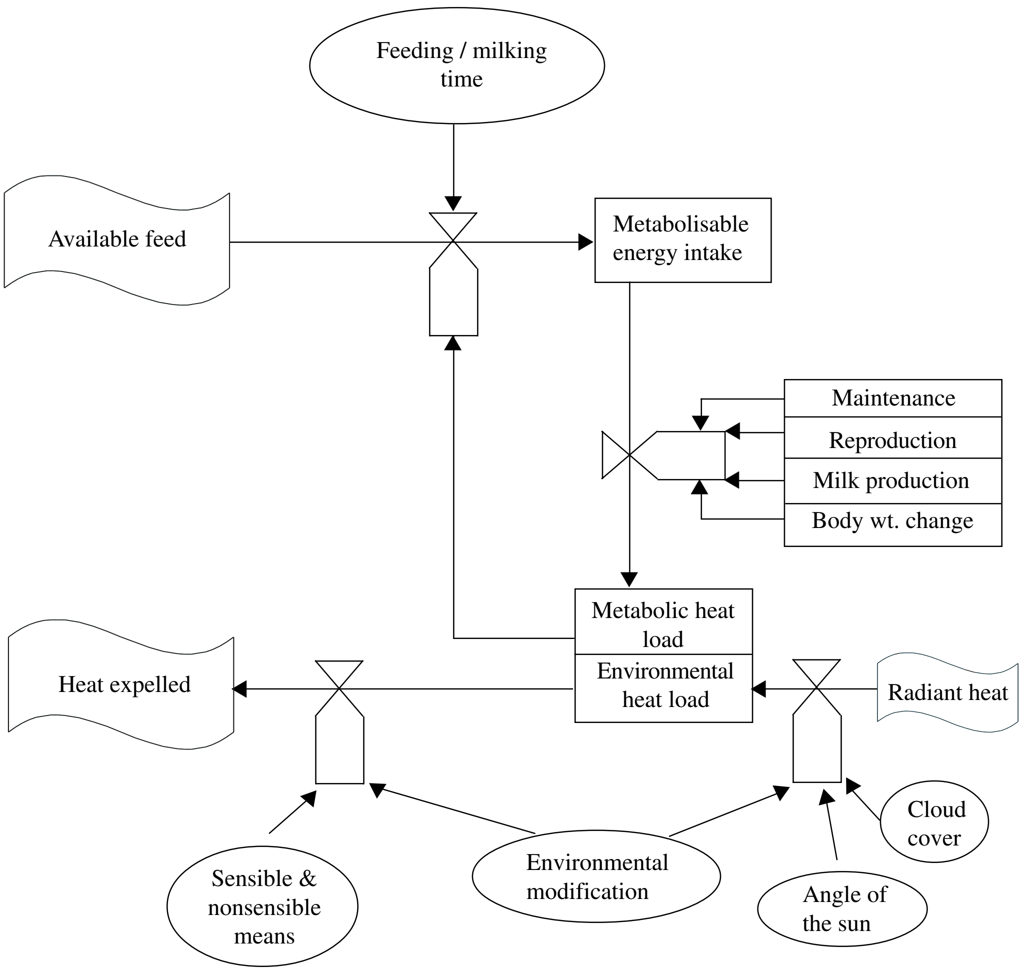

Figure 1. Flow diagram of diurnal heat balance model

needed for body maintenance, feed ingestion, standing and walking.

Heat production sub-model

The sources of heat production in the animal are from its own metabolic process and those gained from radiant energy. The rate of production depends upon its activities and is calculated from the maintenance energy expenditure, the ingestion of feed, standing, walking, lactating and body weight loss or weight gain. The amount of radiant heat absorbed by the animal depends on factors such as time of the day, the amount of cloud cover and the environmental modification provided for the animal.

Maintenance heat of production

Maintenance energy requirement is the energy required to maintain energy equilibrium in an animal. It is the sum of fasting heat of production and fasting urinary loss of energy divided by the efficiency of utilization of metabolizable energy (ARC 1980). This energy is converted to heat that has to be dissipated by the animal. In the model, estimates of fasting heat of production and efficiency of utilization of metabolizable energy recommended by ARC (1980) were used in this study.

The temperature effect on the maintenance requirement was also included in the model. Purwanto et al. (1993b) estimated that metabolizable energy requirement for maintenance under 15 °C and 30 °C as 464.9 and 554.7 kJ/kg$^{0.75}$ d, respectively. This value, which was used in this study, is equivalent to 6.0 kJ/kg$^{0.75}$d/°C increase in environmental temperature.

Heat produce from standing and walking

Heat produced from standing provided by Purwanto et al. (1993a) and heat produced due to walking as suggested by ARC (1980) were used for this study. Animals are assumed to spend about 38% of the time or approximately 9 hours a day standing (McLean et al. 1982). Six out of the 9 hours are assumed spent standing during the day and 3 hours at night. At each hour the animals stand, they are assumed to be walking for a distance of 20 m. During milking and feeding, which normally takes about 2 hours, the animals are assumed to be standing throughout the hour. The animals are also assumed to be standing for 2 hours before the morning feeding in anticipation of the food and for washing.

Heat from the ingestion of feed

Very little information is available for cattle on the energy cost or heat produced associated with the ingestion of different types of feed. The values used in this study are entirely based on the work by Adam et al. (1984).

Based on this limited information, the heat produced from the ingestion of concentrate is assumed to occur at the same hour as feeding. Concentrates are assumed given twice a day at the time of milking. The time forage is provided to the animals can be varied. Only once a day feeding is assumed and the animals are assumed to eat about 2.5 kg of dry matter at each meal and the remainder about 8 hours later. According to McLean et al. (1982), heat of production rises 40–50% during feeding and the heat increment of feeding is still evident after 5 hours. Since rate of heat production is not available, based on observation made by McLean et al. (1982), an assumed equation is developed for this purpose. The rate of heat production due to ingestion of roughage was drawn by using the computer program *TableCurve* using an assumed equation as follows:

$$\text{Ratioy} = 0.63x - 0.0839x^{2.5} + 0.0177x^3 - 0.0835x^{0.5}$$

where Ratioy is the ratio of the area under the curve over xth hour after feeding. Heat produced (Htforg) at hour y is calculated as:

$$\text{Htforg}(y) = \text{Ratio} / 3.491 * \text{THP}$$

Where 3.491 is the total area under the curve and THP is the total heat produced from the ingestion of feed.

Heat from the synthesis of milk

Energy source for the milk secreted is derived from the metabolisable energy of the diet and from maternal tissues. If the source is from the metabolizable energy of the diet, efficiency of utilization of the energy depends on the quality of the feed. However, when energy is derived from maternal tissues, efficiency of utilization is about 0.84 (ARC 1980). Thus from these two sources, the heat produced will be equivalent to one minus the metabolizability of the feed and 0.16 MJ for each MJ of the metabolizable energy of the diet allocated and maternal tissues utilized for milk, respectively.

Although the amount of heat produced for milk synthesis is known, the rate at which the milk is being synthesized after milking is not available. For this purpose, the rate of heat produced is assumed to vary with the expected amount of milk being produced. According to Schmidt et al. (1984), milk produced by once a day milking is about 60% that of twice daily milking and twice daily milking is about 17.5% less than 3 times a day milking. Based on this information, the estimated rate of milk produced in 24 hours was drawn by using the computer program *TableCurve*. The area under the curve was used as the basis to determine the amount of milk produced, which in this case is 47.42 square units for the 24-hour period. The equation derived is as follows:

$$S = 10 - 3.4m^{0.33}$$

where S is the ratio of the area under the curve during the m^{th} hour. The amount of heat produced from milk synthesis (Heatmilk) for hour y is:

$$Heatmilk(y) = s / 47.42 * Milkht$$

where Milkht is the total amount of heat produced per day.

Environmental heat load

The major source of environmental heat load gained by the animal is from solar radiation. The amount of radiant heat absorbed by the animal depends on factors such as time of the day, the amount of cloud cover and the environmental modification provided for the animal. The method of calculating radiant heat load in this section is taken entirely from Clapperton et al. (1965) and Blaxter (1989).

Following Blaxter (1989) the overall radiation balance of an animal can be expressed as:

$$R_{OD} = (1 - p)(R_{S(D)} + R_{S(I)} + R_{S(R)}) + ((L_U + L_D) / 2) - \sigma T^4_F$$

where R_{OD} is the radiant heat load gained out-of-doors; (1 – p) is the proportion of the solar energy absorbed. $R_{S(D)}$, $R_{S(I)}$ and $R_{S(R)}$ are the solar radiation impinging on the animal by direct, indirect and reflected components, respectively. L_U is the long wave radiation from the sky and L_D is the long wave radiation from the terrain. σ is the Stefan-Boltzmann constant and T^4_F is the absolute temperature of the fur in Kelvin (°K).

For animals kept under shade, the absorbance of long wave radiation is considered the most important component in heat exchange. Due to difficulty in calculating all these factors and that since animals in the tropics are kept under shade with open sides, the equation for radiant heat gain can be expressed from part of the equation above as:

$$R_{US} = (L_U + L_D) / 2 - \sigma T^4_F$$

where R_{US} is the radiant gain under shade; and L_U and L_D which have the same value is given as:

$$L_U \text{ and } L_D = 1.2T_E^4 - 171$$

where T_E is the air temperature in Kelvin.

Heat loss sub-model

Animals lose heat by both sensible and evaporative means. They have very limited ability to control sensible heat loss. The evaporative loss of heat, on the other hand, can be reduced to a minimum or increased to a considerable amount depending on the amount to be dissipated. In warm environment, heat loss is largely through the evaporative means. Both evaporative means, respiratory and sweating heat loss, increase at the same time. Due to difficulty in solving both parameters simultaneously, respiratory heat loss by environmental temperature is fixed in the model and heat loss through sweating is allowed to vary.

Sensible heat loss

Losing heat by means of radiation, convection and conduction is termed as sensible loss of heat. The amount of losses depends on the air temperature, the radiation to its surroundings, and the amount air movement. The method used in this study was adapted from the study of ruminants in cold environments by Blaxter and coworkers (Blaxter et al. 1959; Blaxter 1962; Joyce et al. 1966; Webster and Blaxter 1966). It has also been used for cattle in warm climate as described by Blaxter (1989). Due to its simplicity and suitability for the present study, the method applied by Blaxter was used.

Respiratory heat loss

Respiratory heat loss in cattle depends on the volume of air inspired and humidified. Much of this method of heat loss is outside the control of the animal. Animal's response to excess heat load may include increase in the rate of respiration. The calculation of respiratory moisture loss used in this study was taken wholly from Stevens (1981).

Sweating heat loss

Sweating is the most efficient mean of removing heat from the body in a hot environment. The minimal and presumptive maximal rates of heat loss by vaporization of water from the skin surface of cattle is reported to be 9 and 98 W/m^2 (Ingram 1974). Blaxter and Wainman (1961) and Gonzalez-Jimenez and Blaxter (1962) use the minimum rate of loss as 17 W/m^2 or 1.47 MJ/m^2 per day for cattle in cold conditions. For this model, the minimal and maximal rates of loss used were 1.47 MJ/m^2 and 9.5 MJ/m^2.

Other means of reducing heat load

Heat, which the animal utilizes to warm drinking water, can be quite large considering the large amount drunk. According to NRC (1981), an average cow producing about 17 kg of milk will consume about 75 kg of water per day at environmental temperature of between 25 °C and 35 °C. The amount of heat that can be removed by drinking this amount of water can be calculated by using the linear relationship as suggested by Stermer et al. (1986). In the model, the amount of water consumed is related to the body temperature of the cow and the amount drunk is calculated according to NRC (1981).

Body temperature

Estimates of body temperature increase due to heat storage provided by Blaxter (1989) were used in the model. Following Blaxter, the change in body temperature (DT_B) can be estimated from the total body mass (W), mean specific heat (Cp) and heat storage (s) as: DT_B = WCp/s. This equation when applied to the model, however, does not portray the expected increase in body temperature. Thus to represent a more realistic figure, the change in body temperature also includes sweating heat loss and was calculated as follows:

$$Tinc(y) = (0.3 * Sreq * 1000) / (BWt * Cp)$$

Where Tinc(y) is the body temperature increase at time y; BWt is the body weight of the animal and Cp is the specific heat of the body taken as 3.47 KJ/kg K.

Model behaviour

The overall diurnal heat balance cycle pattern of the cow is shown in *Figure 2*. The management inputs included in the model were milking at 0700 h and at 1500 h, feeding of concentrate during milking and feeding of roughage, at 1000 h. The average air temperature to which these animals are exposed is about 26.7 °C and ranges from an average low of about 22 °C to an average high of about 31 °C. The relative humidity ranges between 65% and 95%. The average cloud cover was assumed about 60%. The study also assumed that the animals were well adapted to the environment to which they were exposed.

The total heat produced by the high-grade Friesian cow, producing about 12.8 kg milk, is about 15.10 MJ/m^2/d. Over the day, the body temperature of the animal is regulated by both the heat production and heat loss mechanisms. However, at about 1200 h, heat gained by the animals exceeds heat loss. When this happen, the animal stores the excess heat and the body temperature increases sharply. The excess heat causes discomfort to the animal and this period, which lasted for about 7 hours, can be considered as the stress period. The period of comfort, on the other hand, started from 2300 h and lasted until 0600 h. During this period, sweating rate is almost at its minimum and the body temperature is close to 38.0 °C.

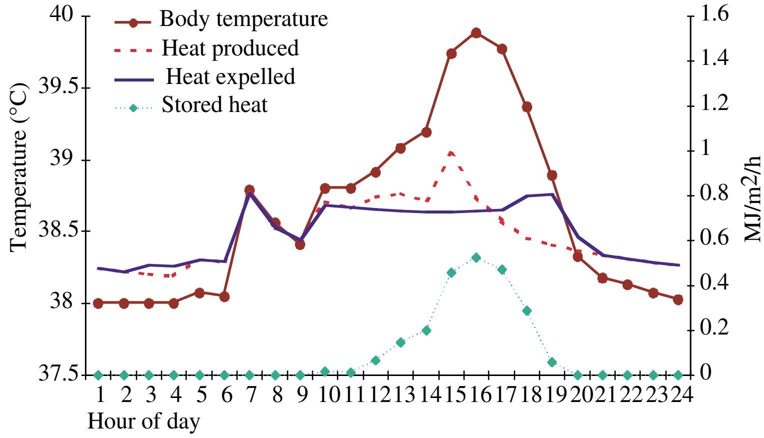

Figure 2. Predicted diurnal body temperature and heat balance cycle of high-grade Friesian cow

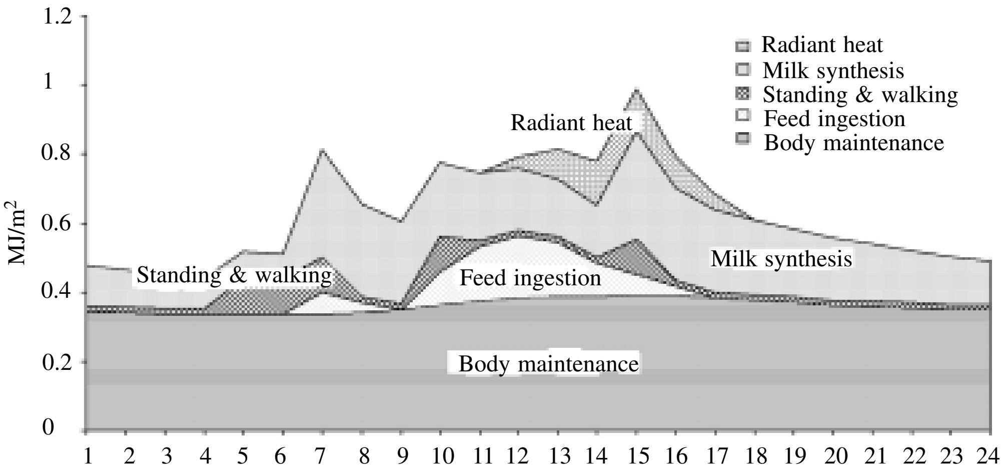

Figure 3. Cumulative hourly heat load of high-grade Friesian cow

A breakdown of the various avenues of heat production indicates that heat produced by the animal during the day is mainly contributed by the increase in its activities. As shown in the cumulative diurnal heat production cycle *(Figure 3),* 2 hours before the morning milking the animals are already standing in anticipation of the feed and milking. By 0700 h, heat production due to standing, walking, milk synthesis and ingestion of concentrate feed increases. This is followed by another increase originated from the ingestion of roughage feed given at about 1000 h. The increase in heat due to feed ingestion continues to rise and peaks at about 1200 h. At 1500 h, there is another increase in heat production contributed by the increase in the synthesis of milk. Very little heat is gained by the animal between 1800 h and 0400 h, except from body maintenance and milk synthesis.

Overall, the main sources of heat load, which make up about 85.36% of the total heat production at peak lactation, are body maintenance (8.62 $MJ/m^2/d$) and milk synthesis (4.27 $MJ/m^2/d$). Heat production due to maintenance is somewhat constant throughout the day, increasing only slightly at mid-day when the air temperature is high. Heat produced from the synthesis of milk, however, is very high during the first hour after milking and declines gradually thereafter. Heat production due to feed ingestion, standing and walking together represent about 1.7 $MJ/m^2/d$ or 11.23% of the total heat produced by the cow. Apart from those produced by the animal, heat is also gained from radiation. The radiant heat impinging on the animals lasted for about 7 hours beginning at 1100 h and peaks at 1500 h.

The amount gained is about 0.51 $MJ/m^2/d$ or about 3.3% to the total heat load. The amount gained, although small, plays an important part in determining the comfort of the animal, as this heat load impinges on the animal at fixed hour. It can be more discomforting to the animal if it is on a cloudless day.

The diurnal heat loss cycle of the cow at peak lactation is shown in *Figure 4.* The major means of heat loss are through sweating (6.38 MJ/m^2) and sensible means (4.67 MJ/m^2), which together account for 72.6% of the total heat loss. Heat loss through respiration and drinking water contributes about 2.03 and 2.13 MJ/m^2 per day, respectively. During the period of comfort, the major means of heat loss are through sensible means, whereas during the stressful part of the day sweating plays the major part and accounts for almost 60% of the total heat loss.

Discussion and conclusion

Based on the model, the results indicated that the rise in body temperature of the animal at mid-day is largely caused by the accumulation of heat generated from its metabolic activities and from the radiant heat absorbed by the animal. The rise in body temperature at this time of the day is further aggravated by the reduced rate of heat loss. Thus to reduce additional heat load and thermal stress, feeding and milking activities should be shifted to the cooler part of the day when there is greater rate of heat loss. As heat load from these activities has a long "trailing" effect, the study suggested that the feeding of roughage and milking are to be carried out at least 5–6 hours before or a couple of hours after the stressful period. The shifting of these activities would alter the temperature regulatory pattern of the animal and can probably cause an increase in heat loss, which can further affects its feed intake and milk production.

There may be many other factors involved to account for the interactions between the animal and its environment. The values used to develop this model were taken from the experimental results from

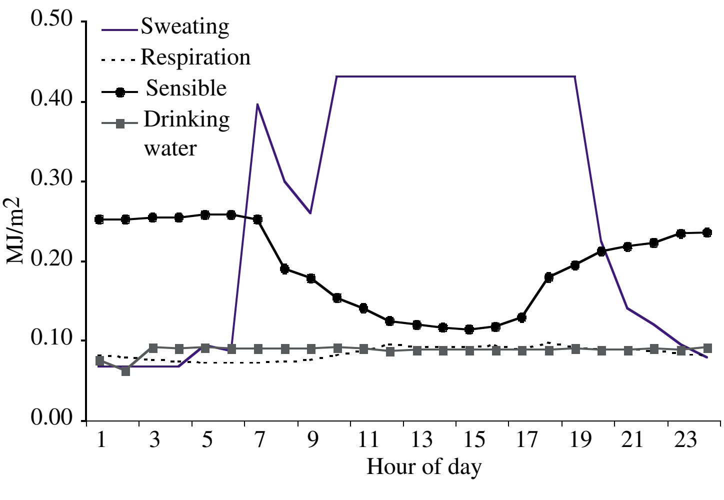

Figure 4. Predicted diurnal heat loss cycle of high-grade Friesian cow

many different sources and some were estimated based on observations made by different workers. It is not possible to carry out such study using the conventional research method; hence it would not be possible to validate such model. Taken as a whole, the model developed in this study does provide additional knowledge and scientific understanding on how animal reacts and how this interaction can affect thermoregulatory pattern of the animal in the warm and hot tropical environment.

References

Adam, I., Young, B.A., Nicol, A.M. and Degens, A.A. (1984). Energy cost of eating in cattle given diets of different form. *Anim. Prod.* ***38:*** 53–6

ARC (1980). *The nutrient requirements of ruminant livestock*, p. 74–119. Farnham Royal, UK: Agriculture Research Council. Commonwealth Agricultural Bureaux

Blaxter, K.L. (1962). *The Energy Metabolism of Ruminants*. London: Hutchinson

—— (1989). *Energy metabolism in animals and man.* Cambridge: Cambridge University Press

Blaxter, K.L., McC. Graham, N., Wainman F.W., and Armstrong, D.G. (1959). Environmental temperature, energy metabolism and heat regulation in sheep. II. The partition of heat losses in closely clipped sheep. *J. Agric. Sci.*(Cambridge) ***52:*** 25–40

Blaxter, K.L. and F.W. Wainman (1961). Environmental temperature and the energy metabolism and heat emission of steers. *J. Agric. Sci.*(Cambridge) ***56:*** 81–90

Bligh, J. (1973). *Temperature Regulation in Mammals and Other Vertebrates*. p. 352. Amsterdam: North Holland Publ. Co.

Clapperton, J.L., Joyce, J.P. and Blaxter, K.L. (1965). Estimates of the contribution of solar radiation to the thermal exchanges of sheep at a latitude of 55^on. *J. Agric. Sci.* (Cambridge) ***64:*** 37–49

Finch, V.A. (1986). Body temperature in beef cattle: Its control and relevance to production in the tropics. *J. Anim. Sci.* ***62(2):*** 531–42

Fuquay, J.W., Zook, A.B., Daniel, J.W., Brown, W.H. and Poe, W.E. (1979). Modification in freestall housing for dairy cows during the summer. *J. Dairy Sci.* ***57:*** 609 (Abstract)

Gonzalez-Jimenez, E. and Blaxter, K.L. (1962). The metabolism and thermal regulation of calves in the first month of life. *British J. Nutrition* ***16:***199–212

Ingram, D.L. (1974) Heat loss and its control in pigs. In: *Heat loss from Animals and Man*, (Monteith J.L. and Mount L.E., ed.) p. 233–54. London: Butterworths

Joyce, J.P., Blaxter, K.L. and Park, C. (1966). The effect of natural outdoor environments on the energy requirements of sheep. *Research in Veterinary Science 7:* 342–59

Mclean, J.A., Downie, A.J., Watts, P.R. and Glasbey, C.A. (1982). Heat balance of ox steers *Bos taurus* in steady-temperature environments. *J. Agric. Sci. Camb.* ***100:*** 315–22

Md. Eusof, A.J. (1995). *The assessment of management strategies for milk production by exotic and cross breeds of dairy cattle in the tropics*. Ph.D. thesis. Department of Agriculture, The University of Reading

NRC (1981). *Effect of Environment on Nutrient Requirements of Domestic Animals*. National Research Council. Washington, DC: National Academy Press

Purwanto, B.P., Matsumoto, T., Nakasuma, F., Ito, T. and Yamamoto, S. (1993a). Effect of standing and lying behaviors on heat production of dairy heifers differing in feed intake levels. *AAAP J. Anim. Sci.* ***6(2):*** 271–4

Purwanto, B.P., Nakasuma, F. and Yamamoto, S. (1993b). Effect of environmental temperatures on heat production in dairy heifers differing in feed intake level. *AAAP J. Anim. Sci.* ***6(2):*** 275–79

Schmidt, G.H., Van Vleck, L.D. and Hutjens, M.F. (1984). *Principles of Dairy Science*. New Jersey: Prentice Hall, Englewood Cliffs

Stermer, R.A., Brasington, C.F., Coppock, C.E., Lanham, J.K. and Milan, K.Z. (1986). Effect of drinking water temperature on heat stress of dairy cows. *J. Dairy Sci.* ***69(2):*** 546–51

Stevens, D.G. (1981). A model of respiratory vapor loss in Holstein dairy cattle. *Transactions of the American Society of Agriculture Engineers* ***24(1):*** 151–8

Webster, A.J.F. and Blaxter, K.L. (1966). The thermal regulation of two breeds of sheep exposed to air temperatures below freezing point. *Research in Veterinary Science 7:* 466–79

Accepted for publication on 14 April 2003