SIMULASI JUMLAH KEHILANGAN HABA DARI PERMUKAAN KULIT LEMBAP BAGI LEMBU TENUSU

(SIMULATION OF TOTAL HEAT LOSS FROM WET SKIN SURFACE OF DAIRY CATTLES)

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LIST OF SYMBOLS

Symbol		**Representation**	**Unit**
$\frac{du}{dy}$	=	Velocity gradient of fluid	s^{-1}
q''_L	=	Conduction heat flux within the laminar boundary layer	W/m^2
q''_T	=	Heat flux in the turbulent layer	W/m^2
$\overline{h}_c$	=	Corrected convective heat transfer coefficient	W/m^2K
q''_r	=	Radiant heat flux	W/m^2
ΔT	=	Temperature difference	^0C or K
A_f	=	Area of the cylinder normal to the flow	m^2
$A_{\underline{f}}$	=	Cross-sectional areas of fur	m^2
A_s	=	Surface area of a cow	m^2
A_t	=	Total area (fur and air)	m^2
Br	=	Breathing rate, average is 38	breaths/min
C_0	=	Concentration of water vapor in the turbulent layer	$Kmol/m^3$
C_f	=	Drag force coefficient	-
C_i	=	Concentration of water vapor at the interface of laminar and turbulent boundary layers	$Kmol/m^3$
Cp_{air}	=	Specific heat of air at body temperature, assumed to be 1.007	kJ/kg K
Cp_{urine}	=	Specific heat of urine at body temperature, assumed to be 4.2	kJ/kg K
C_{skin}	=	Concentration of water vapor on the skin surface	$Kmol/m^3$
D	=	Mass diffusion coefficient of water vapor	M^2/s
d	=	Characteristic dimension, assumed the animal as a cylinder and perpendicular to the flow, and is 0.8 (equivalent to the diameter of a cow)	m
d_h	=	Hair diameter, assumed to be 0.0464	mm
F_D	=	Friction drag	N

f_{eff}	=	Coefficient of the effective radiant area ≈ 0.71	-
f_{fur}	=	Coefficient of fur surface or the ratio of fur surface area to skin surface, assumed to be 0.956	-
h_{c}	=	Convective heat transfer coefficient	$\mathrm{W/m^2K}$
H_{exhale}	=	Relative humidity of exhaled air, assumed to be 80	%
h_{fg}	=	Enthalpy of moist air at body temperature	kJ/kg K
H_{inhale}	=	Relative humidity of inhaled air	%
h_{m}	=	Convective mass transfer coefficient	m/s
h_{r}	=	Coefficient of radiant heat transfer ≈ 5.7	$\mathrm{W/m^2K}$
j	=	Total flux of water vapor	$\mathrm{Kmol/m^2s}$
j_{L}	=	Mass flux in the laminar boundary layer	$\mathrm{Kmol/m^2s}$
j_{T}	=	Mass flux in the turbulent layer	$\mathrm{Kmol/m^2s}$
k_{a}	=	Thermal conductivity of air, assumed to be 0.026	W/mK
k_{air}	=	Effective conductivity of air	W/mK
k_{f}	=	Thermal conductivity of fur layer, assumed to be 10 times of air	W/mK
k_{x}	=	Thermal conductivity of fur layer along the horizontal direction (parallel to skin surface)	W/mK
k_{y}	=	Thermal conductivity of fur layer along the vertical direction (perpendicular to skin surface)	W/mK
Nu	=	Nusselt number	-
P_0	=	Pressure of moist air at humid and ambient temperature	Pa
$P_{0\mathrm{s}}$	=	Pressure of moist air at ambient temperature	Pa
Pr	=	Prandtl number, assumed to be 0.70	
P_{s}	=	Pressure of moist air at skin temperature	Pa
P_{ss}	=	Pressure of moist air at surface skin temperature	Pa
Q_{c}	=	Convective heat loss from animal skin surface	W or kJ/time
Q_{evap}	=	Evaporative heat loss from the skin surface	W or kJ/time
Q_{Latent}	=	Latent heat loss	W or kJ/time
Q_{rad}	=	Radiant heat exchange between animal and its surrounding	W or kJ/time
$Q_{\mathrm{respiration}}$	=	Respiration heat loss	W or kJ/time

Q_{Sensible}	=	Sensible heat loss	W or kJ/time
Q_{Total}	=	Total heat loss from the animal	W or kJ/time
Q_{urine}	=	Urine heat loss	W or kJ/time
R	=	Gas constant, which is 8.3145×10^3	J/kg mol K
Re	=	Reynolds number	-
RH	=	Relative humidity	%
R_{sv}	=	Volume of air inhaled per breath, assumed to be 100	cc/breath
R_{tissue}	=	Heat resistance of tissue, assumed to be 0.0585	m^2K/W
Sc	=	Schmidt number	-
Sh	=	Sherwood number	-
St	=	Stanton number	-
T^*_{skin}	=	Estimation of the initial skin surface temperature	^{0}C or K
T_0	=	Temperature of air in the turbulent layer	^{0}C or K
t_{a}	=	Ambient air temperature	^{0}C
T_{a}	=	Ambient temperature	K
T_{body}	=	Average internal body temperature, assumed to be 38.7	^{0}C or K
T_{i}	=	Temperature of air at the interface of the laminar and turbulent boundary layers	^{0}C or K
T_{mrt}	=	Mean radiant temperature, assumed to be equal to the ambient temperature	^{0}C or K
t_{s}	=	Skin temperature	^{0}C
T_{skin} or T_{s}	=	Skin surface temperature	K
u	=	Air velocity	m/s
V_{urine}	=	Volume of urine discharged	l/h
W	=	Body weight of a cow, assumed to be 600	Kg
β	=	Percent of wet area of the skin surface	%
δ	=	Thickness of the laminar boundary layer	m
δ_1	=	Thickness of the hair coat, assumed to be 0.003	m
δ_2	=	Thickness of air layer beyond thickness of hair coat	m
ε	=	Radiant emissive coefficient of animal skin (non-dimensional) ≈ 0.97	-
ε_{s}	=	Area porosity of the hair coat	-

λ = Latent heat of vaporization of water at the skin surface temperature kJ/kg water

μ = Viscosity of fluid Pa s

v = Kinetic viscosity of air, assumed to be 16 x 10^{-6} m^2/s

ρ = Air density, assumed to be 1.2 kg/m^3

ρ_{air} = Density of air at body temperature, assumed to be 1.13 kg/m^3

ρ_h = Fur density, assumed to be 26 $hairs/mm^2$

ρ_{urine} = Density of urine at body temperature, assumed to be 1020 kg/m^3

τ_w = Shearing stress N/m^2

ABSTRAK

Dalam suasana yang panas dan lembap, lembu mengalami tekanan haba yang tenat yang mengakibatkan pengurangan dalam pengeluaran susu dan pertenakan yang tidak cekap. Secara umumnya, penurunan dalam penghasilan susu sebanyak 20% sehingga 30% berikutan dengan panas dan lembapan yang berterusan adalah lazim bagi penghasilan kelompok lembu tanpa kelengkapan pendinginan atau penyejukan. Oleh yang demikian, tujuan utama penyelidikan ini adalah mambangunkan satu simulasi model yang mengira pemindahan haba dan jirim daripada permukaan kulit dan bulu lapisan lembu yang dibasahkan. Tambahan pula, kehilangan haba melalui pernafasan dan air najis turut termasuk dalam model tersebut. Kombinasi model pemindahan haba dan jirim meramalkan kehilangan haba bagi penyejatan, perolahan, radiasi, pernafasan dan air najis berkenaan dengan perubahan dalam paras kelembapan kulit lembu (25, 50 and 75%), halaju udara (0.5, 1.0, 2.0 m/s), relatif kelembapan udara (20, 40, 80%), suhu udara persekitaraan (30, 35, 38^{0}C), kadar nafasan (40, 60, 80 nafas/min) and isipadu air najis yang dikeluarkan (0.5, 1.0, 1.5 l/j). Dalam model tersebut, angappan yang dibuat bagi lapisan bulu (bulu kulit lembu) seperti ketebalan dan kepadatan bulu adalah untuk keadaan musim panas. Ramalan ini dilaksanakan melalui penyelesaian dengan menggunakan perisian Matlab versi 6.5. Projek ini membincangkan secara terperinci kesan-kesan lima parameter atau factor (paras kelembapan kulit lembu, halaju udara, relatif kelembapan udara, suhu udara persekitaraan, kadar nafasan and isipadu air najis yang dikeluarkan) terhadap jenis kehilangan haba yang disebutkan di atas dengan berdasarkan nilai ramalan yang diperolehi. Graf dan jadual diwujudkan untuk menunjukkan hubungan antara kehilangan-kehilangan haba dan setiap parameter. Selain itu, cadangan-cadangan dan rekomen bagi kerja pada masa depan juga disertai di hujung tesis.

ABSTRACT

In hot and humid environments, cows suffer from several heat stress that causes reduction in milk production and breeding inefficiencies. Generally, drops in milk yield of 20% to 30% following hot, muggy stretches are not uncommon in high producing herds without supplemental cooling. Therefore, the main purpose of this study is to develop a simulation model that simultaneously calculates heat and mass transfer from a wetted skin surface and fur layer of a cow. In addition, respiration and urine heat losses are also included in the model. The model predicts evaporative, convective, radiant, respiration and urine heat losses with respect to the changes of levels of skin wetness (25, 50 and 75%), air velocity (0.5, 1.0, 2.0 m/s), relative air humidity (20, 40, 80%), ambient air temperature (30, 35, 38^{0}C), breathing rate (40, 60, 80 breaths/min) and volume of urine discharged (0.5, 1.0, 1.5 l/h). In the model, fur layer (hair coat) properties such as fur thickness and hair density assumed are that of summer condition. This prediction is done through the numerical solution by using the commercial Matlab software with version 6.5. This project discussed in detail about the effect of the five parameters or factors (levels of skin wetness, air velocity, relative air humidity, ambient air temperature, breathing rate and volume of urine discharged) on the types of heat losses as mentioned above based on the predicted values obtained. Graphs and tables of results are generated to show the relationship between the heat losses and each parameter. Besides that, the suggestions and recommendation for the future work are also included in the end of the thesis.

CHAPTER 1

INTRODUCTION

Milk production of dairy cattle is negatively affected by the heat stress caused by hot and humid environment. Dairy cows show heat stress by increased respiration rates, higher internal body temperature and reduced milk production.

1.1 Background

Gerald and Charles (1999) pointed out that the ideal ambient temperature for a dairy cow is between 41 and 77° F. At temperatures above 77° F, cows have to use energy to cool themselves through heat loss via surface skin and the respiratory tract. As ambient temperature increases, it becomes more difficult for a cow to cool herself adequately. High producing cows are the animals most sensitive to heat stress because of their high feed intake.

Besides that, dry matter intake starts to drop (8-12%) and milk production losses of 20-30%, which may exceed 10-25 lb./day, occur when temperatures exceed 90° F. It has been found that milk yield peaked at 9 lb. more milk per day by cooled than non-cooled cows. The cows generate the huge amount of heat. To reduce the heat, they need release the heat continually to prevent overheating and elevating their body temperature to unhealthy level.

There are few methods to get rid of the excessive heat that produced by cow's body as shown in Figure 1.1. Cattle shed heat primarily through evaporation from the skin and through respiration (breathing). As relative humidity increases, the effectiveness of evaporative heat loss diminishes.

In hot and humid subtropical regions, evaporative cooling always requires the use of forced ventilation, which is wetting the skin (evaporative cooling) and fur layer followed blowing air over it (convective cooling). As the moisture evaporates from the wet skin surface and fur layer, the surface moisture will take up much of the heat conducted through the skin. Through this, it will cool the skin and allows it to receive more body heat. The water vapor moves through the hair coat by diffusion under still-air conditions and by convection when air is blowing over the hair coat. Among the two, diffusion is a slower process while convection is a faster process. Through these two mechanisms, it allows moisture to continue evaporating from the wet skin surface and fur layer and taken up by the air surrounding the cows. Consequently, more and more moist air will be able to move through the hair coat. At the same time, radiant heat loss also occurs which involves the radiant heat exchange between the cow and it's surrounding when the thermal radiation emitted by the cow's skin surface as a result of its temperature changes.

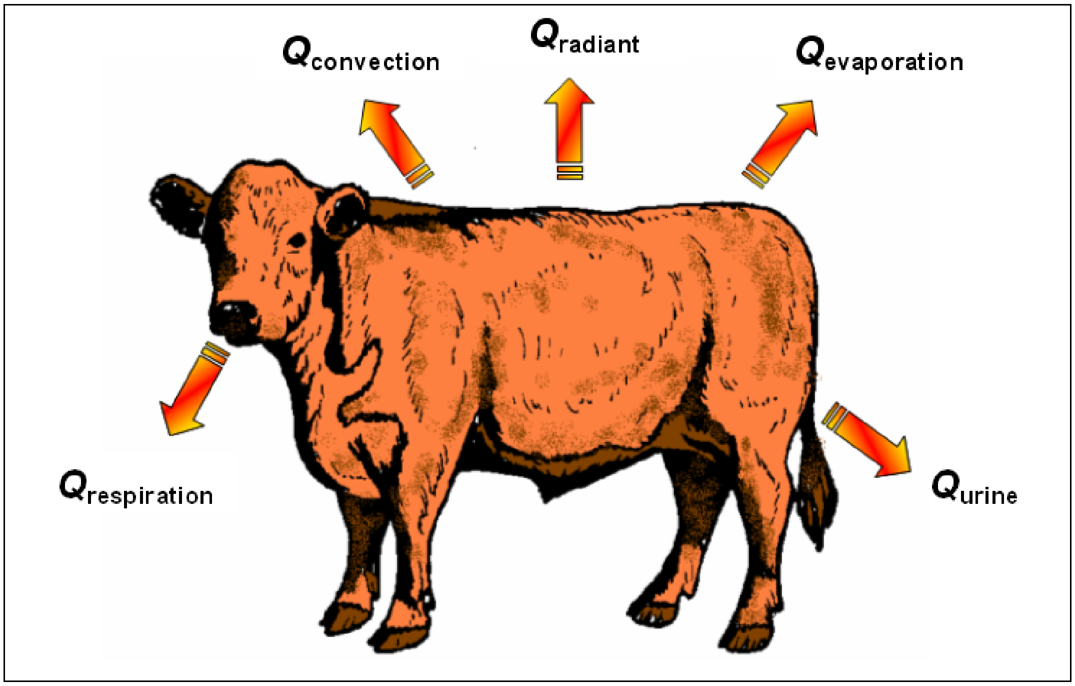


Fig 1.1 Five types of heat losses from dairy cattle

Another effective way that being employed by the cows to reduce the body heat is through panting. It is a respiration process by which heat is lost either by warming inhaled cold air (in cold environment) before being exhausted or by vaporization of moisture in the lungs (in warm environment) (Gebremedhin and Wu, 2001). Stowell pointed out that respiration rates of 80-90 breaths per minute are a clear indication that cows are experiencing heat stress (Gebremedhin and Wu, 2002). As ambient temperatures rise, the respiratory rate increases with panting progressing to open-mouth breathing. Consequently, cow breaths more as compare to when in normal condition. However, it is said that cows are lousy at panting and have about 25% heat loss through panting; the rest of the heat loss is through skin (Coblentz, 2000).

Like human being, animal also discharges urine and faeces. By doing so, the animal not only discharges wastes from its body, but in the mean time, it also looses heat through this way. The cow compensates by increasing urinary output of bicarbonate, and rumen buffering is affected by decreased salivary bicarbonate pool. Lameness, with sole ulcers and white line disease, will appear in a few weeks to a few months after the heat stress occurs (Gerald and Charles, 1999).

1.2 Heat and Mass Transfer

Heat and mass transfer seek not merely to explain how heat energy may be transferred, but also predict the rate at which the exchange will take place under certain specified conditions (Holman, 2001). In addition, it also predicts the amount of energy required to change from one equilibrium state to another.

When a mixture of gasses or liquids is contained such that there exists a concentration gradient of one or more of the constituents across the system, there will be a mass transfer as the result of diffusion from regions of high concentration to regions of low concentration (Holman, 2001). Mass transfer is different from heat transfer in that mass - water vapor is transported from one place to another in the flow system.

1.3 Objectives and Scope of Work

One of the objectives of this research is to develop a coupled heat and mass transfer model that simultaneously predicts the total heat loss, which consists of evaporative, convective, radiation, respiration, and urine heat losses from a cylinder that simulates a full-size dairy cattle under different environment and skin wetness conditions.

Using the model developed, a computer code program is developed using the commercial Matlab software with version 6.5 to solve the coupled heat and mass transfer model. Then, simulation and parametric studies on evaporative, convective, radiation, respiration and urine heat losses from dairy cattle will be carried out for changes in: ambient air temperature, relative humidity, air velocity, and level of wetness of skin surface and fur layer.

Nevertheless, it is important to remember that the simulated results are not experimentally validated.

CHAPTER 2

LITERATURE REVIEW

Hot environments affect the performance of dairy cattle both directly and indirectly. Therefore, careful management that can alleviate heat stress is needed. In Japan, fans are the most common type of cooling device being used. Fans were used by 98% of farmers in the Kyushu area in the southern part of Japan, with an average of 5 (2-8) cows per fan, while some farmers prefer to use sprinklers, installed on the roof or at various places in the barn (Kurihara and Shioya, 2003).

Sprinkling water onto the hair coat and skin surface of cows and promoting its rapid evaporation is a common and effective way of cooling the animals especially in hot and dry environment (Garner et al., 1989). Sprinkling method uses a large droplet size to wet the hair coat to the skin of the cow, and then water evaporates and cools the hair and skin. Sprinklers without fans, or fans without sprinklers, will not give an effective cooling system. Sprinkler and fan offer promise as means of reducing heat stress in cows (Turner et al., 1992). Blowing air over cows greatly enhances the rate of evaporation and quickly removes evaporated moisture from the cow. Consequently, the temperature of the skin and deep body decreased thereby reducing heat stress. Therefore, the effective cooling using sprinkling systems are to make sure cows are soaked to the skin and good airflow is provided.

Many studies have been conducted on heat transfer through dry fur, but only a few researchers have quantified heat transfer through wet hair coat. Cena and Monteith (1975) analyzed water vapor diffusion through the hair coat by applying the modified Lewis number. It was done by considering a thin film of water on the skin surface, and ignoring the interaction between sensible heat (convection and radiation heat) and mass transfer across the wet hair coat. It is found out that greater rates of heat transfer in coats can account for by radiative transfer between hairs, or free convection induced by temperature gradients.

Arkin et al. (1991) experimentally determined heat and mass transfer properties of dry and wet furs layers of dairy cows. The skin was stretched over a heat flux assembly, inserted into a wind tunnel, and heat and mass transfer were examined at different air velocities with fur either dry or wet. The dry coat was divided into two layers - the fur and the boundary layer. The thermal resistance of the fur itself hardly changed with air velocity, while the resistance to heat transfer of the coat boundary layer was found to be proportional to the square root of air velocity. For the wet fur, the efficiency of forced evaporative cooling was determined by a single parameter of 'wettedness', which equaled unity for a saturated fur and decreased, as the coat got drier. Experiments were performed to measure the relationship between the wettedness and the amount of water sprinkled over the fur. The maximum water content of a coat wet by means of a commercially available sprinkler was some 230 g/m^2, which corresponded to wettedness of 0.6. The results of this investigation may be used to design the most cost effective procedure of forced evaporative cooling for the relief of heat stress in cattle.

Not long after that, Kimmel together with Arkin and Bernam developed a theoretical model that presents simultaneous transfer of heat and mass in a wet animal fur when an animal is cooled by blowing air over its wetted hair coat (Gebremedhin and Wu, 2001). In this model, evaporation of water at any distance from the skin to the fur-air interface is being considered. The dissipation of heat conduced through the skin in the case of forced evaporation is made possible by the continuous exchange between sensible and latent fluxes throughout the entire depth of the wet fur.

Coblentz (2000) reported that Dr. Scott Willard recently joined forces with visiting scientist Peter Hillman, environmental physiologist at Cornell University, to study heat stress in daily cows. In the experiment, Hillman tested three cows with various combinations of wind speed and how often they were wetted. The cows’ internal temperature, respiration rate, evaporation rate from the skin and the relative humidity of the air are being measured and analyzed. The results were then compared to one cow that was not cooled. Hillman's test system got the cows' hides wet, then blew them dry with a fan. This was repeated several times, drawing down the cows' internal temperature 1 to 1.5 degrees in an hour. The result concluded that wetting the cows was an effective mechanism for decreasing body temperature. When the skin surface and hair coat were wetted, evaporative heat loss accounted for more than 82% of the total heat flux. But when not wetted, heat loss by convection was dominant at high air velocities.

Gebremedhin and Wu (2002) presented a simulation model that simultaneously calculated heat and mass transfer from a wetted skin surface and fur layer of a cow. In the model, evaporative, convective and radiant heat losses are predicted with respect of different levels of skin and fur wetness, air velocity, air temperature and relative humidity. They assumed that fur layer (hair coat) properties such as fur thickness and hair density are that of summer conditions. The simulation model showed that evaporative cooling from wet-skin surface and hair coat is the dominant mode of heat mitigation mechanism in stressful hot environments and is further enhanced by increased air velocity. Nevertheless, due to the deficit of water vapor concentration between the skin surface and ambient air, evaporative cooling is depressed by increased relative humidity.

CHAPTER 3

METHODOLOGY

3.1 Mathematical Development and Model Formulation

Numerical simulations were performed to predict sensible and latent heat losses based on the flow field surrounding the cow. It is indeed difficult to develop a complete and couple heat and mass transfer model that describes the sensible and latent heat losses from the skin surface because of changing physiological responses and ambient conditions. To do so, certain assumptions are made and they are listed below.

3.1.1 Specific assumptions

(1) The coupled heat and mass transfer being considered is in one-dimension.
(2) The geometry of the simulated animal is represented by a cylinder.
(3) The skin surface is considered to be a black body.
(4) Heat and mass transfer is assumed to be steady state.
(5) Air movement within the hair coat is assumed to be laminar flow.
(6) The internal body temperature is assumed to be constant.
(7) The mean radiant temperature is assumed to be equal to the indoor wall temperatures.
(8) Mass diffusion coefficient of water vapor is assumed to be constant.
(9) Laminar boundary layer includes the fur layer and a thin film of air layer above the hair coat. In this layer, only conduction (heat) and diffusion (mass) are considered.
(10) Only convective heat and mass transfer are considered in the turbulent boundary layer.

3.1.2 Definition of the boundary layer

The definition of the boundary layers is given in Figure 3.1. In this analysis, the animal is represented as a cylinder with an internal heat source. The flow field between the animal and the environment is divided into two boundary layers – laminar and turbulent boundary layer.

The laminar boundary layer (δ) consists of the thickness of the fur layer (δ_1) and a thin film of air layer above it (δ_2). The fur layer consists of a matrix of thin fibers (hairs) surrounded by saturated air. The thickness of the hair coat is equal to the hair length.

The laminar boundary layer (δ) is dependent upon air velocity. If, for example, the calculated $\delta \leq \delta_1$, then $\delta_2 = 0$. This means that no laminar boundary air layer exists above the hair coat. If, however, the calculated $\delta > \delta_1$, then $\delta_2 = \delta - \delta_1$. This means that there exists a thin laminar boundary air layer above the thickness of the hair coat. As for the convective turbulent boundary layer, it exists within the depth of the hair coat only when the Reynolds number is greater than or equal to 1.5×10^5.

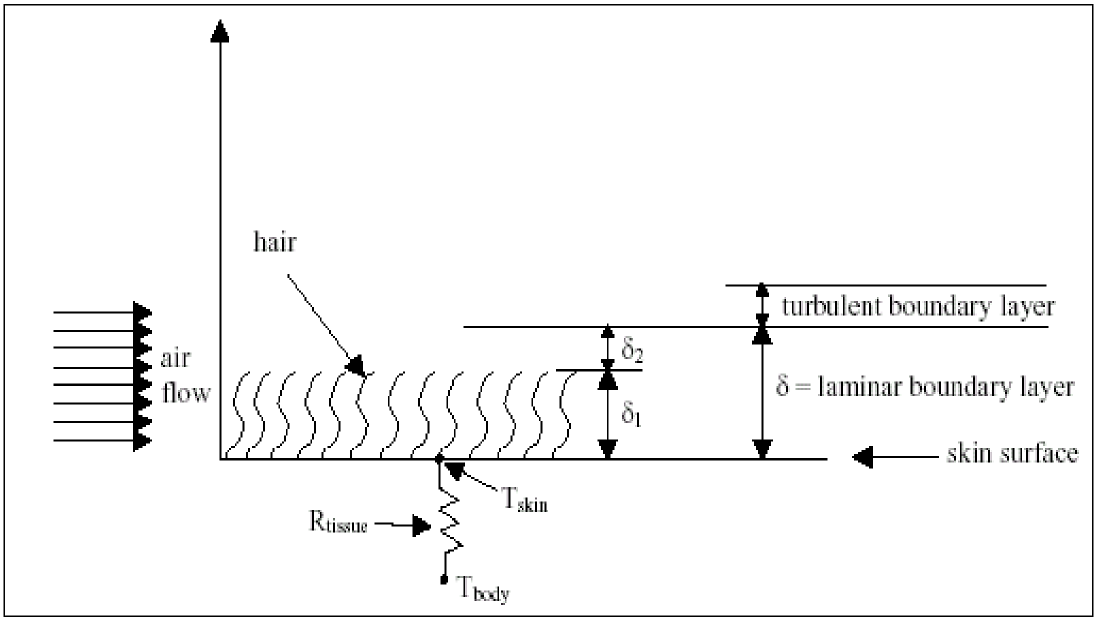


Fig 3.1: Definition of laminar and turbulent boundary layers within the fur layer. (Gebremedhin and Wu, 2001)

According to Newton's law of internal friction, the shearing stress (τ_w) that occurs in the δ_1 segment of the laminar boundary layer can be calculated as

$$\tau_w = \mu \frac{du}{dy} \tag{1}$$

The shearing stress (τ_w) for airflow across a cylinder at a velocity of u is expressed as

$$\tau_{\mathrm{w}} = \mu \frac{u}{\delta_2} \tag{2}$$

As air flows across a cylinder, the friction drag (F_{D}) can be calculated as

$$F_{\mathrm{D}} = \frac{1}{2} C_{\mathrm{f}} \rho u^2 A_{\mathrm{f}} \tag{3}$$

In terms of the friction drag, the shearing stress (τ_w) can also be defined as

$$\tau_{\mathrm{w}} = \frac{F_{\mathrm{D}}}{A_{\mathrm{f}}} \tag{4}$$

Substituting equation (3) into equation (4) yields

$$\tau_{\mathrm{w}} = \frac{1}{2} C_{\mathrm{f}} \rho u^2 \tag{5}$$

The thickness of the laminar boundary layer above the hair coat (δ_2) can be obtained by combining equations (2) and (5), and yields,

$$\delta_2 = \frac{2\mu}{\rho u \ C_{\mathrm{f}}} = \frac{2\nu}{u \ C_{\mathrm{f}}} \tag{6}$$

According to Colburn analogy (the relation between fluid friction and heat exchange), the drag force coefficient (C_{f}) can be calculated as

$$C_{\mathrm{f}} = 2St(Sc)^{2/3} \tag{7}$$

The Stanton Number is calculated as

$$St = \frac{Sh}{\mathrm{Re}\, Sc} = \frac{h_m}{u} \tag{8}$$

Substituting equation (8) into equation (7) yields

$$C_f = 2 \frac{h_m}{u} (Sc)^{2/3} \tag{9}$$

By substituting equation (9) into equation (6), δ_2 can be obtained.

3.1.3 Determination of effective thermal conductivity of fur layer, k$_{\text{eff}}$

By using standard series-parallel thermal circuit techniques, Kowalski and Mitchell determined the thermal conductivities of the fur layer along the parallel and perpendicular direction. Their determination was based on the effective fiber density of artificial fibers. The same technique was applied herein except the density of the hair coat was obtained from actual cow pelt (Gebremedhin and Wu, 2001).

The thermal conductivity of fur layer along the horizontal direction or parallel to the skin surface (k_{x}) is calculated as

$$k_x = \frac{A_f}{A_t} k_f + (1 - \frac{A_f}{A_t}) k_a \,, \tag{10}$$

where

$$\frac{A_f}{A_t} = \rho_h \frac{\pi d_h^2}{4} \tag{11}$$

The thermal conductivity of the hair coat along the vertical direction or perpendicular to the skin surface is calculated as

$$k_{\mathrm{y}} = \frac{k_{\mathrm{a}}(l_{\mathrm{c}} - d_{\mathrm{h}})}{l_{\mathrm{c}}} + \frac{d_{\mathrm{h}} k_{\mathrm{a}} k_{\mathrm{f}}}{d_{\mathrm{h}} k_{\mathrm{a}} + (l_{\mathrm{c}} - d_{\mathrm{h}}) k_{\mathrm{f}}} \,, \tag{12}$$

where

$$l_{\mathrm{c}} = 1 / \sqrt{\rho_{\mathrm{h}}} \tag{13}$$

The mean effective thermal conductivity (k_{eff}) of the fur layer normal to the skin surface is calculated as the average of the thermal conductivities along the vertical and horizontal directions of the fur layer, which is expressed as

$$k_{\mathrm{eff}} = 0.5(k_x + k_y) \tag{14}$$

3.1.4 Modeling heat transfer through the fur layer

Based on Fourier's law, the conduction heat flux ($q_{\mathrm{L}}^{"}$) within the laminar boundary layer can be calculated as

$$q_{\mathrm{L}}^{"}=\frac{T_{\mathrm{skin}}-T_{\mathrm{i}}}{\delta_1/k_{\mathrm{eff}}+\delta_2/k_{\mathrm{air}}} \tag{15}$$

According to the law of conservation of energy, the heat flux from the skin surface to the hair coat is equal to the heat transfer from the laminar boundary layer into the turbulent boundary layer, and is expressed as

$$q_{\mathrm{T}}^{"}=h_{\mathrm{c}}(T_{\mathrm{i}}-T_0) \tag{16}$$

The convective heat transfer coefficient, h_c, can be obtained from the Nusselt Number (Nu) as

$$Nu=\frac{h_{\mathrm{c}}d}{k_{\mathrm{eff}}}=\left\{\begin{array}{ll}(0.43+0.50\,\mathrm{Re}^{0.5})\,\mathrm{Pr}^{0.38} & \text{for}\,1<\mathrm{Re}<10^3,\\ 0.25\,\mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.38} & \text{for}\,10^3<\mathrm{Re}<2\times10^5\end{array}\right. \tag{17}$$

However, the convective heat transfer must be corrected for area porosity of the hair coat and is expressed as

$$\bar{h}_{\mathrm{c}}=\varepsilon_{\mathrm{s}}Nu\frac{k_{eff}}{d}, \tag{18}$$

where area porosity (ε_{s}) is calculated as

$$\varepsilon_{\mathrm{s}}=(1-A_{\mathrm{f}}/A_{\mathrm{t}}) \tag{19}$$

The convective heat flux ($q_{\mathrm{c}}^{"}$) can be calculated by combining equations (6), (15) and (16), and yields

$$q_{\mathrm{c}}^{"}=(T_{\mathrm{skin}}-T_0)\Big/\left(\frac{1}{h_{\mathrm{c}}}+\frac{\delta_1}{k_{\mathrm{eff}}}+\frac{\delta_2}{k_{\mathrm{air}}}\right) \tag{20}$$

where $q_{\mathrm{c}}^{"}=q_{\mathrm{L}}^{"}=q_{\mathrm{T}}^{"}$, $T_0=T_a$

Using Brody's formula, the surface area of a cow (A_s) can be estimated from its body weight as

$$A_{\mathrm{s}}=0.15\,W^{0.56} \tag{21}$$

The convective heat loss from the animal skin surface (Q_{conv}) can then be calculated as

$$\begin{aligned} Q_{\mathrm{conv}} &= q_{\mathrm{c}}^{''} A_{\mathrm{s}} \\ &= A_{\mathrm{s}} (T_{\mathrm{skin}} - T_0) \Big/ \left(\frac{1}{h_{\mathrm{c}}} + \frac{\delta_1}{k_{\mathrm{eff}}} + \frac{\delta_2}{k_{\mathrm{air}}}\right) \end{aligned} \tag{22}$$

The radiant heat flux ($q_{\mathrm{r}}^{''}$) can be expressed by linear temperature difference as

$$q_{\mathrm{r}}^{''} = \varepsilon\, f_{\mathrm{fur}} f_{\mathrm{eff}} h_{\mathrm{r}} (T_{\mathrm{skin}} - T_{\mathrm{mrt}}), \tag{23}$$

where $T_{\mathrm{mrt}} = T_{\mathrm{a}}$

The radiant heat exchange between an animal and its surrounding can be calculated as

$$\begin{aligned} Q_{\mathrm{rad}} &= q_{\mathrm{r}}^{''} A_{\mathrm{s}} \\ &= A_{\mathrm{s}} \varepsilon\, f_{\mathrm{fur}} f_{\mathrm{eff}} h_{\mathrm{r}} (T_{\mathrm{skin}} - T_{\mathrm{mrt}}) \end{aligned} \tag{24}$$

The heat loss through the urine discharged from the animal can be calculated as

$$Q_{\mathrm{urine}} = V_{\mathrm{urine}} \rho_{\mathrm{urine}} C_{p\,\mathrm{urine}} (T_{\mathrm{body}} - T\ ) \big/ 3600 \tag{25}$$

The sensible heat loss is then calculated as the sum of the convective, radiant and urine heat losses.

$$Q_{\mathrm{Sensible}} = Q_{\mathrm{conv}} + Q_{\mathrm{rad}} + Q_{\mathrm{urine}} \tag{26}$$

3.1.5 Modeling mass transfer through the fur layer

According to Fick's law, the mass flux (j_{L}) of water vapor that evaporates from the skin surface can be calculated as

$$j_{\mathrm{L}} = \frac{D}{\delta} (C_{\mathrm{skin}} - C_{\mathrm{i}}) \tag{27}$$

According to the law of conservation of mass, the mass flux that transfers from the skin surface to the hair coat is equal to the mass transferred from the laminar boundary layer to the turbulent layer, and is expressed as

$$j_{\mathrm{T}} = h_{\mathrm{m}} (C_{\mathrm{i}} - C_0) \tag{28}$$

The mass diffusive coefficient of water vapor (D) can be calculated as

$$D = 1.87 \times 10^{-10} [(T_{\mathrm{a}} + T_{\mathrm{s}})/2]^{2.072} \tag{29}$$

According to dimensional analysis of fluid flow correlation, the mass transfer coefficient (h_{m}) can be obtained from Sherwood number (Sh) as

$$Sh = \frac{h_{\mathrm{m}} d}{D} = 0.28\,\mathrm{Re}^{0.6}\, Sc^{0.44} \tag{30}$$

Then, h_{m} can be calculated as

$$h_{\mathrm{m}} = \frac{D}{d} 0.28\,\mathrm{Re}^{0.6}\, Sc^{0.44} \tag{31}$$

where the Reynolds number (Re) is calculated as

$$\mathrm{Re} = u_0 d/\nu\,, \tag{32}$$

and the Schmidt number (Sc) is calculated as

$$Sc = \nu/D \tag{33}$$

The total mass flux of water vapor that evaporates from the skin surface can be obtained by combining equations (6), (27) and (28), and yields

$$j = (C_{\mathrm{skin}} - C_0) \Big/ \left(\frac{1}{h_{\mathrm{m}}} + \frac{\delta_1 + \delta_2}{D}\right) \tag{34}$$

where $j = j_{\mathrm{L}} = j_{\mathrm{T}}$.

The concentration of water vapor in the turbulent (C_0) and the concentration of water vapor on the skin surface (C_{skin}) are determined using following formulas:

$$C_{skin} = \frac{P_s}{R \times T_s}\,, \tag{35}$$

$$C_0 = \frac{P_0}{R \times T_a}\,, \tag{36}$$

where $P_s = P_{ss} = 610.78 \times e^{\frac{t_s \times 17.2694}{(t_s + 238.3)}}$, $P_0 = RH \times P_{0s}$, and $P_{0s} = 610.78 \times e^{\frac{t_a \times 17.2694}{(t_a + 238.3)}}$

The evaporative heat loss (Q_{evap}) from the skin surface of a cow can then be calculated as

$$Q_{\text{evap}} = \lambda\, j\, \beta\, A_{\text{s}} \times 18000 \tag{37}$$

with latent heat of vaporization of water at the skin surface (λ) can be obtained from Table A-1 as shown in Appendix A.

The respiration heat loss from the animal depends upon the breathing rate and is calculated as

$$Q_{\text{resp}} = \frac{B_r}{60}[R_{SV}\,\rho_{\text{air}}C_{p\,\text{air}}(T_{\text{body}} - T_{\text{a}}) + R_{SV}\,\rho_{\text{air}}(H_{\text{exhale}} - H_{\text{inhale}})h_{\text{fg}}] \tag{38}$$

The latent heat loss is then calculated as the sum of evaporative and respiration heat losses, expressed below:

$$Q_{\text{Latent}} = Q_{\text{evap}} + Q_{\text{resp}} \tag{39}$$

3.2 Simulation Procedure

The total heat exchange (Q_{Total}) between the animal and its surrounding is the sum of sensible and latent heat losses, expressed as

$$Q_{\text{Total}} = Q_{\text{Sensible}} + Q_{\text{Latent}} \tag{40}$$

The skin temperature is calculated from

$$Q_{\text{Total}} = A_{\text{s}}(T_{\text{body}} - T_{\text{skin}}) / R_{\text{tissue}} \tag{41}$$

Solving for T_{skin} yields

$$T_{\text{skin}} = T_{\text{body}} - \frac{Q_{\text{Total}} R_{\text{tissue}}}{A_{\text{s}}} \tag{42}$$

Since the heat and mass transfer are coupled, heat fluxes, mass flux and skin temperature must be solved by iteration. The general steps needed to solve the coupled heat and mass transfer model are listed below.

3.2.1 General description for solving the coupled heat and mass transfer model

The following is the sequences for solving the coupled heat and mass transfer model:

(1) Estimate an initial skin temperature (T^{*}_{skin}).

(2) Solve equations (10)-(14) to obtain the mean effective thermal conductivity (k_{eff}).

(3) Calculate surface area, A_{s} from equation (21).

(4) Calculate the mass diffusive coefficient of water vapor, D, from equation (29).

(5) Calculate Reynolds Number, Re, from equations (32).

(6) Calculate Schmidt Number, Sc, from equation (33).

(7) Solve equations (17), (18) and (19) to obtain the convective heat transfer coefficient (h_{c}).

(8) Solve equation (31) to obtain the convective mass transfer coefficient (h_{m}).

(9) Solve equations (6) – (9) to obtain the thickness of the thin film of air above the fur layer (δ_2).

(10) Solve equation (20) to obtain the convective heat flux (q''_{c}).

(11) Solve equation (23) to obtain the radiant heat flux (q''_{r}).

(12) Solve equations (22), (24), (25) and (26) to obtain the convective (Q_{conv}), radiant (Q_{rad}), urine (Q_{urine}) and total sensible (Q_{Sensible}) heat flows, respectively.

(13) Solve equations (35) and (36) to obtain the total mass flux of water vapor (j) from equation (34).

(14) Solve equations (37), (38) and (39) to obtain the evaporative (Q_{evap}), respiration (Q_{resp}), and total latent (Q_{Latent}) heat flows, respectively.

(15) Solve equation (40) to obtain the total heat loss (Q_{Total}).

(16) Solve equation (42) to obtain the temperature of the skin surface (T_{skin}).

(17) Substitute the skin surface temperature from Step (16) for the initially assumed skin surface temperature (T^{*}_{skin}) and go back to Step (2) and repeat the subsequent steps until convergence.

3.2.2 Program for solving the coupled heat and mass transfer model by iteration

Based on the theoretical model developed, a computer program is written in Matlab language using the commercial Matlab software with version 6.5 to solve the coupled heat and mass transfer model.

Matlab is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solution are expressed in familiar mathematical notation. The name Matlab stands for matrix laboratory. Matlab offers programming features similar to those of other computer programming language. Files that contain code in the Matlab language are called M-files. M-files are created using text editor, then use them as any other Matlab function or command.

There are two kinds of M-files: scripts and functions. In this project, scripts are chosen as they are the simplest kind of M-file, suitable and they have no input and output arguments. They are useful for automating series of Matlab commands, such as computations that have to perform repeatedly from command line. Scripts operate on existing data in the workspace, or they can create new data on which to operate.

After the program for solving the coupled heat and mass transfer model is written in M-file in the form of script, the written program is being executed and debugged to check for errors if any. The corrected program is then *run* to collect the corresponding results. The Matlab program written can be shown in Appendix B and the sample of result obtained from the simulation can be shown in Appendix C.

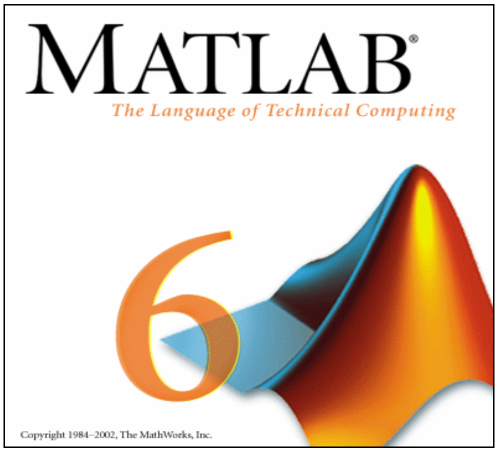


Fig 3.2: Matlab 6.5

The Figure 3.3 in the following page shows a flow chart that is generated to summarize the sequence of the written Matlab program when it is being executed.

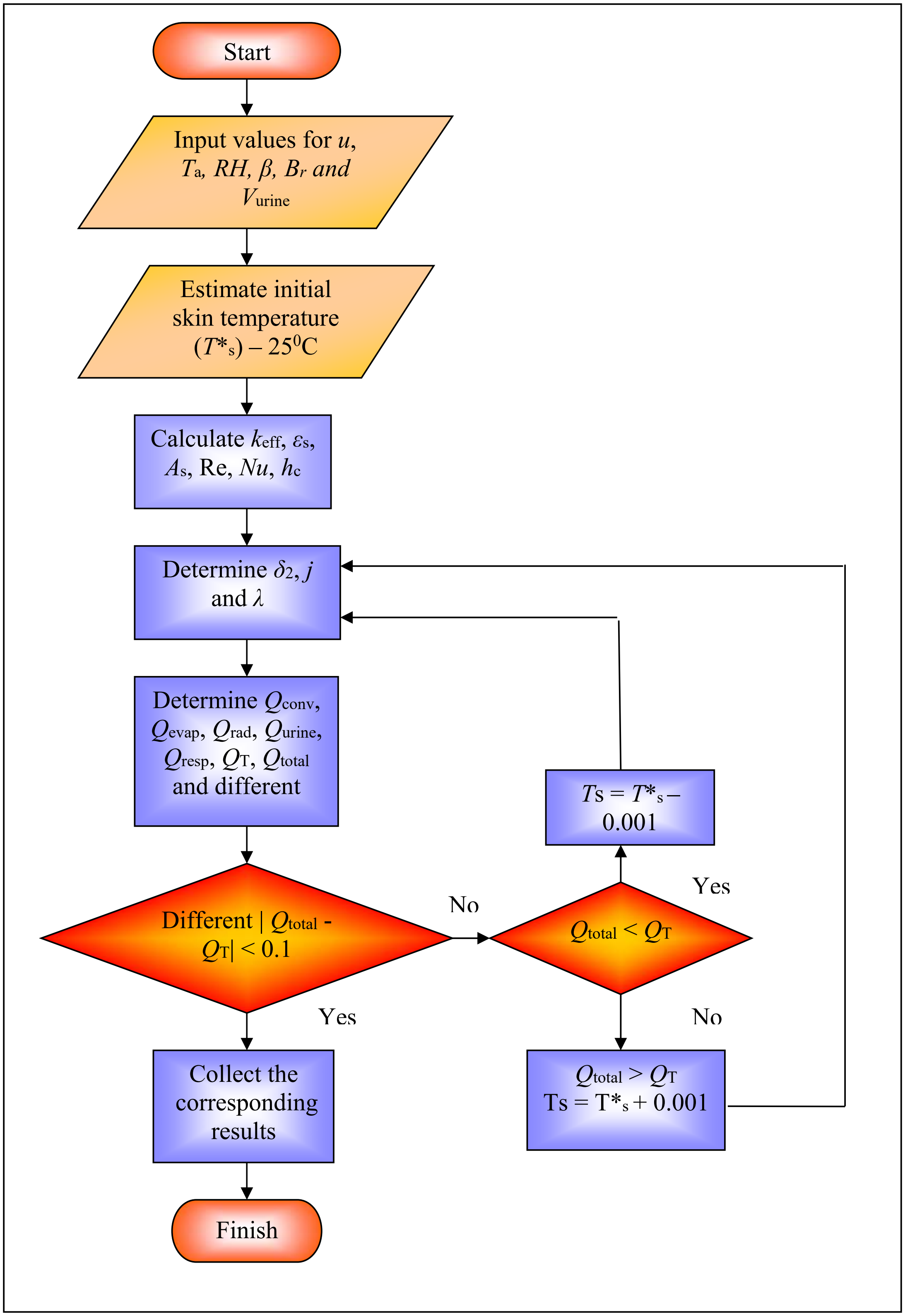
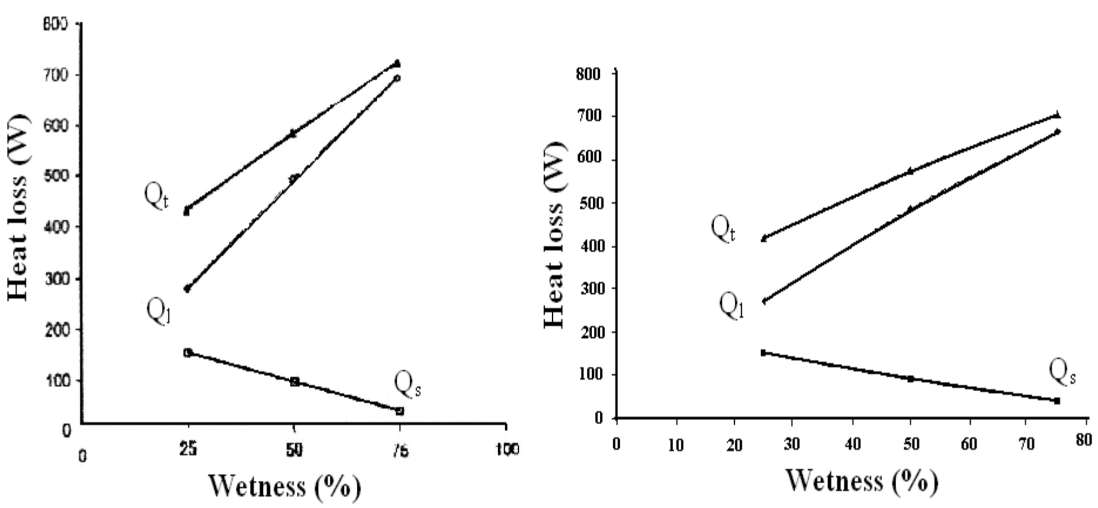


Fig 3.3: Flow chart summarized the sequence of Matlab program written

CHAPTER 4

RESULTS AND DISCUSSION

The verification of the program developed cannot be done because this is a totally new project and there is no any similar literature result that can be used for verification. However, verification for the program that consist of radiant, convective and evaporative heat losses have been made by comparing the results that obtained from Matlab and the literature results (refer to Gebremedhin & Wu, 2002). The comparison shows that the simulated result from Matlab is agreed well with the literature result where the graphs that have been plotted from the simulated result have the similar trend with the literature result (refer to Gebremedhin & Wu, 2002). The samples of the results obtained can be shown in the figures below. As a result, due to the confidence gained, this program is continue to be used to obtained the results for this project by adding another two heat losses, which is respiration and urine heat losses.



(a) (b)

Fig 4.1: Simulated (a) result obtained from literature (b) result obtained from Matlab, latent (Q_l), sensible (Q_s), and total (Q_t) heat losses as a function of percent of wetness (fixed parameters are: 1.0 m/s air velocity, 30°C ambient temperature, 20%relative humidity, 26 hairs/mm^2 hair density, 3 mm fur depth and 38.7°C internal body temperature)

The simulated results are based on the changes in: level of wetness, air velocity, relative humidity, ambient air temperature, breathing rate and volume of urine discharged. In order to study the effect and relationship of these five factors respectively on heat losses, the heat losses are predicted by varying one of the factors (parameters) and the rest of the factors are fixed. For instance, if the level of wetness is the factor to be studied, this factor is then varied within the range considered whereas the rest of the five factors or parameters mentioned above are kept constant throughout the simulation.

In addition, the following factors are also kept constant in all the relationships discussed below. The hair properties, fur depth and hair density are selected to represent summer condition.

- Internal body temperature = 38.7^0C,
- Fur depth = 3mm, and
- Hair density = 26 hairs/mm^2.

The collected results from the simulation process are recorded in the form of tables as shown in the following pages. Then using the results from the table, graphs are plotted to show the relationship of sensible, latent and total heat losses with respect to each of the six factors mentioned above.

There are five tables and six graphs generated all together. Based on that tables and graphs, the effect of each of these six factors on radiant, evaporative, convective, respiration, urine heat losses, sensible, latent and total heat losses is discussed in detailed in the following pages.

4.1 Effect of Level of Wetness, *β*

Wetness represents the percent of skin surface that is being wetted. For instance, 50% wetness means that half of the skin surface area of the animal is wet and the other half is considered to be dry where no evaporation is taking place.

The effect of level of wetness on sensible and latent heat losses is shown in Figure 4.2. The heat losses are predicted for three levels of wetness that is 25%, 50% and 75%. The predictions are at 30^0C ambient air temperature, 2.0 m/s air velocity, 20% relative humidity, 38 breaths/min breathing rate and 1.0 l/h urine discharged. These conditions are meant to simulate hot and dry environment.

As shown, latent heat loss increases with increased level of wetness. The response is non-linear even though the points in the figure are connected by straight line. At the same time, sensible heat loss decreases linearly as the level of wetness increased. From the results shown in Table 4.1, it is evident that latent heat loss increases because of the significant increase in evaporative heat loss. When the level of wetness increases from 25% to 50%, evaporative heat loss increased by 75%. It increases but at a lower rate of 34.3% as the level of wetness further increased from 50% to 75%. Evaporative cooling was enhanced when air velocity increased along with the increasing of level of wetness.

Both convective and radiant heat losses are influenced by temperature difference (ΔT) between the skin and ambient air. Cooling the skin surface decreases skin temperature as shown in Table 4.1. As a result, ΔT drops which causes decrease in convective and radiant heat losses. Consequently, sensible heat loss decreases.

When the skin temperature is lower than the assumed ambient temperature, the sensible heat is gained instead of losing, leading to the negative value as shown in Figure 4.2 and Table 4.1. Respiration and urine heat losses remain constant and unchanged throughout the way even though with the increasing of level of wetness. This is because the level of wetness does not influence them.

The increase rate of latent heat loss is greater than the decrease rate of sensible heat loss, therefore the total heat loss increased as shown in Figure 4.2.

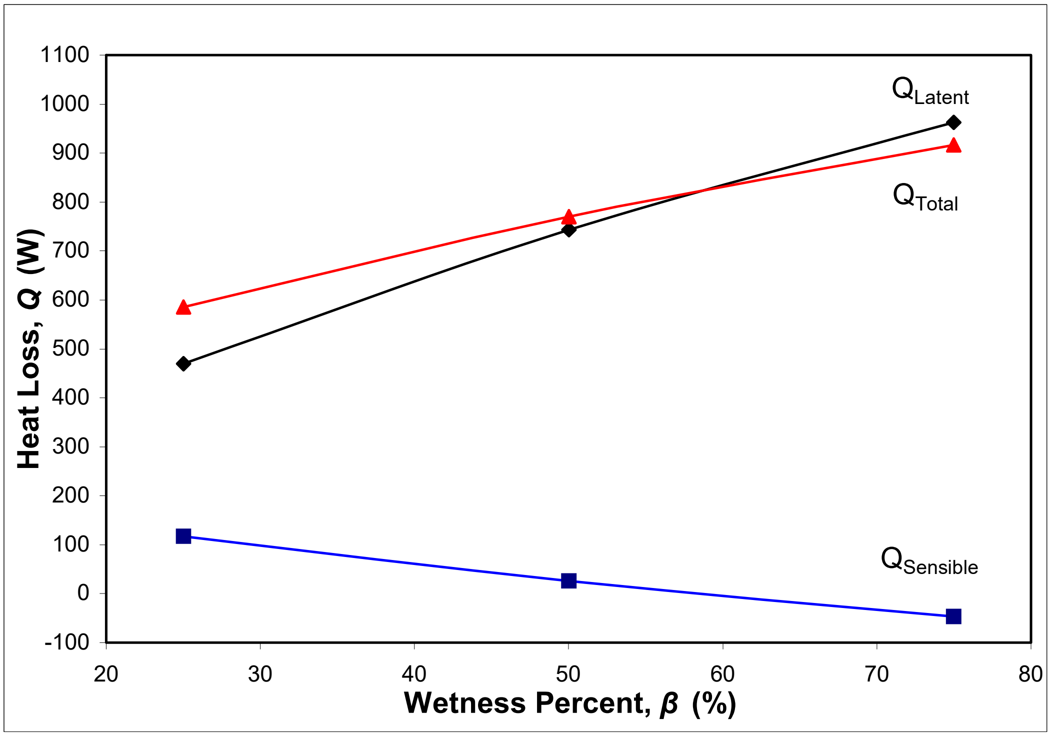


Fig 4.2: Simulated latent (Q_{Latent}), sensible ($Q_{Sensible}$), and total (Q_{Total}) heat losses as a function of percent wetness (fixed parameters are: 30^0C ambient temperature, 2.0 m/s air velocity, 20% relative humidity, 38 breaths/min breathing rate, 1.0 l/h urine discharged, 26 hairs/mm^2 hair density, 3 mm fur depth and 38.7^0C internal body temperature)

Table 4.1: Skin temperature, radiant, convective, evaporative, urine, respiration, latent, sensible and total heat losses variation as a function of air velocity and level of wetness

Wetness Percent β (%)	Air Velocity U (m/s)	Skin Temperature T_s (^{0}C)	$Q_{Radiant}$ (W)	$Q_{Convection}$ (W)	$Q_{Evaporative}$ (W)	Q_{Urine} (W)	$Q_{Respiration}$ (W)	Q_{Latent} (W)	$Q_{Sensible}$ (W)	Q_{Total} (W)
25	0.5	34.15	83.94	43.01	178.95	10.35	103.49	282.43	137.30	419.74
	1.0	33.35	67.81	53.82	257.74	10.35	103.49	361.22	131.98	493.21
	2.0	32.34	47.40	59.00	365.84	10.35	103.49	469.33	116.75	586.08
50	0.5	32.91	58.94	30.21	330.58	10.35	103.49	434.06	99.50	533.57
	1.0	31.74	35.32	28.04	464.06	10.35	103.49	567.54	73.72	641.26
	2.0	30.35	7.06	8.80	640.26	10.35	103.49	743.75	26.21	769.96
75	0.5	31.84	37.26	19.10	462.18	10.35	103.49	565.67	66.72	632.39
	1.0	30.41	8.22	6.53	636.09	10.35	103.49	739.58	25.10	764.68
	2.0	28.75	-25.22	-31.41	859.68	10.35	103.49	963.17	-46.28	916.89

* The above simulation are based on: 30^{0}C ambient temperature, 20% relative humidity, 38 breath/min breathing rate, 1.0 l/h urine discharged, 26 hairs/mm^2 hair density, 3 mm fur depth and 38.7^{0}C internal body temperature