

The Effect of a Cooler on the Rate of Heat Loss from a Horse Post-Exercise

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Executive Summary:

Coolers are large wool blankets put on horses after exercising or bathing during cold weather. They are intended to allow moisture to travel away from the body of the horse while providing an insulating layer to help stabilize their body temperature and to prevent them from getting a chill. We tested the effectiveness of these wool coolers by comparing the rate of heat loss from a horse's skin with and without the added wool layer. Using the modeling software of FIDAP we were able to simulate the coupled processes of heat transfer from the horse's skin and sweat evaporation.

The model was run in FIDAP after determining an optimized mesh size and time step, which allowed accurate finite element modeling but maintained a reasonable run time. The model shows that the wool helps maintain a constant body temperature post exercise by providing an insulating layer.

Since accurate diffusivity and conductivity values for wool and hair were hard to find, a sensitivity analysis was performed to determine the effect of an error on the temperature and mass profiles. After varying the diffusivities by one order of magnitude and the conductivities by 10%, the model determined that errors in these variables have little to no effect on horse body temperature approximations after one half hour.

Introduction and Design Objectives:

Background and Importance of the Problem

Horses require consistent exercise to remain in good physical condition throughout the year. In areas such as Ithaca, the cold weather requires that much of the year will be spent in an indoor arena. Indoor facilities are generally warmer than the outside environment. Some, including Cornell University's Oxley Equestrian Center, are heated, and others remain warmer due to heat generated by metabolic activity in attached stabling areas. Like many other animals, horses develop a winter coat, or layer of longer and thicker hair, during the cold months. This thicker coat combined with the effects of exercise in a warm indoor arena can lead to large amounts of perspiration. It is important that horses are carefully and slowly cooled down to resting temperature after exercise. For a sweat-lathered horse a caretaker must be sure that they are completely dry before putting them back into their stalls. A damp horse can easily catch a chill leading to increased susceptibility for illness and discomfort. A wool blanket, commonly called a cooler, is frequently used to stabilize the temperature of a horse while allowing moisture to travel away from their body. Coolers are typically left on a horse for a half an hour.

Problem Definition

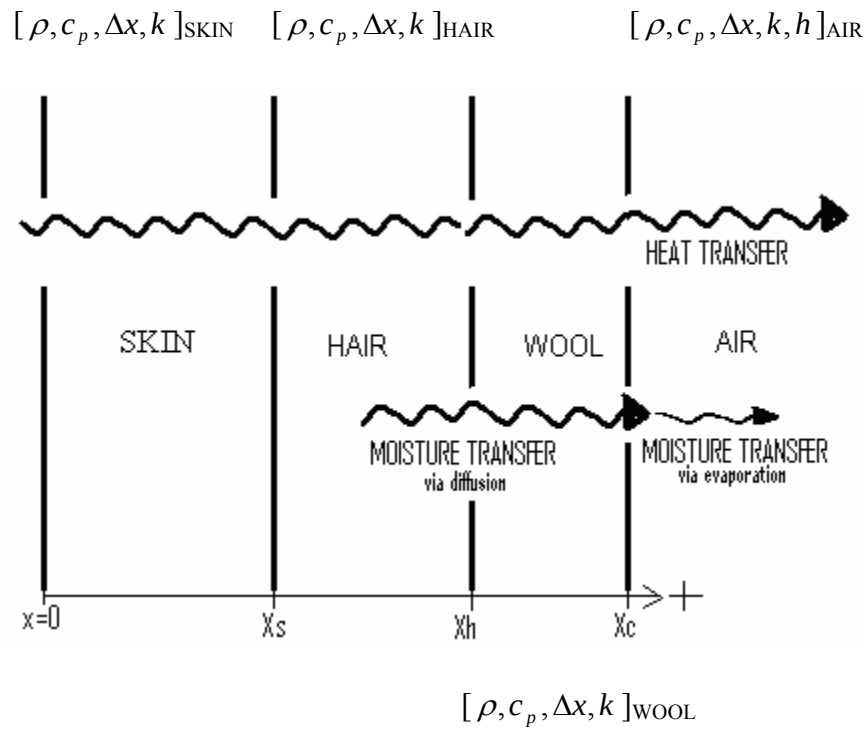
The cooling of a horse involves coupled heat and mass transfer. We will be modeling the cooling process with and without the wool cooler to determine the effect of this layer on the rate of heat loss to the surrounding air. The mass species of interest, water, diffuses in liquid form from saturated hair through a wool cooler (if present), evaporates and is convected away from the outer surface as water vapor. The heat and mass transfer processes are coupled by the fact

that evaporation of water requires a certain amount of heat, the latent heat of water, which is drawn from the horse.

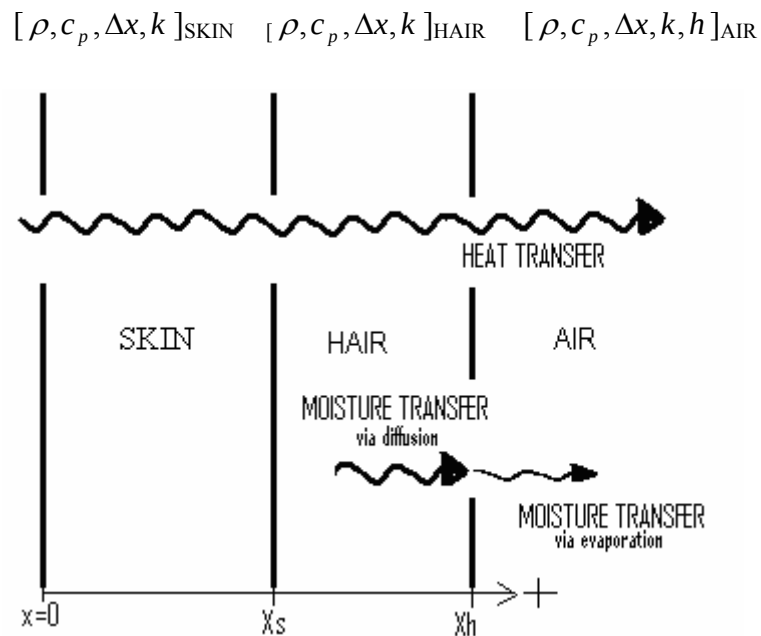
Due to the large area of the horse covered by the wool cooler, we will treat the problem as having two-dimensional, slab geometry with one dimensional heat and mass gradients. Layers included are horse skin and hair, wool cooler and the surrounding air. The horse will have an initial temperature of 101.5°F throughout the skin. We will assume that the body (inner surface of skin layer) will remain at the post-exercise temperature of 101.5°F throughout the cooling process. The hair layer will begin at ambient temperature, assumed 40°F for a covered barn in a cold climate. No wicking will be considered, it will be assumed that water transport occurs by diffusion only.

Schematic

Schematic of horse with cooler



Schematic of horse without cooler



Design Objectives

The goal is to study the cooling of a horse with and without wool coolers. A two dimensional model will be created in GAMBIT and imported into FIDAP to incorporate coupled heat and mass transfer processes implemented using a subroutine. The physical process is simplified by the assumption that the hair layer is initially saturated with sweat (modeled as pure water), which diffuses through the wool layer (if present), evaporates from the surface of the wool and is convected away.

Results and Discussion

The first step in validating our model was to determine the appropriate mesh size. The simulation was run over 30 minutes, a typical amount of time for which a cooler is used. Following each test, the flux at the outer surface of the wool was calculated. We continued to reduce the mesh until this flux reached a stable value. Heat flux at the surface of the wool versus number of nodes is shown in *Figure 1*. From the graph we determined that a mesh size of 363 nodes was sufficient, this mesh size corresponds to a distance of 0.5mm between nodes in the x-direction (parallel to the heat and mass transfer).

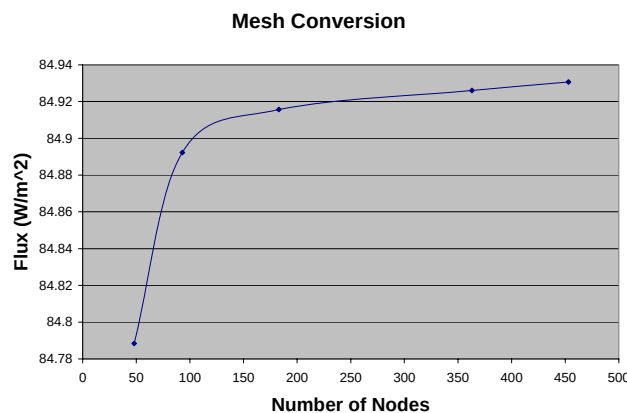


Figure 1: Heat flux at the outer wool surface versus the number of nodes used. The flux becomes relatively independent of mesh size when at least 200 nodes are used.

Once the optimal mesh was determined an appropriate time step was found based on the run time of our model. A fixed time step of 0.5s was used over a total run time of one half hour, or 1800s. This time step resulted in good continuity in our results and also allowed the simulation to run in a reasonable amount of time.

Once an optimal mesh and time step were found, the simulation was run with and without the wool layer. The effect of the wool layer is illustrated in Figures 2 and 3 below.

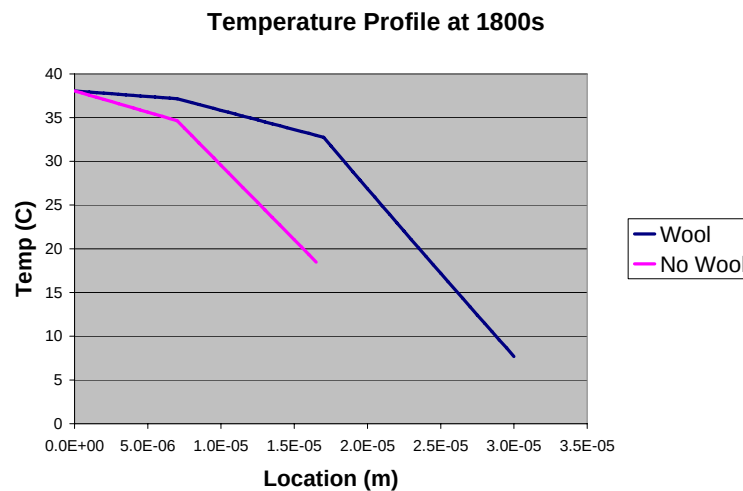


Figure 2: Temperature profile through the skin, hair and wool (if present) layers at 1800s. The profile without the wool shows temperatures that are significantly lower than those reached at a comparable position with the wool layer.

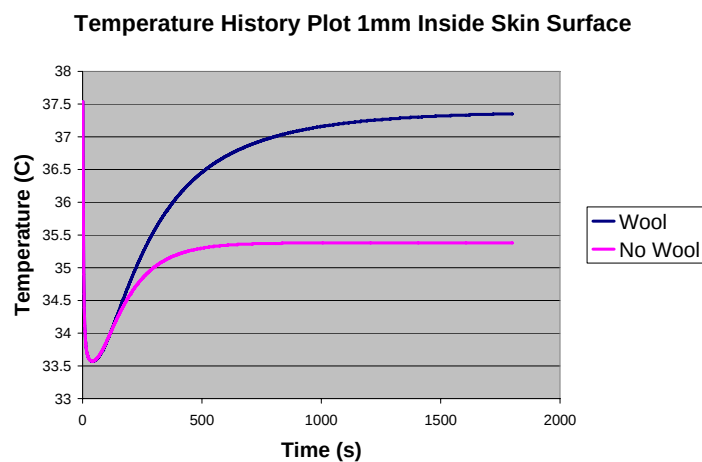


Figure 3: Temperature versus time at a point 1mm below the skin surface at 1800 sec. The temperature with the wool layer levels out at a much higher value than temperature without a wool layer.

Figure 2 shows that after a half an hour the temperature in the skin does not significantly changed when a cooler is used but when no cooler is used the skin temperature drops several degrees. This profile is consistent with our model as the temperature at the inner skin surface remains at the initial temperature of 38°C.

Figure 3 shows the change in temperature of the skin surface over the half hour period. The initial drop in temperature is due to the large initial temperature difference between the hair, which was at ambient temperature or 4°C, and the skin which was initially at 38°C. Once the temperature equilibrated the skin temperature warmed up to a temperature close to the internal body temperature of the horse. This initial drop could have been reduced if the initial temperature in the horse hair had a gradient from the inside to outside which would be more realistic but this was omitted to keep the model simple. Both of these figures show that coolers keep the horse skin temperature near the horse's body temperature during the cool down period. They also indicate that failure to use a cooler results in a skin temperature several degrees below body temperature.

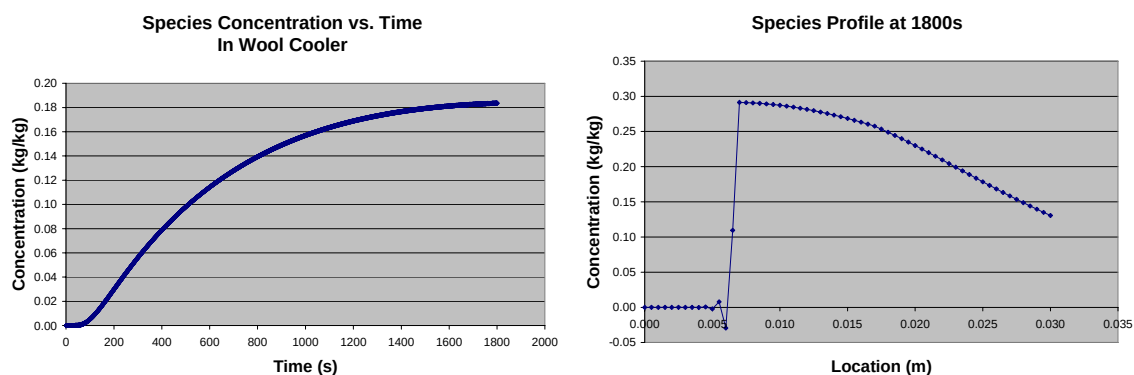


Figure 4 (left) shows the sweat concentration in the wool cooler as a function of time. Figure 5 (right) shows the sweat concentration as a function of position after 30 minutes of cooler use.

Figure 5 shows the concentration of sweat as function of position within the layers of skin, hair and wool. The hair started almost saturated with a concentration of sweat equal to

0.7kg/kg. After thirty minutes the concentration of sweat in the horse hair has declined by more than 50%. This is what we would hope for because when we take the cooler off we want the horse to be dry so that it will not get chilled. The decrease in sweat is due to the diffusion of sweat through the wool and the eventual evaporation of the sweat at the surface of the wool. The large drop in sweat concentration near 0.005 meters is due to the low diffusivity of the horse skin which prevents sweat from diffusing back into the horse.

Figure 4 shows that initially the cooler is dry and as time goes on it sweat diffuses into the wool, thus increasing the concentration. The sweat concentration initially rises due to sweat diffusing from the hair to the wool. As the hair dries out less sweat diffuses into the wool. This relationship in addition to the evaporation of sweat at the outer surface of the wool causes the concentration in the wool to level off near 20% saturation. If the cooler were left on longer the hair and cooler would eventually dry out completely.

During the development of the model some of the constants were estimated because published values were unattainable. The thermal conductivity and the diffusivity of the horse hair were two constants that were difficult to find but essential to the accuracy of the model. So these values were chosen for study in the sensitivity analysis. The properties of the wool were also hard to find although values were eventually found. Thermal conductivity and diffusivity of wool are also important to the accuracy of the model so these values were studied in the sensitivity analysis as well. The diffusivity values of hair and wool were varied by plus and minus one order of magnitude in order to determine the affects of such changes. Based on the results even such drastic changes have very little affect as the temperature profiles for the diffusivities used and the profiles for the varying diffusivities looked the same.

Later in the sensitivity analysis the conductivity values of wool and hair were varied by 10%. These changes had no noticeable affect on the temperature profile plots. Based on the results of the sensitivity analysis we were able to determine that even though several variables were estimated to an order of magnitude these estimations were not detrimental to our model because large variation in these values resulted in little change. The graphs from the sensitivity analysis can be seen in Appendix C.

Overall our model seems to accurately model the cooling processes of a horse using a cooler. The results show that the cooler does indeed keep the horse warm while allowing the horse to dry off.

One chief assumption of our model is that the latent heat removed by the evaporating sweat had a significant cooling effect on the horse. To build this into the model the evaporation of the sweat was coupled to the temperature at the surface of the wool using a subroutine. The desired affect was to create a heat sink at the cooler air boundary. It was hypothesized that the chief benefit of the cooler is that it wicks moisture away from the skin surface of the horse, therefore moving the cooling effect of evaporation away from the heat surface. To test this hypothesis the mass temperature coupling was turned off. The results shown in Figure 6 indicate that the coupling has a minimal affect on the temperature of the horse's skin. This indicates that the primary affect of the cooler is not that it wicks moisture away from the skin surface but that it provides an insulating layer that keeps the horse's body heat from being convected away by the surrounding air.

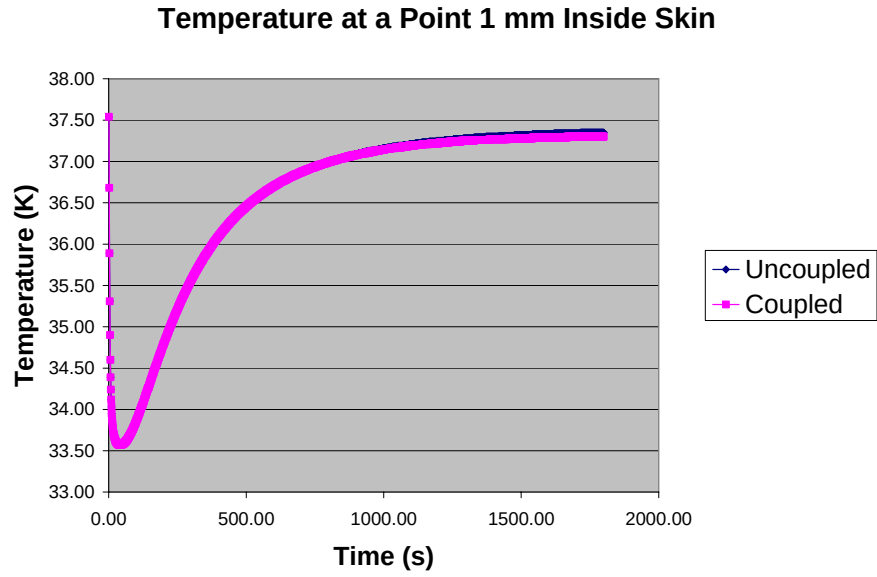


Figure 6: Temperature history at 1mm inside skin

Conclusions and Design Recommendations

Conclusions

The model shows that the wool helps maintain a constant body temperature post exercise by providing an insulating layer. Mass transfer effects are discounted due to the similarity of results between the coupled and uncoupled models. This may be explained by the fact that wool is not hygroscopic and has a low diffusivity. Furthermore, FIDAP was not able to accommodate evaporation and the associated heat loss at the skin surface. Instead, our model was based on evaporation at the wool surface, which limits heat loss at the skin surface.

Since accurate diffusivity and conductivity values for wool and hair were hard to find, a sensitivity analysis was performed to determine the effect of an error on the temperature and mass profiles. After varying the diffusivities by one order of magnitude and the conductivities

by 10%, the model determined that errors in these variables have little to no effect on horse body temperature approximations after one half hour.

Design Recommendations and Realistic Constraints

Health and Safety

The main concern when caring for a warm, sweaty horse in cold weather is to ensure the horse's health. If an animal is left uncovered, or with blankets that do not allow moisture transport they may become quite uncomfortable and lose heat rapidly. A chilled horse may suffer from decreased resistance to disease, decreased energy levels and increased susceptibility for respiratory infections (Hill). The cooler must allow the horse to dry completely while providing sufficient insulation to prevent rapid heat loss. Also out of concern for the health of the horse, the cooler must be made of a material that does not irritate the horse's skin. In our model, the wool satisfies the above criteria. It allows moisture transport while providing an insulating layer. It also is compatible with the horses' skin.

Safety is another issue in designing an equine cooler. First, the material should be as close to flame-retardant as possible. Stables are packed full of dry material that allow fires to propagate quickly after ignited. Although flame-resistant coolers would not protect the animal, they would provide valuable extra time to transfer the horse to a safe environment. Wool has been shown to be relatively difficult to ignite when compared with untreated natural fibers such as cotton. The flammability of fleece varies with the specific material composition used. Fleece with high cotton content is fairly flammable and should be avoided. A more synthetic fleece would be moderately flammable, as these fibers often melt and extinguish their own flame (The Flammability of Textile Products in Canada). Material requirements such as flame resistance may compromise the wicking and/or insulating capabilities.

A second safety concern involves how the cooler is secured to the horse. Straps are positioned to not only hold the cover in place, but also to minimize the risk of the horse getting caught or tangled in any way. Horses panic when they meet resistance such as would be created by getting, for example, a leg stuck in one of the straps. Panic may lead to thrashing, kicking etc, and may put the horse and those around him in danger. The strap design may also affect the process of heat and moisture transfer from the horse. A tightly secured cooler may encourage moisture transport by the applied pressure of the material against the saturated hair layer.

Economic

Economic factors also constrain the optimal cooler design and material. On one side, the labor costs of those working with the horses could be minimized by using a material that allows for rapid moisture transport while also serving as an insulating layer. This would reduce the amount of time and attention that would be required to care for each horse after exercise. On the other side, the cooler and its maintenance must be relatively inexpensive. A horse owner or stable manager would look for a balance between cost and ease of use and maintenance.

Appendix A:

Mass Transfer

Governing Equation

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}$$

Boundary Conditions

$$\begin{aligned} -D \frac{\partial c}{\partial x} \Big|_{x=0} &= 0 \\ -D \frac{\partial c}{\partial x} \Big|_{x=A} &= k^* h_m (c_A - c_\infty) \end{aligned}$$

$$k^* = 0.2$$

Interpolated from *International Critical Tables, Vol. II*.

Where $A = x_c$ with the cooler and $A = x_h$ without the cooler.

Calculating the mass transfer coefficient, h_m

$$Sh = 0.664 Re_L^{\frac{1}{2}} Sc^{\frac{1}{2}} = \frac{h_m L}{D_{\text{water / wool}}}$$

$$Re_L = \frac{u_\infty L \rho}{\mu}$$

$$u_\infty = 1.39 \frac{m}{s}$$

$$\rho_{\text{air}, T=277.6K} = 1.26 \frac{kg}{m^3}$$

$$L = 0.02m$$

$$\mu_{\text{air}, T=277.6K} = 1.73 \times 10^{-5} \frac{kg}{m \cdot s}$$

$$Re_L = 2024.74$$

$$Sc = \frac{\mu}{\rho D_{\text{water / wool}}} = 274.6$$

$$h_m = 1.23 \times 10^{-3} m/s$$

Heat Transfer

Governing Equation

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

Boundary Conditions

$$T|_{x=0} = T_{high}$$

$$-k \frac{\partial T}{\partial x} \Big|_{x=A} = h(T_{x=A} - T_{\infty}) + \lambda \left(-D \frac{\partial c}{\partial x} \Big|_{x=A} \right)$$

Where $A = x_c$ with the cooler and $A = x_h$ without the cooler.

Initial Conditions

$$T_{skin}|_{t=0} = T_{high}$$

$$T_{hair}|_{t=0} = T_{wool}|_{t=0} = T_{\infty}$$

Calculation of heat transfer coefficient, h .

$$\text{Re}_L = \frac{u_\infty L \rho}{\mu}$$

$$u_\infty = 1.39 \frac{\text{m}}{\text{s}}$$

$$\rho_{\text{air}, T=277.6\text{K}} = 1.26 \frac{\text{kg}}{\text{m}^3}$$

$$L = 0.02\text{m}$$

$$\mu_{\text{air}, T=277.6\text{K}} = 1.73 \times 10^{-5} \frac{\text{kg}}{\text{m} \cdot \text{s}}$$

$$\text{Re}_L = 2024.74$$

$$\text{Re}_L < 2 \times 10^5$$

$\therefore$ laminar

$$\text{Nu}_L = 0.664 \text{Re}_L^{\frac{1}{2}} \text{Pr}^{\frac{1}{3}} = \frac{hL}{k_{\text{air}}}$$

$$\text{Pr} = 0.714$$

$$k_{\text{air}} = 0.0245 \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$h = 32.71 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

Table of Input Parameters

Variable	Value	Significance
x_s	0.007m	Skin thickness
x_h	0.017m	Distance to outer hair boundary
x_c	0.030m	Distance to outer wool boundary (if wool is present)
T_{high}	311.205K	Horse body temperature post-exercise
T_{∞}	277.594K	Ambient temperature
H	80%	Relative humidity
c_{∞}	0	Surrounding water vapor concentration
$D_{water/skin}$	$1.00 \times 10^{-19} \text{ m}^2/\text{s}$	Diffusivity of water vapor through skin
$D_{water/wool}$	$5.00 \times 10^{-8} \text{ m}^2/\text{s}$	Diffusivity of water vapor through wool
$D_{water/hair}$	$1.00 \times 10^{-7} \text{ m}^2/\text{s}$	Diffusivity of water vapor through hair
K_{wool}	0.04 W/mK	Thermal conductivity of wool
K_{skin}	0.63 W/mK	Thermal conductivity of skin
K_{hair}	0.18 W/mK	Thermal conductivity of hair
$c_{p \text{ wool}}$	1.26 kJ/kg $^{\circ}$ C	Specific heat of wool
$c_{p \text{ skin}}$	3.79 kJ/kg $^{\circ}$ C	Specific heat of skin
$c_{p \text{ hair}}$	1.20 kJ/kg $^{\circ}$ C	Specific heat of hair
ρ_{wool}	380 kg/m 3	Density of wool
ρ_{skin}	1030 kg/m 3	Density of skin
ρ_{hair}	265 kg/m 3	Density of hair
h	32.71 W/m 2 K	Heat transfer coefficient
h_m	$1.23 \times 10^{-3} \text{ m/s}$	Mass transfer coefficient
k^*	0.2	H $_2$ O(l) to H $_2$ O(vap) conversion factor
μ	$1.73 \times 10^{-5} \text{ kg/m}^*\text{s}$	Viscosity of Air

Appendix B:

PROBLEM Statement

PROB (2-D, ENER, NOMO, TRAN, FIXE, SPEC = 1.0)

The PROBLEM statement states that our system is modeled in 2-D. We utilize the energy equation, but since there is no fluid movement, momentum is turned off. Our analysis is transient. The boundaries of our model are fixed and we have one species.

SOLUTION Statement

SOLU (S.S. = 50, VELC = 0.100000000000E-02, RESC = 0.100000000000E-01,
SCHA = 0.000000000000E+00, ACCF = 0.000000000000E+00)

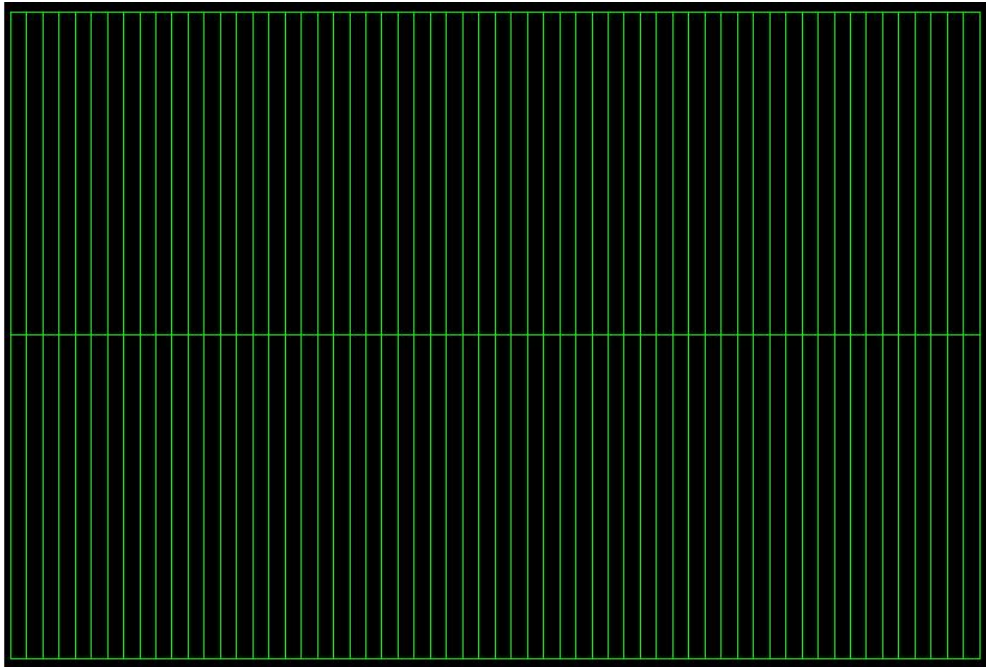
We used a successive substitution method with a solution tolerance of 0.002 and a residual tolerance of 0.01.

TIMEINTEGRATION Statement

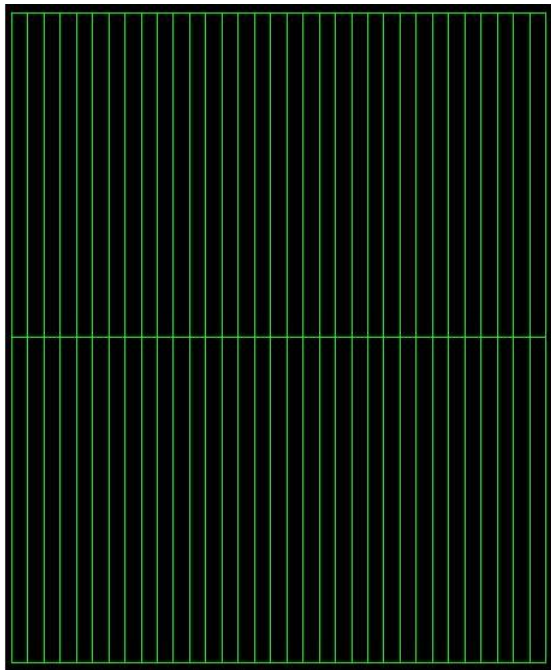
TIME (BACK, NSTE = 100000, TSTA = 0.000000000000E+00, TEND = 1800.0, DT = 0.5,
FIXE)

The TIMEINTEGRATION Statement indicates that we used the backward time integration algorithm with a maximum number of time steps set to 100000. Our start time is 0 and our end time is 1800, with a time step of 0.5. Our time steps are fixed and not variable.

Mesh with Wool



Mesh without Wool



Appendix C:

**Temperature Profile at 1800s
Varying Wool Conductivities**

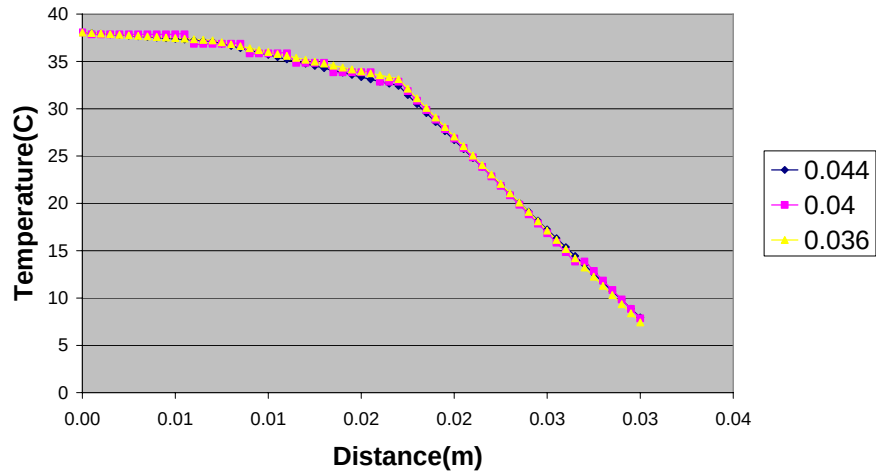


Figure 7: Sensitivity Analysis for Wool Conductivity

**Temperature Profile at 1800s
Varying Wool Diffusivities**

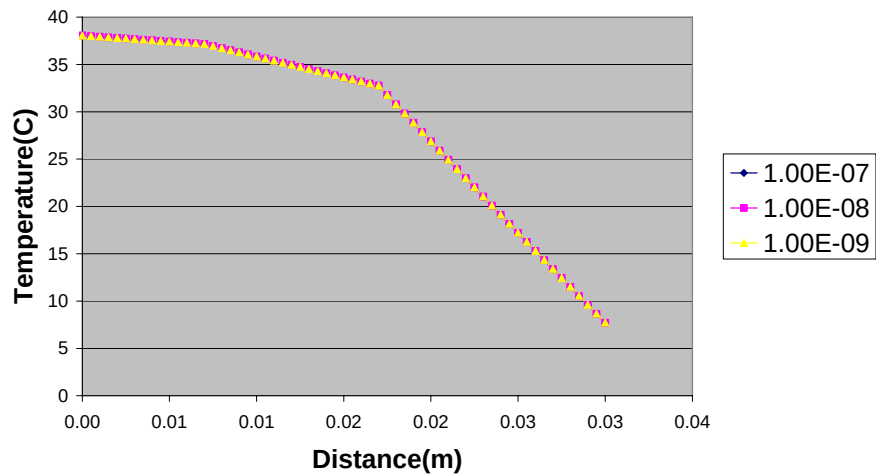


Figure 8: Sensitivity Analysis for Wool Diffusivity

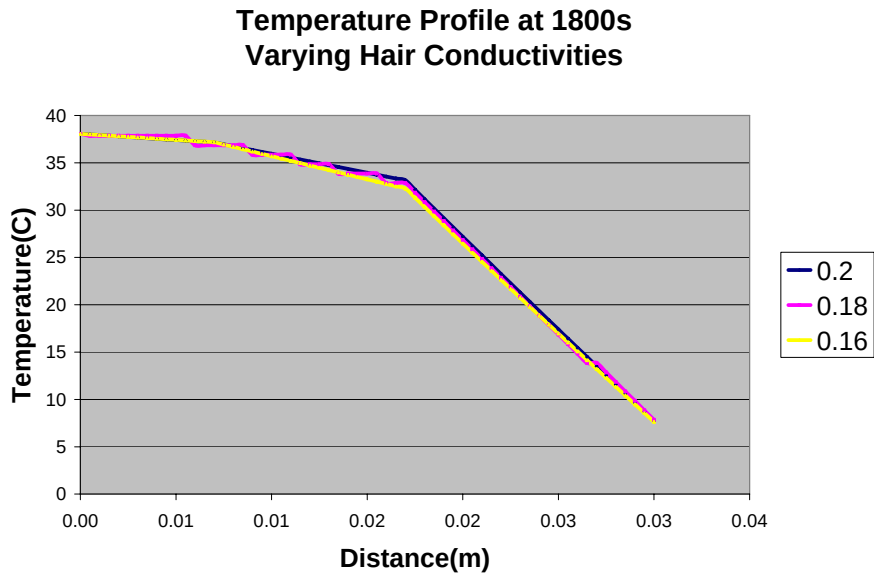


Figure 9: Sensitivity Analysis for Hair Conductivity

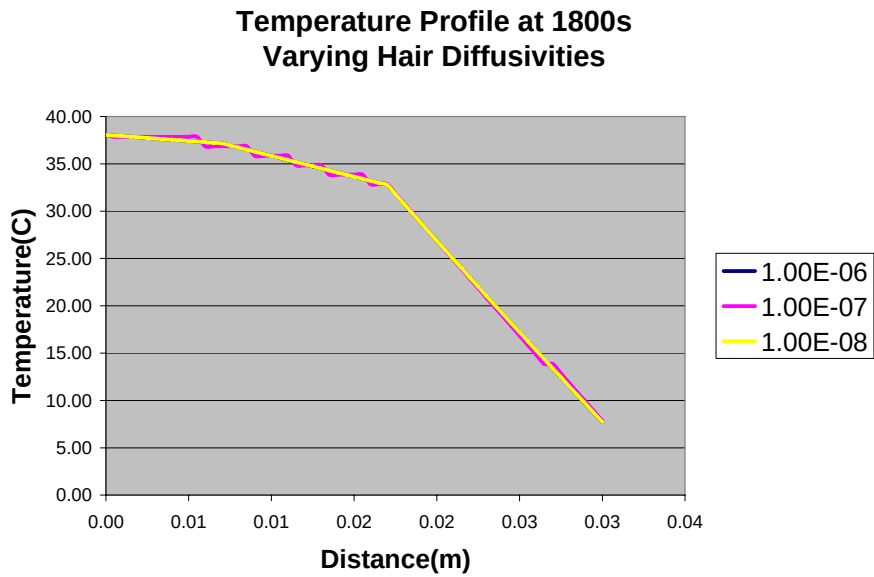


Figure 10: Sensitivity Analysis for Hair Diffusivity

Appendix D: References

Cherry Hill. 2001. To Blanket or Not to Blanket.

http://www.horsekeeping.com/horse_care/blanket_or_not.htm. 03 May 06

Datta, A.K. 2004. *Computer-Aided Engineering: applications to Biomedical Processes*. Dept. of Biological and Environmental Engineering, Cornell University, Ithaca, NY.

Health Care Canada. 2003. The Flammability of Textile Products in Canada. Her Majesty the Queen in Right of Canada. Canada

National Research Council. 1929. *International Critical Tables, Vol. II*. New York: McGraw-Hill Book Company.

Li Y, Lou Z. 1999. An Improved Mathematical Simulation of the Coupled Diffusion of Moisture and Heat in Wool Fabric. *Textile Research Journal*. USA