Group Members: Lisa Allen, Brenda Chen, Sonam Pokwal, Steve Graunke

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Title

THE ADVANTAGE OF UNDER ARMOUR FOR WINTER SPORTS PERFORMANCE

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Executive Summary

Under Armour produces apparel designed for winter sports athletes. This apparel aims to keep athletes comfortable by retaining body heat and removing moisture due to perspiration. Special wicking properties are claimed to enable the material to remove moisture quickly and provide insulation. This study will propose a mechanism by which the Under Armour clothing material achieves these effects. We will model moisture transfer and heat transfer through the cloth, considering skin surface temperature and moisture content as measures of comfort. Additionally, we will compare the effects of Under Armour to cotton clothing which has different material properties, considering diffusivity, conductivity, partition coefficient, and porosity. The goal of this study is to use our proposed model to show the advantages of Under Armour for winter sports performance.

Background and Importance

Winter sports performance-wear is designed to enhance comfort for athletes. In this study we will consider the two major components that influence comfort to be skin temperature and moisture conditions.

Athletes engaging in physical activity will accumulate moisture from perspiration in the layers of clothing they wear. Retaining moisture on the skin surface results in discomfort. Clothing material must be designed to minimize moisture retention by allowing moisture to quickly diffuse through the cloth and evaporate. The properties of clothing that affect moisture loss are diffusivity, porosity, and the partition coefficient (where the partition coefficient describes the equilibrium of moisture at the cloth-air boundary). Clothing that is effective in providing comfort will remove moisture quickly by having high values for the diffusivity and the partition coefficient.

Skin temperature also directly affects comfort levels. In this situation skin temperatures are affected by three mechanisms of heat loss: conduction, convection, and evaporation. Radiative heat loss is not significant in this case. Heat loss by conduction depends on the properties of the cloth layer: conductivity, specific heat, density, and moisture content. In this situation, the cloth is either completely or partially saturated with moisture depending on the progress of drying. The degree of saturation will alter the thermal properties such that increased moisture content will result in properties that increase heat loss. Convection occurs at the surface and depends on the environmental conditions and is independent of material properties. Evaporation of moisture at the cloth surface causes heat loss due to phase change of moisture to vapor. Evaporative heat loss depends on environmental temperatures, the latent heat of vaporization, and the flux of moisture out of the cloth surface. To minimize heat loss, cloth material must have low conductivity and moisture content, as well as high values of specific heat and density.

The properties of Under Armour that provide comfort also help to maintain core body temperature. Although the core body temperature is not a direct factor in influencing comfort, it plays an important role in homeostasis. Under Armour clothing can prevent extreme cases of hypothermia where core body temperature can fall below 35^0C.

Project Objective

We will model a situation in which an athlete who is wearing Under Armour has just stopped physical activity. At this time, the clothing is saturated with moisture from perspiration. We will model both transient moisture and heat transfer through the cloth.

We propose a mechanism that includes the moisture loss by diffusion and evaporation, and heat loss by conduction, convection, and evaporation. We will couple heat transfer to moisture transfer by considering thermal properties to be functions of moisture content. The mass transfer process influences heat transfer as shown in the project design map (see Figure 1).

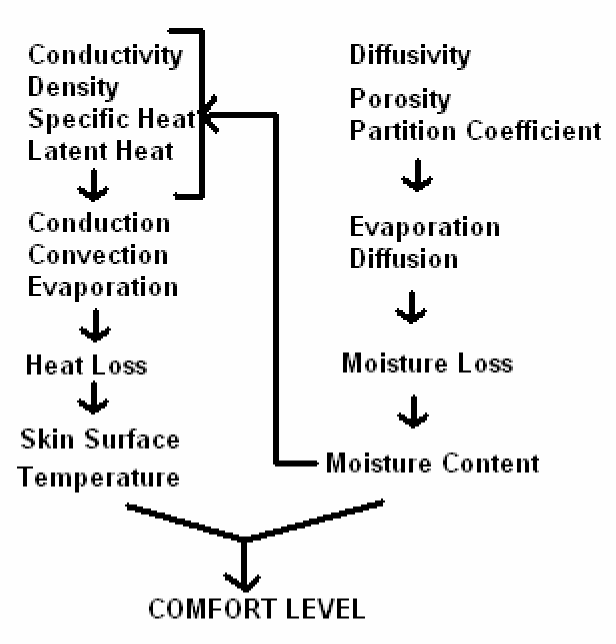


Figure 1. Project Design Map

Since there is not a lot of existing literature about properties and physics of Under Armour, we will follow this process to build our model:

1. Create schematic:
   - Approximate the system as a two layer slab consisting of cloth and tissue.
   - Determine boundary conditions and initial conditions, including partition coefficient, K'.
2. Determine Properties:
   - Create steady state model of heat and mass transfer through cloth to determine value of cloth layer diffusivity. Appropriate values resulted in reasonable skin surface temperatures above 0^0C.
   - Determine effective thermal properties of cloth by calculating a weighted average of cloth, water, and air.

3. Finite Element Analysis:
    - Run mass transfer simulation with constant properties
    - Run mass transfer and heat transfer simulation with constant properties and no evaporation
    - Run mass transfer and heat transfer simulation with constant properties and evaporation coupled to mass transfer via a subroutine
    - Run mass transfer and heat transfer with thermal properties and evaporation coupled to mass transfer via a subroutine
4. Comparison of Materials:
    - Run coupled simulation with different material properties
5. Sensitivity Analysis:
    - Run coupled simulation while varying parameters within uncertainty range

Problem Solution

Schematic:

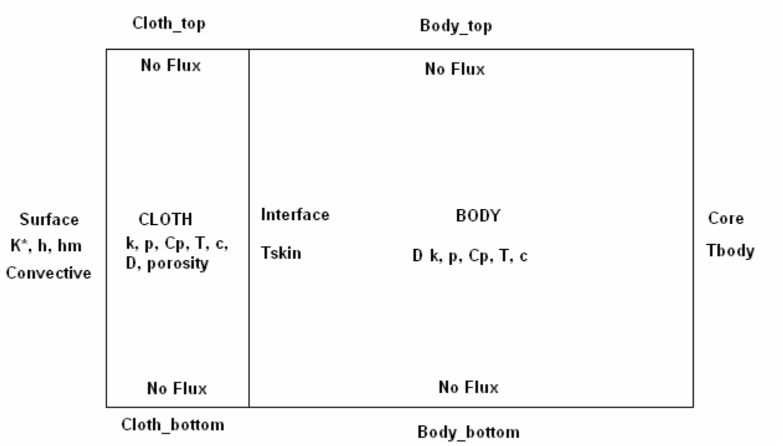


Figure 2. Problem Schematic. For dimensions and property values, see appendix A: tables A4, A5.

The schematic we will use includes two layers: the cloth layer, and the skin layer. The cloth layer has an associated diffusivity, D, concentration, c, temperature T, and porosity, Φ. The thermal properties of the cloth layer; conductivity, k, density, ρ, and specific heat, Cp, depend on the saturation level of the cloth, S_w. The effective thermal property values, P_{eff}, will be determined by the following formula, a volume weighted average of the thermal properties of air, P_{air}, water, P_{water}, and pure cotton, P_{fiber}:

$$P_{eff} = P_{fiber}(1-\Phi) + P_{water}\,\Phi\, S_w + P_{air}\,(1 - S_w)\,\Phi \qquad (1)$$

The layers of skin, fat, and muscle beneath the cloth have similar properties, and are therefore lumped into one body layer. The body layer has an associated diffusivity, conductivity, density, specific heat, temperature, and concentration.

The interface between the body and skin layer has an associated temperature, T_{skin}.

The surfaces boundary has an associated partition coefficient, K', convective heat transfer coefficient, h, and a convective mass transfer coefficient, h_m.

The core boundary has an associated temperature, T_{body}.

Hypothesis:

We hypothesize that Under Armour achieves the high skin temperature and low moisture content shown in clinical studies by:

- eliminating moisture quickly with a high diffusivity value
- keeping skin temperature high by minimizing heat loss by conduction
- quick elimination of moisture results in lower effective conductivity which minimizes heat loss
- Conductivity is the primary mode of heat transfer.

Assumptions:

In order to build our model, we had to make the following assumptions:

- 1-D heat and mass transfer
- Moisture transfer by diffusion, evaporation
- Heat transfer by conduction, convection, evaporative heat loss
- Conduction is the primary mode of heat loss
- Moisture transfer affects thermal properties
- Model wicking process with higher diffusivity value
- Sweat properties are same as water
- Constant ambient conditions
- Constant core body temperature
- Isotropic materials

Governing Equation:

Our model requires two governing equations, the species equation and the energy equation. Both governing equations are for one dimensional transport. The two terms required are transient and conductive or diffusive. (See appendix A, eqns. A1 and A2)

Boundary Conditions:

There is no flux at any of the top or bottom boundaries, since the problem is a one dimensional transport problem. The core boundary has a specified constant temperature, and no species flux. The surface boundary is convective for both heat and species, and also includes the effects of evaporation. (See appendix A, table A1)

Initial Conditions:

A constant initial temperature is specified for all layers. A constant initial concentration is also specified for each layer. (See appendix A, table A2)

Results:

Qualitative Description:

We will look at skin surface temperature and skin surface moisture concentration to measure how well our model approximates Under Armour.

The first step taken to build our model was to determine the partition coefficient to be used in the boundary condition. The partition coefficient describes the equilibrium between liquid water and water vapor at the surface boundary. (See Appendix C: *'Determining K': Partition Coefficient')*

Next, appropriate property values for the Under Armour cloth layer were determined.

The diffusivity value of Under Armour cloth fibers was unavailable in literature, so an approximate one was determined through a steady-state model. The diffusivity was determined on the following constraints: (1) Under Armour maintains its surface temperature above 0 ^{o} C, and (2) Under Armour diffuses moisture quickly. (See Appendix C '*Determining Diffusivity: Steady-state Analysis*').

The thermal properties of the cloth layer depend on air, water, and cloth fiber properties. The cloth layer is a porous material. The pore spaces can be occupied with either liquid water, or air. The effective thermal properties of the entire layer are assumed to be a volume weighted average of the three components of the layer. Thermal properties of each component (air, water, and cloth fibers) are assumed to be constant, but the volumes of air and water are variable. Since water volume depends on mass transport, which is a function of time, thermal properties will also be time dependent. (See Appendix C: '*Thermal Property Coupling*').

After determining appropriate property values we were able to run finite element analysis using the program FIDAP. The simulation was run in several stages, with each progressive stage adding a layer of complexity to the model.

Stage 1: Mass transfer
In this stage, only mass transfer was modeled, using constant properties. Results from this stage were used to evaluate the mass flux as a function of diffusivity. (See Appendix C: '*Stage 1Results:')*

Stage 2: Heat and Mass transfer
In this stage, heat transfer with constant properties and no evaporation was added to the model. Results confirmed that the heat and mass transfer could be run simultaneously.

Stage 3: Heat and Mass transfer, with evaporation
The effects of heat loss due to evaporation, dependent on mass flux, were added to the surface boundary of the heat transfer process in this stage. A subroutine was required to obtain the mass flux needed to define the boundary condition in the heat transfer problem. The boundary

condition for heat transfer at the surface was described with a specified flux (see Appendix A, Table A1).

Stage 4: Heat and Mass transfer, with evaporation and coupled thermal properties

In this stage, thermal properties were changed from constant to variable. A subroutine was required to define the effective thermal properties of the cloth layer, using equation (1) described in the problem solution, (also see Appendix C, *'Thermal Property Coupling,'* eqn. C1). The results obtained were used to validate our hypothesis on the physics of Under Armour (see Appendix C, '*Under Armour Results'*).

Stage 5: Comparison of Materials:

In this stage, the model used for stage 4 was run with a different diffusivity to simulate a different cloth material. This material, cotton, was compared to Under Armour to verify that our model for Under Armour supports clinical findings (see Appendix C, '*Cotton Results'*).

Results

From the complete Under Armour model from stage 4, we found that the skin surface temperature dropped to 16.5 ^{o}C after a period of 15 minutes. The final mass concentration at the skin surface was 46.97 kg/m^{3}. (See Appendix C, '*UnderArmour Results*,' Figure C7, C8)

The model for cotton material from stage 5, resulted in a final skin surface temperature of 32.7 ^{o}C. The final mass concentration at the skin surface was 100 kg/m^{3}. (See Appendix C, '*Cotton Results*,' Figure C12, C13)

Sensitivity Analysis

We analyzed the sensitivity of our results to fiber conductivity, density, specific heat, cloth porosity, diffusivity, and partition coefficient. We determined a range of parameter values that resulted in a +/- 1^{o}C change in skin surface temperature. A small range for a parameter value indicates that the solution is very sensitive to that parameter.

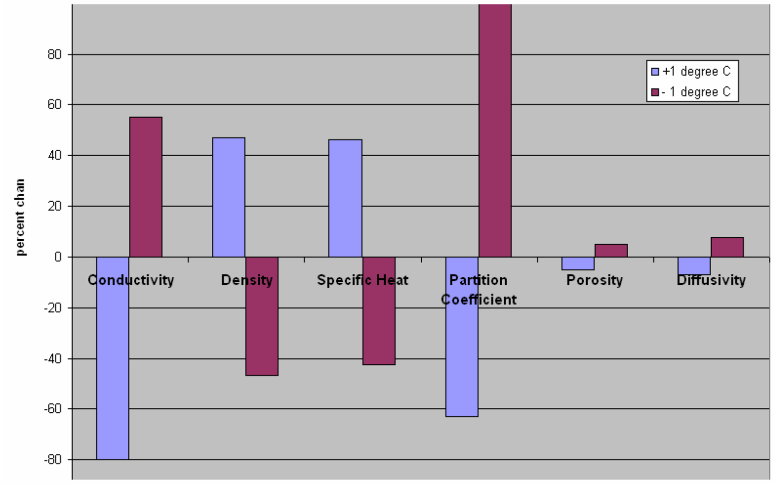
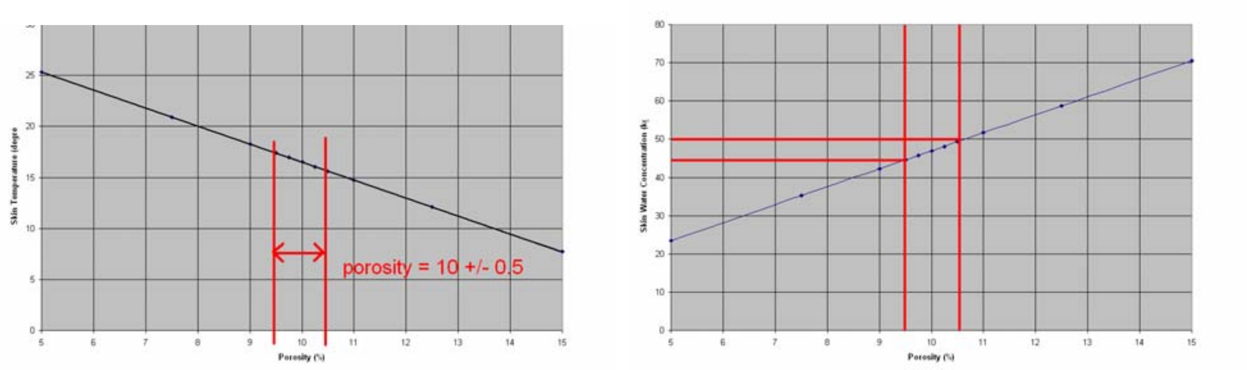


Figure 3. Range of parameters for sensitivity analysis.

Figure 3 shows the six parameter ranges resulting in 1^{o} C change in skin surface temperature. The purple bars show the range of parameter values that resulted in a positive change in temperature, while the red bars show resulting negative temperature change. Density and specific heat are directly related to surface temperature, while the other parameters are inversely related. When the positive and negative ranges are approximately equal, it can be concluded that the solution is linearly dependent on the parameter. The partition coefficient is unique in that the range required for a negative 1^{o} C change in surface temperature was so great that we can conclude that our solution is insensitive to a large positive change in K'. We expect this is due to the fact that mass flux out of the surface is not the limiting process in mass transfer for that range of K'.

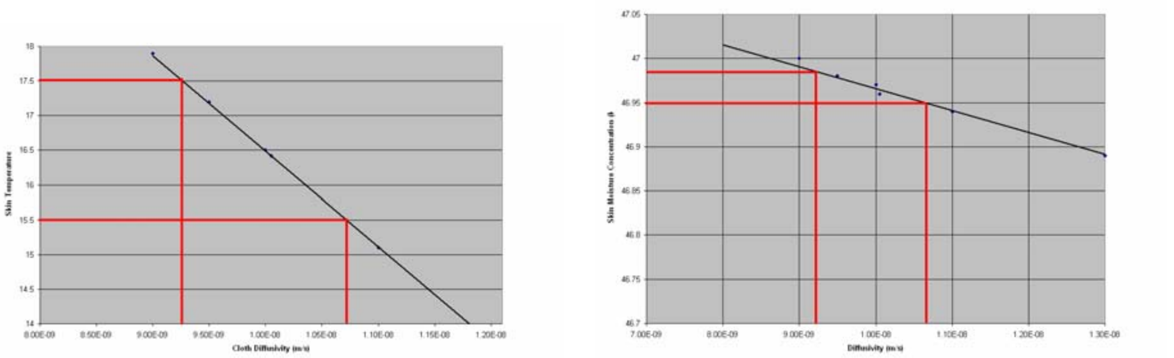
From our analysis, we determined that our solutions were most sensitive to cloth porosity and diffusivity values. Using the ranges for these two parameters, we then looked at the resulting surface moisture concentrations.



a) Skin temperature vs. Porosity
For +/- 1 degree C change
porosity = 0.1 +/- 0.005

b) Skin Concentration vs. Porosity
For porosity range
Skin concentration = 45 – 50 kg/m^3

Figure 4 a, b. Sensitivity plots for cloth porosity.



a) Skin Temperature vs. Cloth Diffusivity
For a +/- 1 degree C change in temperature
Diffusivity = 0.925 E -8 – 1.07 E -8 m/s

b) Skin Concentration vs. Diffusivity
For diffusivity range
Skin concentration = 46.95 – 46.98 kg/m^3

Figure 5 a, b. Sensitivity plots for cloth diffusivity.

Discussions

Comparison

Our hypothesis predicted that our model of Under Armour would be superior to cotton in terms of both quicker drying, and heat retention. From the results obtained by the coupled model (see Appendix D, '*Under Armour Results'*, '*Cotton Results'*), we see that Under Armour does eliminate moisture faster, but cotton is better at retaining heat. The skin surface temperature of the cotton does not drop below 30^{o}C, while the temperature for Under Armour drops to 16^{o}C. We expected that the quick elimination of moisture would result in less heat loss by conduction, since the thermal properties of the cloth would be closer to air than water if the cloth had less moisture. However, it appears that a large amount of heat was lost by a mode other than conduction. We referred to our sensitivity analysis to determine what variable could have affected our solution more than conductivity.

Sensitivity

From the results of our sensitivity analysis (see Figure 3), we saw that our solution was not very sensitive to changes in the conductivity of the cloth fibers. The solution had the greatest sensitivity to diffusivity and porosity. These results confirmed that conduction was not the primary mode of heat loss in this model. Since convective conditions were the same for both the cotton and Under Armour models, we concluded that an unexpectedly large amount of heat was lost due to evaporation in the Under Armour model. Due to the high diffusivity for Under Armour, there was a large mass flux out of the surface of the cloth which took a proportional amount of heat to evaporate.

Conclusion

Insufficient model

While our proposed model gave results that successfully modeled the quick drying of Under Armour, it failed in modeling the heat transfer process. Clinical studies of heat and mass transfer through the actual Under Armour cloth show that Under Armour both wicks moisture quickly, and retains heat better than other materials. We must therefore conclude that our model does not accurately describe the physical process by which Under Armour wicks moisture while retaining heat.

New Proposal

Since our hypothesis and model are incorrect for the situation, we propose a new model to describe Under Armour. A revised schematic could more accurately model the situation.

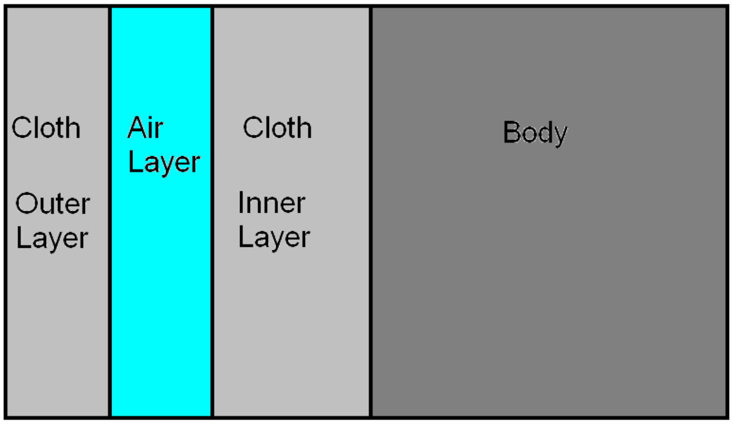


Figure 6. Revised schematic.

In this revised schematic (Figure 6), the cloth layer is broken into three separate layers: two layers of cloth separated by an empty layer. The empty layer is a section of the cloth layer that has 100% porosity, and is occupied by either water or air. The thermal properties of this layer are volume weighted as in our previous model. This empty layer increases the effect of changing moisture content on conductivity, which could make conduction the primary mode of heat transfer as we had originally hypothesized.

Design Recommendations

From our study of Under Armour, we have found that changes and variability in several parameters could impact manufacturability.

Manufacturers must be aware of the effect of these parameters on their product’s function. Under Armour’s ability to maintain heat is highly sensitive to the cloth’s porosity and diffusivity. The processing involved in creating the polymer used in Under Armour cloth must be carefully regulated to preserve the desired diffusivity. The post-processing involved in weaving the fibers of the cloth must also be highly regulated to maintain porosity specifications.

The complications in manufacturing also have economic implications. Such highly specific processes are expensive to maintain. This is a possible explanation for the high cost of the product. However, without rigorous adhesion to these specifications, Under Armour would not show the advantage in winter performance sports wear that we have come to know and love.

APPENDIX A: MATHEMATICAL MODEL

Governing Energy Equation:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial x^2} \tag{A1}$$

Governing Species Equation:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \tag{A2}$$

Boundary Conditions:

Boundary	**Heat**	**Mass**
Cloth_top	No Flux	No Flux
Cloth_Bottom	No Flux	No Flux
Body_top	No Flux	No Flux
Body_bottom	No Flux	No Flux
Core	T = 37 ^{o} C	No Flux
Surface	Flux = - h ($T_{surface}$- T_{inf}) – Lv * (Species Flux) h = 4.30 W/m^2K T_{inf} = 0 ^{o}C Lv = 2600000 J/kg	Flux = hm (K') * ($c_{surface} – c_{inf}$) hm = 0.021 m/s c_{inf} = 0 kg/m^3 K' = 0.0087 kg_{vapor}/kg_{liquid}

Table A1: Boundary conditions

Initial Conditions:

Layer	**Initial Concentration**	**Initial Temperature**
Cloth	C_o = 100 kg/m^3	T_o = 37^{o}C
Body	C_o = 0kg/m^3	T_o = 37^{o}C

Table A2: Initial conditions

Input Parameters:

-Dimensions:

Layer	**Width (m)**	**Height (m)**
Cloth	0.003	0.01
Body	0.015	0.01

Table A3: Dimensions

-Properties:

Layer	Diffusivity (m/s)	Porosity (%)	Density (kg/m^3)	Specific Heat (J/kgK)	Conductivity (W/mK)
Cloth (UnderArmour)	10 E -8	10	$P_{eff} = P_{fiber}(1- \Phi) + P_{water} \Phi S_w + P_{air} (1 - S_w) \Phi$ * Φ = porosity of cloth layer = 10% * P_{eff} = effective property value of cloth * These properties vary with moisture concentration		
Cloth (Cotton)	10 E -10	10			
Body	10 E -14	N/A	1000	3333	0.24

Table A4: Property values

	Density (kg/m^3)	Specific Heat (J/kgK)	Conductivity (W/mK)
Fiber	1300	1550	0.2
Water	1000	4183	0.606
Air	1.2929	1000	0.026

Table A5: Property values

Specific Boundary Types (Edges):

Name	Type	Description
Surface	ESPECIES	Cloth-air interface
Cloth_top	PLOT	Top boundary of cloth layer
Cloth_botton	PLOT	Bottom boundary of cloth layer
Body_top	PLOT	Top boundary of body layer
Body_bottom	PLOT	Bottom boundary of body layer
Core	PLOT	Semi-infinite boundary of body

Table A6: Boundary Types

Specific Continuum Types (Faces):

Name	Type	Description
Cloth	SOLID	Entire cloth region
Body	SOLID	Entire body region

Table A7: Continuum Types

APPENDIX B: PROBLEM STATEMENT

Objective:
Our primary objective was to develop a model to describe the mechanism by which Under Armour eliminates moisture quickly and maintains body temperature. Our secondary objective was to compare how Under Armour maintains comfort – determined by skin temperature and moisture concentration at the skin surface – better than conventional cloths (one with a lower diffusivity). From the results of our analysis, we evaluated how accurately our model described the physics behind Under Armour.

Solution Statement
From observing the final skin and moisture concentration, we are able to conclude that our model does not successfully describe the effects of Under Armour. Since our final moisture concentration was sufficiently low, we could conclude that our model correctly described Under Armour's ability to quickly eliminate moisture. However, since the final skin temperature was lower than the cotton model's, we can conclude that our heat transfer process did not model the actual process by which Under Armour maintains heat.

Time Integration Statement:
In order to see the effects of varying diffusivities on skin surface temperature and moisture concentration, we used a time period of 15 minutes (900 seconds). We used a time step of 0.001, since there are large changes in temperature and concentration initially. Because large changes were only during the initial stages of the processes, we used a varying time-stepping algorithm with the following data inputs:

Descriptor	**Variable**	**Value**
No. of time steps	Nsteps	2000
Starting time	Tstart	0
Ending time	Tend	900
Time increment	Dt	0.001
Max change in time increment	DtMax	1
Max increase factor	IncMax	1.2
Time stepping algorithm	Variable	0.001
Number fixed time steps	NoFi	10

Table B1: Time integration

Plot of Element Mesh:

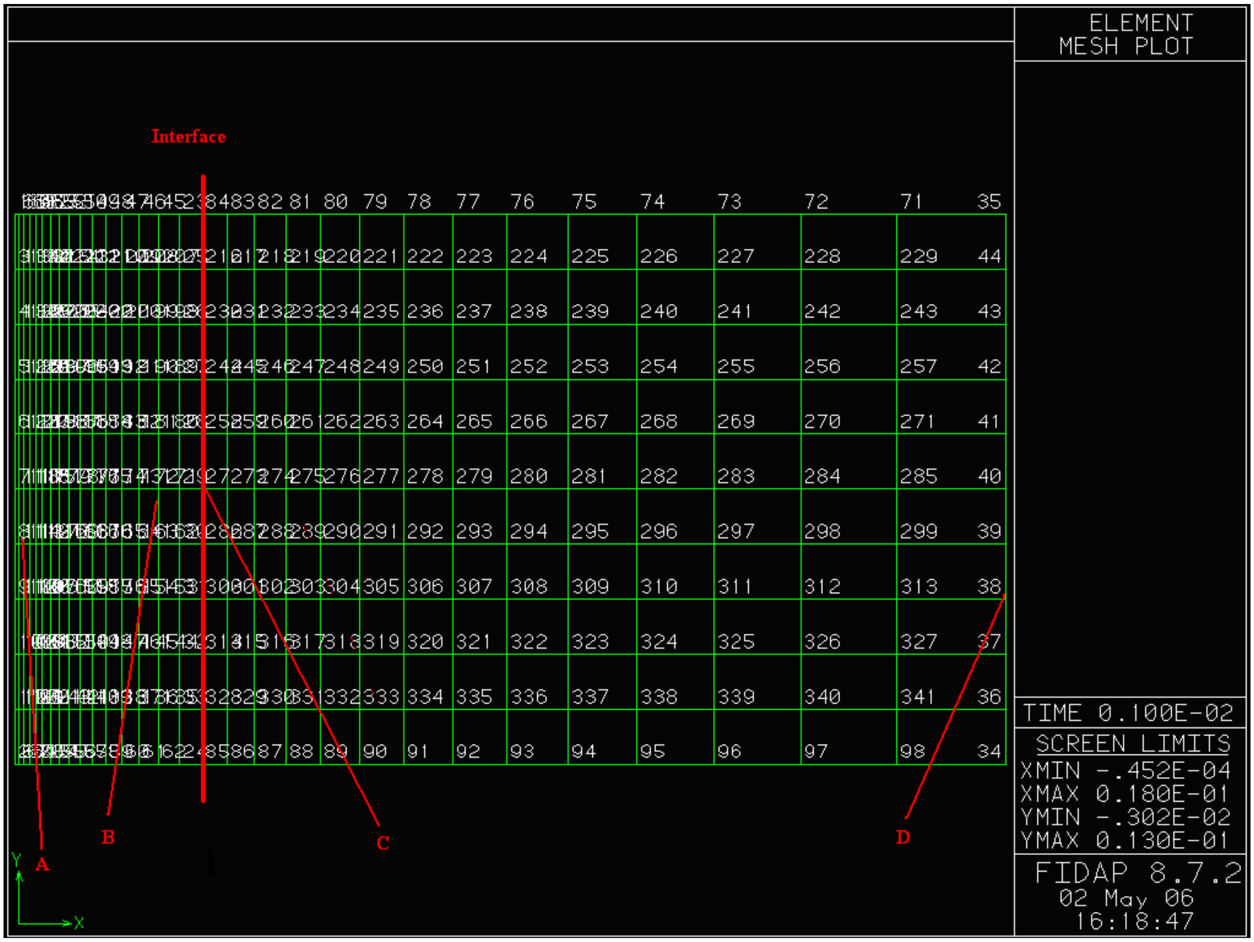


Figure B1: Plot of mesh. ***A****: indicates node 8 used for surface temperature.* ***B:*** *indicates node 175 used for skin surface moisture concentration.* ***C:*** *indicates node 275 used for skin surface temperature. Note that the skin surface concentration is not taken from the interface. Moisture readings are taken in the cloth layer since there is no moisture in the body layer, and close to the interface to avoid the boundary effects caused by FIDAP's inability to model zero diffusivity in the body.* ***D:*** *indicates node 38 used for core body temperature.*

APPENDIX C: DATA

Determining K': Partition Coefficient

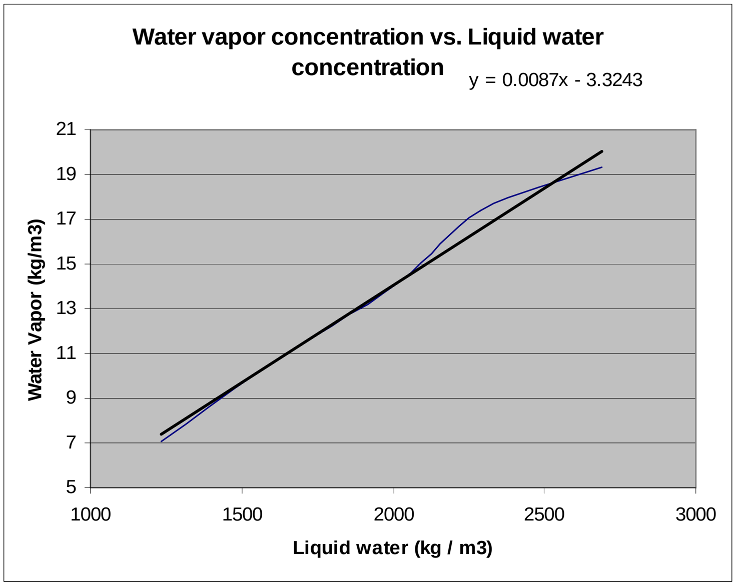


Figure C1: Determining equilibrium partition coefficient, K', which is the slope of the graph above.

Relative Humidity	kg water/kg linen	Density of linen (kg/m^3)	Liquid water Concentration (Kg water/m3)	Kg water/kg air (at 30C)	Density of air (kg/m^3)	Vapor Concentration (Kg water/m3)
20	2.75	448.52	1233.422	5.5	1.29	7.095
30	3.5	448.52	1569.809	8	1.29	10.32
40	4.5	448.52	2018.326	11	1.29	14.19
50	5.1	448.52	2287.437	13.5	1.29	17.415
60	6	448.52	2691.102	15	1.29	19.35

Table C1: data relating concentration of water vapor to concentration of liquid water, from linen cloth. Underarmour assumed to behave like linen in water-vapor equilibrium.

Determining Diffusivity: Steady-state Analysis

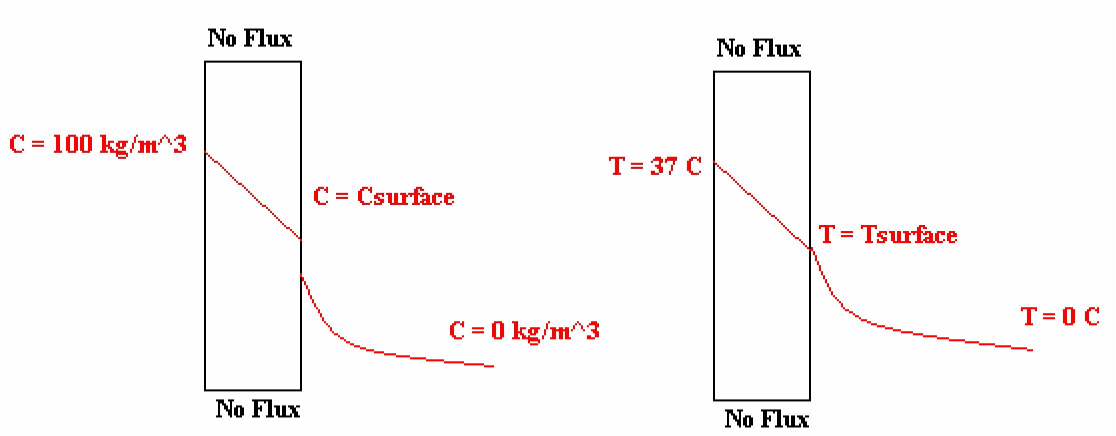


Figure C2: Schematic for steady state mass and heat transfer in cloth layer. Left edge is "body" side. Right edge is surface exposed to air.

- Steady State Mass Transfer:
(used to determine mass flux)

F = Mass flux
D = Diffusivity
Cs*l* = Concentration of liquid water at the surface
Cw*l* = concentration of liquid water in the body
L = length
Hm = convective mass transfer coefficient
Csg = concentration of water vapor at the surface
C∞g = concentration of water vapor far from the surface
K' = equilibrium partition coefficient at the cloth surface for liquid water and water vapor
Diffusive flux of liquid at the boundary is equal to convective flux of vapor at the boundary.

Mass flux = F = -D $\frac{Cs\ell - Cw\ell}{\Delta L} = hm(Csg - C\infty g)$

Cw*l* – Cs*l* = F $\frac{\Delta L}{D}$

Relating concentration of water vapor at the surface, Csg, to concentration of liquid water at the surface, Cs*l* by

Csg = K' * Cs*l*

K'* Cs*l* - C∞ = F *1/hm

Adding the equations, subbing in $C\infty = 0$, we have:

$$F = \frac{Cw}{\frac{\Delta L}{D} + \frac{1}{K'^{*}hm}}$$

- *Steady State Heat Transfer:*
(used to relate diffusivity to surface temperature, by evaporative heat loss due to mass flux)

q" = heat flux
k = conductivity
Ts = temperature at the surface
Tbody = temperature in the body far from the surface
T∞ = temperature far from the surface
L = length
h = convective heat transfer coefficient
Lv = latent heat of vaporization
F = mass flux out of surface

Conductive heat flux at the surface is equal to flux from convection and evaporation at the surface:

$$q'' = -k\,\frac{Ts - Tbody}{\Delta L} = Lv * F + h(Ts - T\infty)$$

Solving for surface temperature, Ts:

$$Ts = \frac{Tbody - Lv * F + \frac{h\Delta L}{k}T\infty}{1 + \frac{h\Delta L}{k}}$$

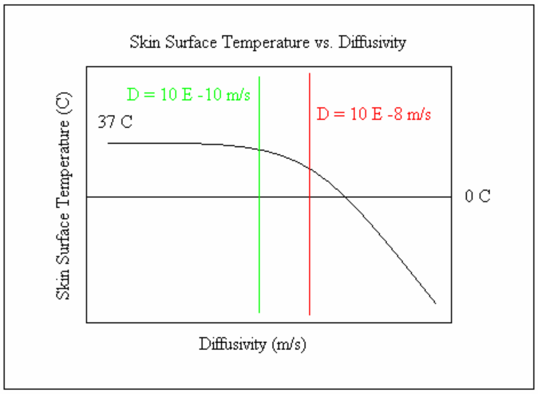


Figure: Plot of Diffusivity vs. Surface Temperature. Diffusivity value for Under Armour cloth layer is determined by selecting a faster diffusivity that still results in a surface temperature above 0 ^{o}C.

$\mathbf{D_{underarmour} = 10^{-8}\ m/s}$
$\mathbf{D_{cotton} = 10^{-10}\ m/s}$

Thermal Property Coupling:

Thermal property values of the cloth layer depend on moisture concentration within the layer.

Assumptions:
- Constant pore volume
- Volume of pores in the cloth is either occupied with liquid water or air
- Effective property value depends on volume of water, air, and cloth fiber in the cloth layer

P_{eff} = effective property value
P_{fiber} = property of pure cloth fiber
P_{water} = property of liquid water
P_{air} = property of air
Φ = porosity
Sw = water saturation

$$P_{eff} = P_{fiber}(1-\Phi) + P_{water}\,\Phi\, S_w + P_{air}\,(1 - S_w)\,\Phi \qquad \text{(C1)}$$

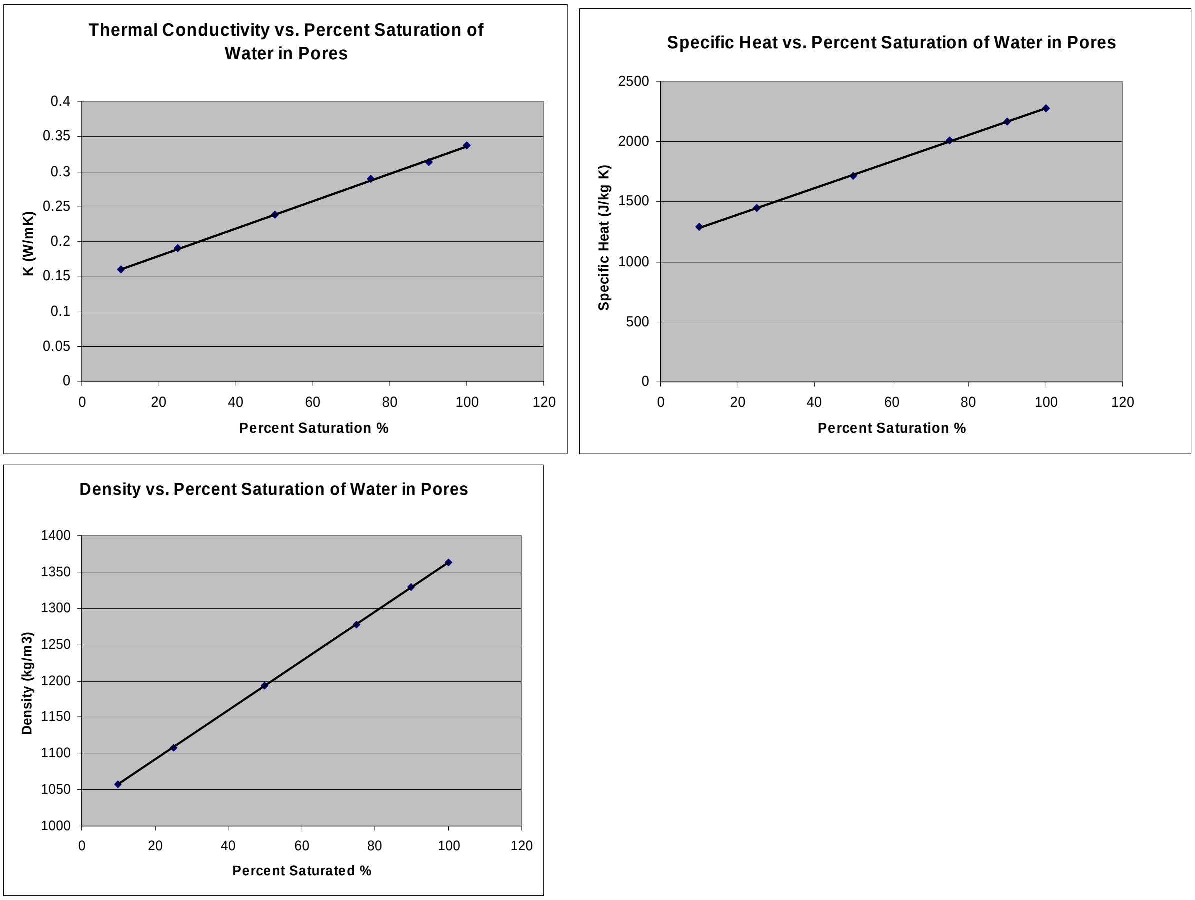


Figure C3: Effective thermal property plots vs percent saturation. Determined using formula C1.
- b) *(top left) Effective thermal conductivity of cloth layer*
- c) *(top right) Effective specific heat of cloth layer*
- d) *(bottom left) Effective density of cloth layer*

STAGE 1 RESULTS:

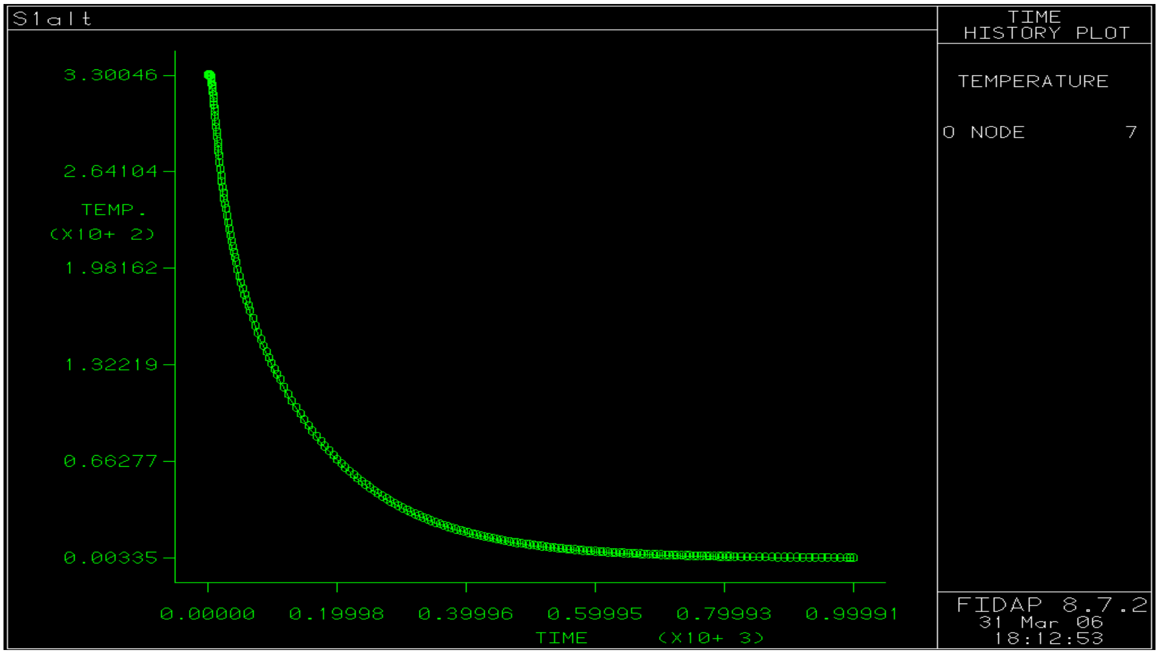


Figure C4a: History species plot for diffusivity value of 1E-8 m/s.

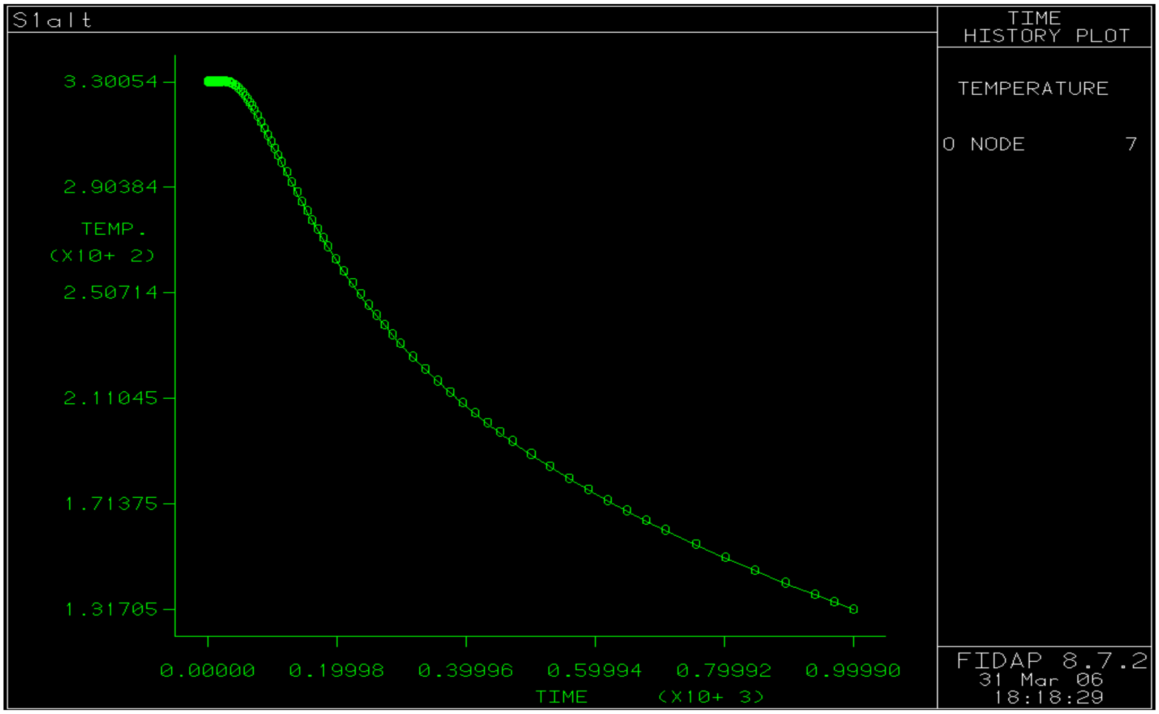


Figure C4b: History species plot for diffusivity value of 1E-9 m/s.

Due to complications in FIDAP, species transfer was modeled as a heat problem in the program. Labels on the graph for temperature correspond to species.

UNDERARMOUR RESULTS: (D = 10^{-8} m/s)

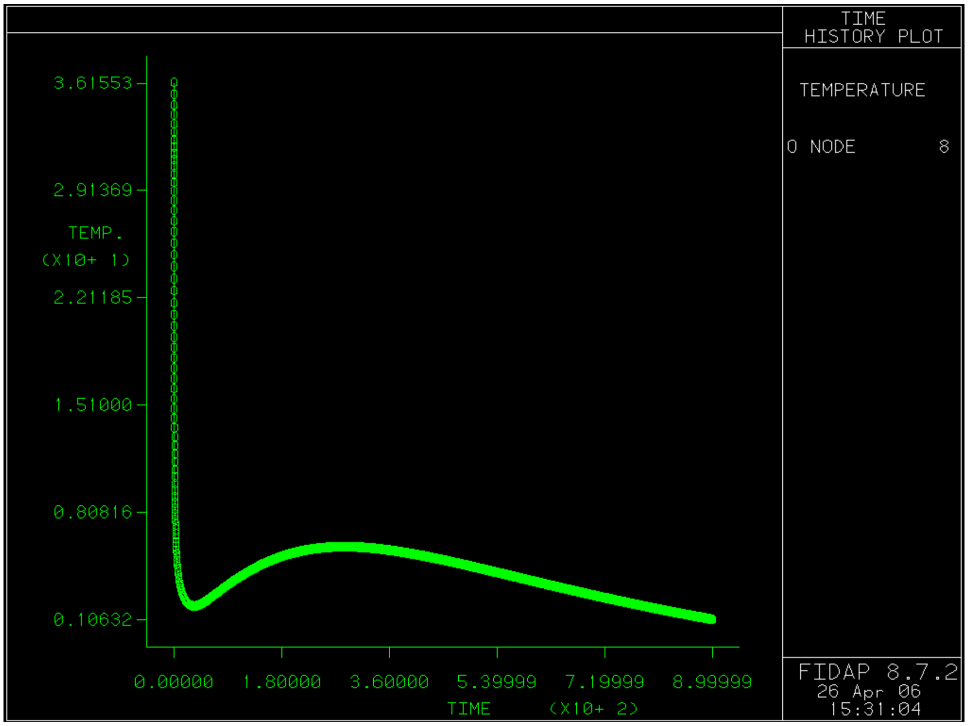


Figure C5: Temperature history plot for node 8, representing the cloth surface.

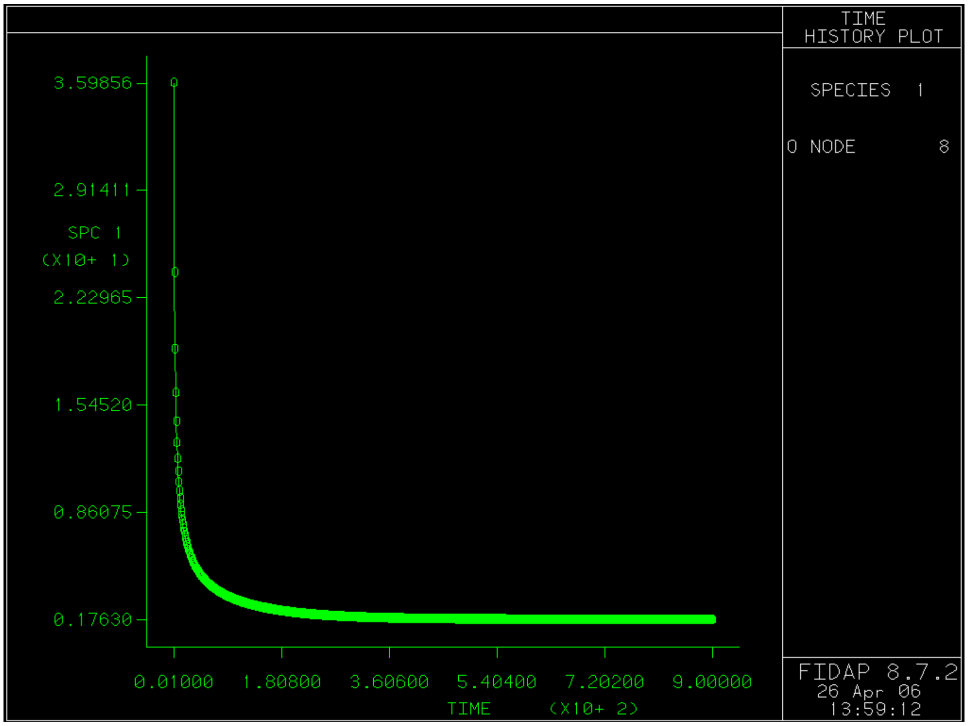


Figure C6: Species history plot at node 8, representing the cloth surface.

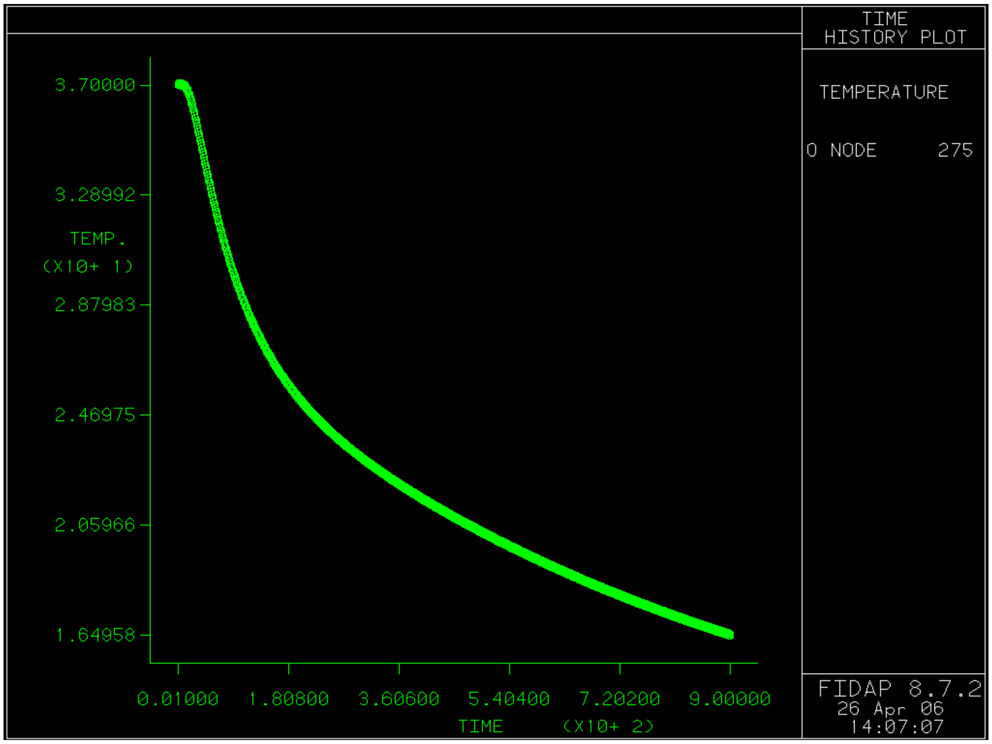
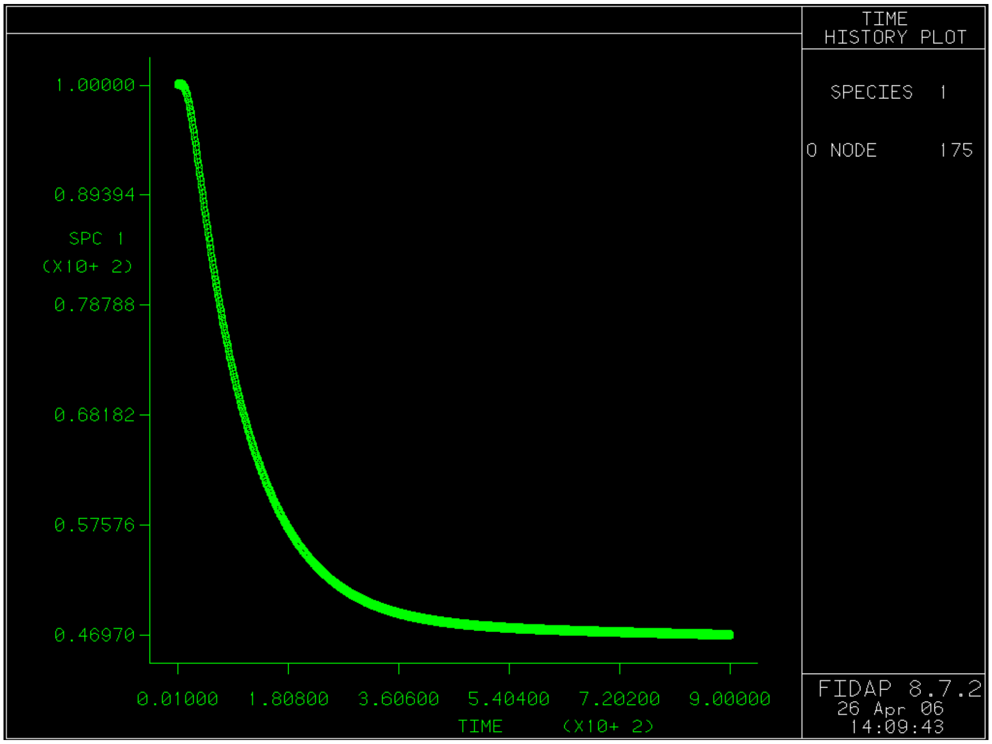
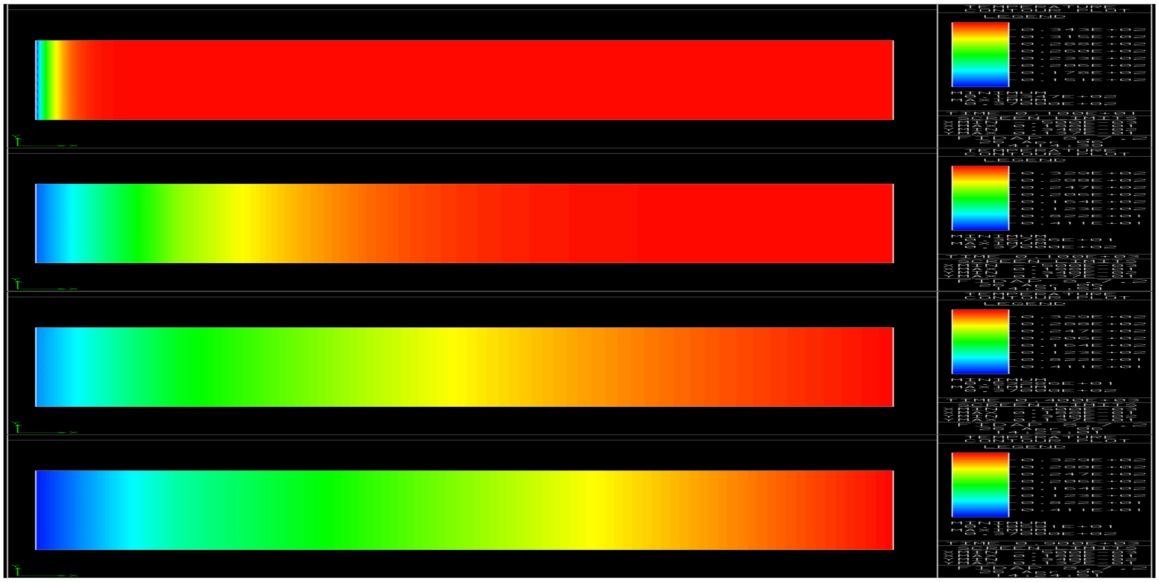


Figure C7: Temperature history plot at node 275, representing the skin surface.



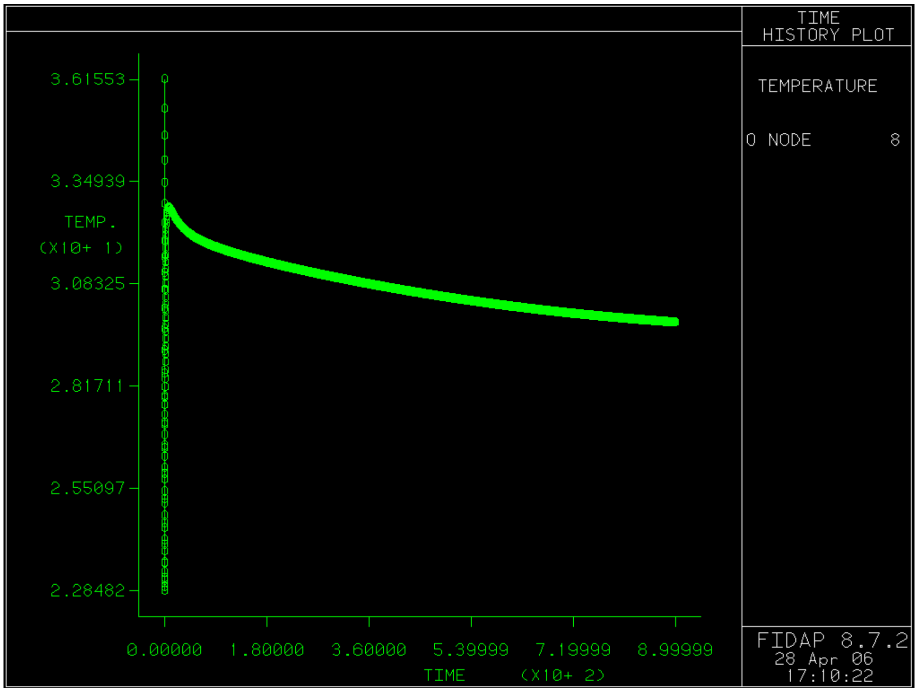
FigureC8: Species history plot at node 175, representing the skin surface.



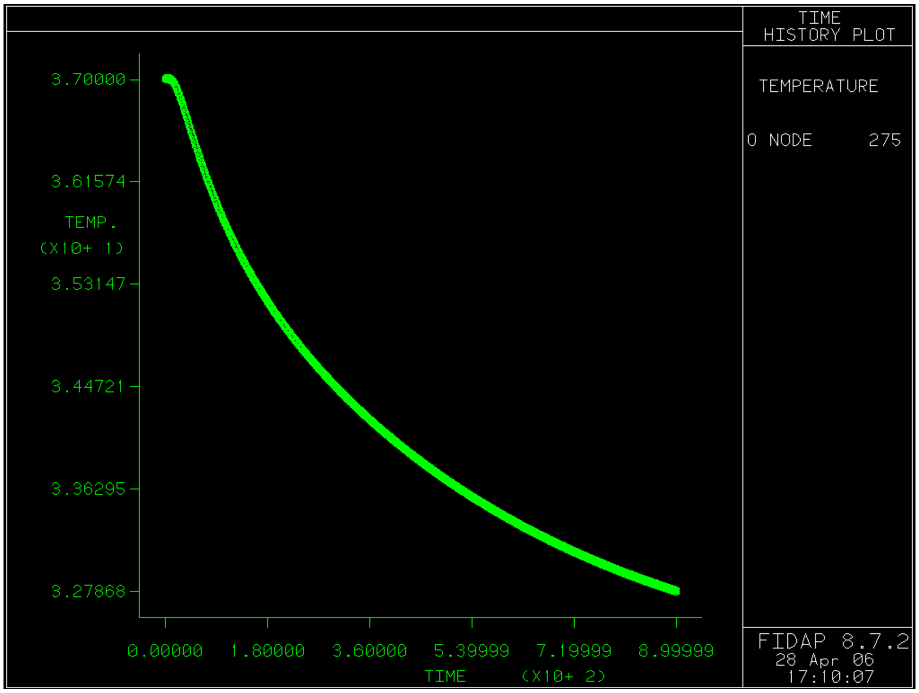
FigureC9: Temperature contours from 0, 100, 400, 900s. Red color is 37^{o}C. Blue color is 0^{o}C.

FigureC10: Species concentration contours at 0,25,50, and 900s. Red color is 100 kg/m^3, blue color is 0kg/m^3.

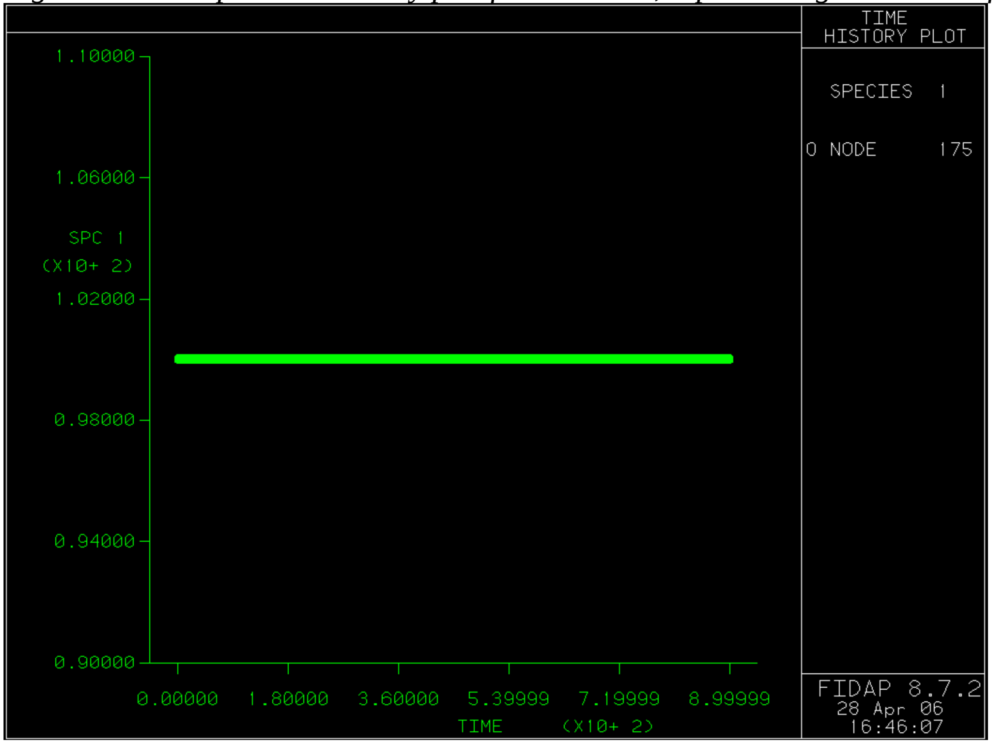
COTTON RESULTS: (D= 10^{-10})



FigureC11: Temperature history plot for node 8, representing the cloth surface.



FigureC12: Temperature history plot for node 275, representing the skin surface.



FigureC13: Species concentration history plot for node 175, representing the skin surface.

FigureC14: Temperature contours at 0, 100, 400, 900s.

FigureC15: Species contours for time 0, 900 s.

APPENDIX D: REFERENCES

Fanger PO (1970) Thermal Comfort. New York: McGraw-Hill

Goldman RF (1978) Prediction of human heat tolerance. In: Folinsbee LJ, Wagner JA, Borgia JF, Drinkwater BL, Gliner JA, Bedi JF (editors). Environmental Stress: Individual Human Adaptations. New York: Academic Press

Gonzalez RR (1995) Biophysics of heat exchange and clothing: applications to sports physiology. Medicine Exercise Nutrition and Health 4, 290-305

Haghi, A.K. (2004) Transport Phenomena in Porous Media: A Review. University of Guilan. Rasht, Iran.

Havenith, George. (2001) An Individual Model of Human Thermoregulation for the Simulation of Heat Stress Response. Journal of Applied Physiology.

Holmer I (1985) Heat exchange and thermal insulation compared in woollen and nylon garments during wear trials. Textile Research Journal 55, 511-518

Lotens, Wouter A. Updated: 2000. Heat exchange through clothing <http://www.ilo.org/encyclopaedia> Accessed: 2006.

Parsons, K.C. (1993) Human Thermal Environments. Taylor and Francis Inc., Bristol, PA.