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MODELING OF HEAT AND FLUID FLOW THROUGH FABRIC SYSTEMS

by
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MESH	VELOCITY	PERMEABILITY	UNIVERSE OF FABRICS
POROUS	WICKING	WATER VAPOR	PROTECTIVE GARMENTS
LAYERS	HUMIDITY	MASS TRANSFER	THERMAL INSULATION
AIR FLOW	HEAT FLOW	THERMAL FLOW	THERMAL RESISTANCE
FABRICS	FLUID FLOW	HEAT TRANSFER	THERMAL CONDUCTIVITY
CLOTHING	MODELING	MOISTURE FLOW	MATHEMATICAL MODELING
COMFORT	PREDICTION	AIR PERMEABILITY	COMPUTATIONAL MODELING
TEXTILES	TEMPERATURE	FLOW PROPERTIES	COMPUTATIONAL FLUID DYNAMICS

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Table of Contents

List of Figures

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1. Preface

Modeling of heat and fluid flow through textile systems was conducted to determine if comfort of desired textile systems for use in protective garments could be predicted based on the flow properties of the individual textile layers that make up the system.

Initial modeling work focused on nonwoven fabrics. The types of modeling performed included:

- computational fluid dynamics (CFD) body modeling
- thermal resistance modeling
- heat and fluid flow modeling

Work on this modeling was discontinued because of lack of funding. Phil Gibson has done a remarkable job on modeling heat and fluid flow through fabrics; it is imperative that this work continue to better understand the roles that fibers, yarns, fabrics, and construction of fabric systems play in comfortable yet protective garments.

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2. Introduction

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Modeling of heat and fluid flow through textile systems was conducted to determine if comfort of desired textile systems for use in protective garments could be predicted based on the flow properties of the individual textile layers that make up the system. Such predictions would eliminate the need for time-consuming testing of heat and gaseous water vapor through the fabric.

Further, with knowledge of heat and fluid flow through individual fabrics, the modeling was intended to facilitate predicting the heat and fluid flow through a garment composed of several unique layers of fabric. Such predictive tools would be useful as they would allow for the creation of comfortable protective fabric systems without the need for building several different prototypes and evaluating them.

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2.1 Modeling Background

As the threat of different weapons, such as chemical and biological, become more understood and prevalent, the military garments designed to protect soldiers become more complex. To provide increased protection many of these protective garments incorporate several layers of fabrics and films. While these layers increase the protection of the garment against a wide range of threats, they reduce comfort by decreasing the amount of body heat and water vapor that can pass through the garment from the body to the outside environment.

Comfort of a garment is dependant upon various factors, including the flow of heat and moisture away from the body, through the garment, and into the environment in warm climates. In the past, it was usually necessary to create garments of different constructions and evaluate each garment individually to determine which combination of fibers, yarns, fabrics, and finishes, or which composite fabric system, provided the best heat and moisture transfer. This process is time-consuming and costly when the number of fabric systems evaluated increases. Thus, if the thermal and fluid flow behavior of fabric systems could be modeled based on physical parameters of the materials involved, time and money could be saved.

Additionally, success in this endeavor would allow prediction of the best combination of fabrics for a given comfort level, which could greatly reduce much of the continuing refining of current protective military garments over a long time period as more research is conducted.

The idea under consideration is this: if some physical properties of the fabrics are known, it should be possible to predict flow of heat and fluid, in the form of water vapor, through the fabric. Such predictions would eliminate the need for testing heat and gaseous water vapor through the fabric, which can be time-consuming to measure. With knowledge of heat and fluid flow through individual fabrics, it might be possible to predict the heat and fluid flow through a garment composed of several unique layers of fabric. Such predictive tools would be useful as they would allow for the creation of comfortable protective fabric systems without the need to build several different prototypes and evaluate them.

2.2 Modeling Methods

There are currently two methods of modeling heat and fluid flow: mathematical modeling and use of computational fluid dynamics software, such as Fluent®. Before modeling efforts can begin, it is important to understand what has been accomplished in the past in this field. There are two states of flow that can be considered: steady state and non-steady state. Steady state is not accurate for evaluating heat and fluid flow through garment fabrics because the human body does not generate heat and sweat steadily under all conditions. Therefore, consideration of non-steady state flow is required to provide the most accurate modeling results. However, initial modeling research used steady state flow, and constant environmental and boundary conditions to simplify modeling efforts, which focused on diffusion and convection as modes of transfer. As this field became better understood, the modeling progressed. For example, Luo et al. and Zhu et al. evaluated the effect of environmental conditions on thermal and fluid transfer through textile materials [1, 2]. Ghali et al. introduced dynamic conditions for modeling flow through fabrics in 2002 [3]. Gibson performed thorough research on modeling of heat and fluid flow, particularly in the field of human, garment, and environmental interactions [4, 5]. Much of the published literature on modeling of heat and fluid flow through textile materials focused on flow through nonwoven textiles, due to their extensive use in filtration applications and their relatively simple structures.

Only two papers addressing modeling of multi-layer textile systems were identified during the literature search. Fohr et al. [6] examined layered fabrics consisting of two fabrics sandwiching a membrane, with all the layers adhered together. The model was derived for coated fabrics and does address many interfacial issues. To create a model examining conduction and heat absorption, Mell and Lawson [7] addressed heat transfer in multilayer firefighter turnout wear. Other papers, such as those of Rossi and Gross [8], and Mohammadi et al. [9] used statistical models based on experimental data.

Computational fluid dynamics (CFD) uses software that incorporates physics and mathematics along with user-defined material properties to model desired behavior, such as thermal and liquid flows through fabrics. CFD can simulate fluid flow and consider interaction of the fluid with the solids, such as fabric, that it encounters during its flow. Modeling and simulation based on CFD have been used very effectively for protective clothing predictions. The current research in computational modeling is divided in to three scales that are given below:

1. Micro scale (fabric characteristics)
2. Meso scale (body parts covered with clothing)
3. Macro scale (whole 3-D human body covered with clothing)

CFD modeling for the micro scale range focuses on fabric transport mass and energy equations. Brasser explained the micro scale modeling technique by considering heat and species transfer through pressure and concentration differences in fiber structures [10]. Since textile materials have more complex structures, it is very complicated to develop a model based on its molecular behavior. At the same time, for technical applications it is necessary to predict design factors based on comparatively easier finite element and continuum models.

Computational fluid dynamics tools for developing meso scale models like the human arm covered by protective clothing are good predictors for clothing behavior analysis. One of the models derived by Barry et al. showed such flow simulation of a single limb covered with clothing material carried out by using Fluent software [11]. This research explained the human-clothing-environment interaction parameters and their influence in transport characteristics. Variables considered for system modeling and simulation are wind speed, air permeability of the fabric, and air gap between the skin and clothing [11]. Diffusion of heat and moisture convective air flow and capillary wicking were the parameters considered for modeling.

Macro scale CFD modeling is defined as a set of coupled structures, such as body structures, covered with protective clothing. This is useful when fabric transport characteristics are known. Hill and Barry pointed out the three-dimensional model of heat and sweat loss from a clothed torso [12]. For garment types with and without closures the transport properties are studied through CFD modeling. A body scanner was used to develop a 3-D human body model, and military standards and clothing specifications are adopted for accurate prediction of chemical protective clothing performance [13]. By analyzing the above research work on CFD modeling, it is clear that the modeling work on Fluent and mathematical equations has been considered only with single layer fabric characteristics and some air gap between layer assemblies. Since the current application of textile materials is mostly in multilayer form, the modeling based on layer assemblies and interfacial transport parameters should be suitable for making predictions in future research.

For computational modeling, the formation of equations based on mass, momentum, and energy is the fundamental starting point.

Multilayer mathematical modeling evaluated that consider interfacial transfer characteristics, such as mass flux, interfacial surface tension, and heat flux between bulk phases, should be utilized for predicting heat and fluid flow.

Following this introduction, this report contains:

- a description of the methods and procedures
- a presentation of the results and a discussion of those results
- a presentation of conclusions drawn from the results
- recommendations for further study
- a list of works cited

3. Methods and Procedures

Note: SI units were used.

3.1 Heat and Moisture Flow

Henry [14] derived a model to predict the diffusion of heat and mass through fabrics based on the following assumptions:

- the volume change of the fibers due to moisture content is negligible,
- moisture transport through fibers can be ignored if the diffusion coefficient of water through the fibers is negligible compared to diffusion through air,
- the fiber orientation has a minimal role in water vapor transport since the fiber diameter is small and water vapor travels faster in air than in fibers.

The fourth assumption is that instantaneous thermal equilibrium between the fibers and water vapor is achieved during the diffusion process in the interfiber space due to the small fiber diameter and the large fiber surface to volume ratio. With these assumptions, Henry derived the following mass balance equation:

$$\varepsilon \frac{\partial C_a}{\partial t} + (1-\varepsilon)\frac{\partial C_f}{\partial t} = \frac{D_a \varepsilon}{\tau}\frac{\partial^2 C_a}{\partial x^2}$$

where the left side of the model describes the accumulation of water vapor in the interfiber space, while the right side is the accumulation of absorbed water in the fibers [14]. C_a represents the concentration of water vapor in the air, C_f is the concentration of water in the fiber, and ε is the fiber porosity, while τ is the time.

If changes in the heat content of the fiber due to conduction, absorption or desorption, or temperature changes are considered, then the conservation heat energy can be derived to be:

$$C_v \frac{\partial T}{\partial t} - \lambda(1-\varepsilon)\frac{\partial C_f}{\partial t} = K\frac{\partial^2 T}{\partial x^2}$$

where C_v the concentration of water vapor, and λ, the heat of sorption, are dependent upon the concentration of water absorbed by the fibers [14].

Crank formulated a model to predict evaporation and condensation as:

$$\frac{\partial C_f}{\partial t} = h_{cf} S_v (C_{fs} - C_a)$$

which is valid when the water content in the fabric is greater than the saturation regain of the fibers [15].

C_{fs} is the water concentration in the fiber surface.
C_a is the water concentration in the surrounding air.
h_{cf} is the mass transfer coefficient at the fiber surface.
S_v is the specific volume of the fabric.
C_f is the concentration of water vapor in the fiber, in the absorbed state.

David and Nordon created a model based on experimentation to determine the relationship between the rate of change of water content of a fiber and the absolute difference in relative humidity levels of the fiber and the surrounding air [16]. This model has the form of:

$$\frac{1}{\varepsilon} \frac{\partial C_f}{\partial t} = (H_a - H_f)\chi$$

where H_f represents the equilibrium relative humidity of the fiber, H_a is the relative humidity of the air, and ε is the packing density of fibers in the unit area. The variable χ can be further expressed as:

$$\chi = k_1(1 - \exp[k_2 |H_a - H_f|])$$

and k_1 and k_2 are adjustable parameters based on the results of experiments done on the desorption of moisture in a single wool fiber [16].

Nordon and David also created a model to predict the rate of moisture exchange between the solid fiber and the gaseous pore space:

$$\frac{1}{\rho(1-\varepsilon)} \frac{\partial C_F}{\partial t} = k(y_A - y_F)$$

where the moisture exchange rate is assumed to be proportional to the difference in relative humidities of the different areas [17]. In this model:

ρ is the fiber density,
ε is the porosity of the interfiber void space,
C_f is the concentration of absorbed water in the fiber,
k is the rate constant for mass transfer, and
y_A and y_F are relative humidity values of the air and fiber.

Li and Holcombe added to the knowledge base by assuming that water vapor absorption rates by a fiber consist of two stages: a first Fickian diffusion and a second exponential absorption [18]. Their model has the form of:

$$\frac{\partial C_f}{\partial t} = (1-p)R_1 + pR_2$$

where R_1 and R_2 represent the two different rates of absorption. The proportion of moisture absorption occurring during the second stage is represented by p. This model was based on experiments involving wool fibers.

Gibson used Whitaker's volume-averaging theory to create a model for multiphase heat and mass transfer through hygroscopic porous media [4]. The model below couples the dynamic behavior of a clothing system to heat regulation of the human body.

$$\begin{aligned}&\langle\rho\rangle C_p \frac{\partial T}{\partial t} + \left(\sum_j (C_p)_j \langle\rho_j v_j\rangle + \rho_\beta (C_p)_\beta \langle v_\beta\rangle + \sum_i (C_p)_i \langle\rho_i v_i\rangle\right).\nabla\langle T\rangle \\ &+ \Delta h_{vap}\langle\dot{m}_{lv}\rangle + Q_l\langle\dot{m}_{sl}\rangle + (Q_l + \Delta h_{vap})\langle\dot{m}_{sv}\rangle \\ &= \nabla.(k_{eff}{}^T.\nabla\langle T\rangle)\end{aligned}$$

Terms in angle brackets < > indicate a volume average over all phases, or over a single phase if a subscript is present.
The variable v is velocity.
k_{eff} is the effective thermal conductivity tensor.
Δh_{vap} is the heat of vaporization of the liquid phase.
Q_l is the heat of desorption from the solid phase.
$\dot{m}_{lv}$, $\dot{m}_{sl}$, $\dot{m}_{sv}$ represent the mass flux desorbing from the solid to the liquid, from the solid to the gas, and evaporating from the liquid, respectively.

Gibson has further elaborated on this model to take into account air and moisture transfer in multi-layer materials and in air spaces.

Another Gibson model [4] is a set of simplified equations for mass and energy balance:

$$(1-\varepsilon_\gamma)\partial C_F/\partial t+\varepsilon_\gamma \partial C/\partial t=(D_a\varepsilon_\gamma/\tau)(\partial^2 C/\partial x^2)$$
$$C_v\partial\langle T\rangle/\partial t-(Q_l+\Delta h_{vap})\partial C_F/\partial t=K\partial^2\langle T\rangle/\partial x^2$$

where the variables are as follows:

ε_γ -	Volumetric fraction of gas phase
C_F -	Concentration of water in the solid
C -	Concentration of water in the gas phase
D_a -	Diffusion coefficient of water vapor in air
τ -	Tortuosity factor
C_v -	Volumetric heat capacity
$\langle T\rangle$	Total thermal energy
Q_l -	Volumetric flow rate of liquid
Δh_{vap}	Enthalpy of vaporization per unit mass
K -	Effective thermal conductivity.

This model is valid when all the following conditions are true:

- There is no liquid or gas phase convection.
- There is no liquid phase present.
- The gas phase heat capacity is negligible.
- The volume of the solid textile remains constant and does not swell.
- The solid and gas phase volume fractions are constant, the thermal conductivity tensor can be expressed as a constant scalar thermal conductivity coefficient.
- The gas phase diffusion coefficient is constant.
- The transport is one dimensional.

Modeling of fluid and heat flow through fabrics has become more complex during the past several decades as understanding of these phenomena has increased. As a result of this increased understanding, more variables must be considered when attempting to predict heat and fluid flow through fabrics. While this can result in greater accuracy in predicting properties, these advanced models also require computers to perform the calculations and time consuming characterization of the fabrics themselves.

3.2 Available CFD Software

There are currently several CFD software packages available for modeling flow through materials: Fluent, Flovent®, PHOENICS, Ansys CFX®, CFD FASTRAN, and CFD ACE+.

Based on a review of modeling literature, Fluent appeared to be the most popular modeling software. Hence, the decision was made to use Fluent for these modeling efforts.

3.3 Initial Modeling Work – Nonwoven Fabrics

3.3.1 Selection of Fabrics

Initial modeling work focused on nonwoven fabrics, as they are relatively easy to model due to their simpler structure; they consist of bonded fibers, rather than interlaced yarns made up of fibers. The nonwovens consisted of a spunbond and thermally bonded polyester, of unknown origin, designated SBPET; 36P, which is Provent 1000 by Kappler, a polypropylene spunbond and thermally bonded nonwoven; and 61S, a spunbond, thermally bonded nonwoven supplied by DuPont and included in the Universe of Fabrics assembled by LEHP researchers.

Air permeability and thermal conductivity have been measured for many of these fabrics with an automatic air permeability tester and a KES Thermolabo II, respectively, both manufactured by Kato Tech. Fabric thickness was evaluated with a thickness tester having a foot diameter of 2.54 cm. All fabrics were conditioned 24 hours at standard temperature and humidity levels per ASTM requirements, D1776 [19].

3.3.2 Modeling Heat and Moisture Flow through Single Layers and Multi-Layered Systems

Initial modeling focused on predicting heat and moisture flow through single layers of SBPET, 36P, and 61S.

Once initial modeling was successfully correlated to measured results, multilayered systems were evaluated and modeled. These systems consisted of the nonwoven fabrics layered in various configurations, some of which were bonded together with a polyvinylalcohol resin, while others were simply stacked together. Airflow measurements consisted of measuring flow through the multifabric systems from both sides to determine if there were any differences in air flow due to construction of the system.

The idea behind modeling of heat and fluid flow through garments is to be able to determine how fabric properties will affect the flows through fabric systems without having to actually create such systems and test them. The scheme follows the flowchart in Figure 1. The original model was created by Gibson and reported previously in a Natick report [4].

Gibson used hypothetical cotton and polyester fabrics for evaluation of his model. Using the same hypothetical fabric parameters, the modeling advances achieved in this project were evaluated to ensure that the modeling methods used in this project were capable of obtaining the same results as Gibson reported. Subsequently, in this project several one-layer fabrics were used for the initial modeling work. The goal was to eventually have the ability to model not only the heat and fluid flow through a single fabric, but also through a fabric system comprising several layers of different fabrics.

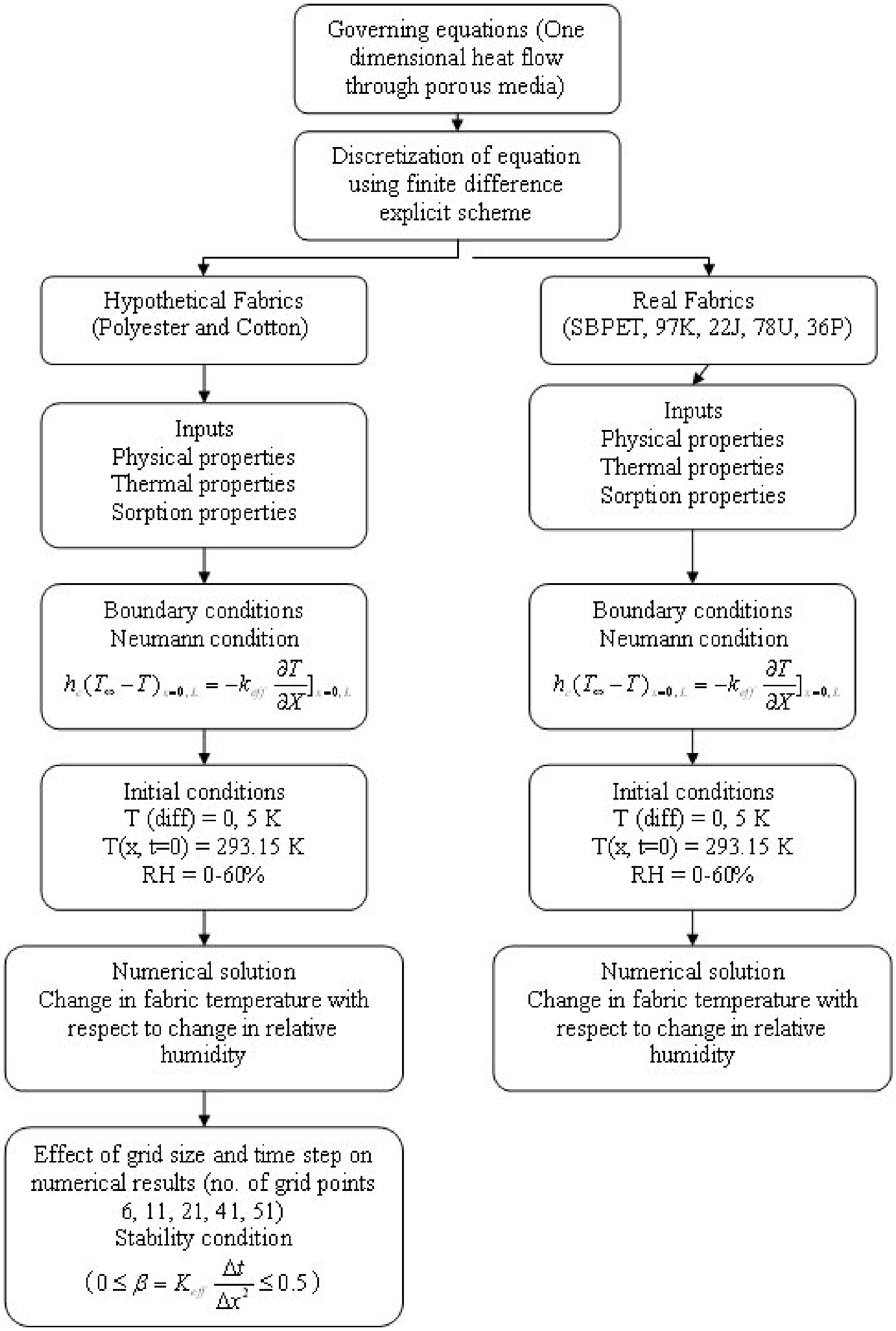


Figure 1. Gibson's General Method of Modeling a Property [4], Modified (Heat Flow Through a Fabric).

A one dimensional model that couples energy and mass diffusion through a material was identified from a Gibson report [4]:

Energy equation:

$$\rho C_p \frac{\partial T}{\partial t} + (Q_l + \Delta h_{vap})\dot{m}_{sv} = \frac{\partial}{\partial x}\left(K_{eff}\frac{\partial T}{\partial x}\right) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Solid phase continuity equation:

$$\frac{\partial \varepsilon_{bw}}{\partial t} + \frac{\dot{m}_{sv}}{\rho_w} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Gas phase diffusion equation:

$$\frac{\partial}{\partial t}(\varepsilon_\gamma \rho_v) - \dot{m}_{sv} = \frac{\partial}{\partial x}\left(D_{eff}\frac{\partial \rho_v}{\partial x}\right) \quad \ldots\ldots\ldots\ldots (3)$$

ρ	-	Volume average density (kg/m^3)
C_p	-	Mass fraction weighted average constant pressure heat capacity
Q_l	-	Enthalpy of desorption from solid phase per unit mass (J/kg)
Δh_{vap}	-	Enthalpy of vaporization per unit mass (J/kg)
T	-	Temperature (K)
$\dot{m}_{sv}$	-	Mass rate of desorption from solid phase to vapor phase per unit volume
K_{eff}	-	Effective thermal conductivity
ε_{bw}	-	Volume fraction of water dissolved in the solid phase
ρ_w	-	Density of liquid water
ε_γ	-	Volume fraction of the gas phase
ρ_v	-	Density of water vapor in the gas phase
D_{eff}	-	Effective gas phase diffusivity

These formulas can be used to model heat and fluid flow through single fabric systems as follows. The first two models uncouple mass (moisture) and heat flow through fabrics to simplify the modeling process and better understand how the fabric parameters affect the flow properties. Gibson's third model re-couples mass and heat flow to provide an overall idea of the flows through the fabric (see Figure 2).

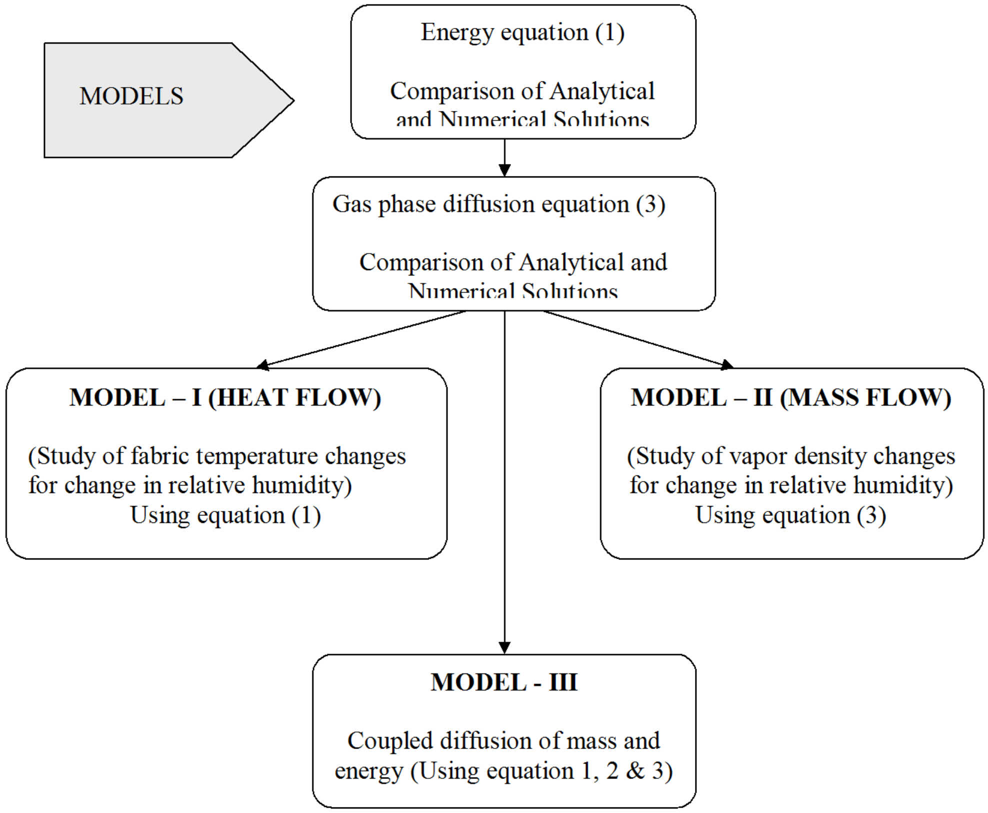


Figure 2. Division of Models into Distinct Models Which Consider One Component of a Fabric's Properties [4].

The ability to separate out heat and mass flow provides the opportunity to determine what fabric parameters affects each flow type individually. The ability to re-couple these flows allows one to approximate actual conditions and thus obtain more realistic results which should better correlate with actual evaluation. Results of these modeling efforts are discussed in the section of this report titled "Heat and Fluid Flow Modeling – Final Results".

3.4 Heat Flow Modeling Efforts

The heat flow modeling effort can be visualized in the chart in Figure 3. Before work on the project was suspended, heat flow modeling had progressed to the point of not only evaluating Gibson's hypothetical fabrics, but also some single layer fabrics from the Universe of Fabrics, as explained in the section titled "Heat and Fluid Flow Modeling – Final Results".

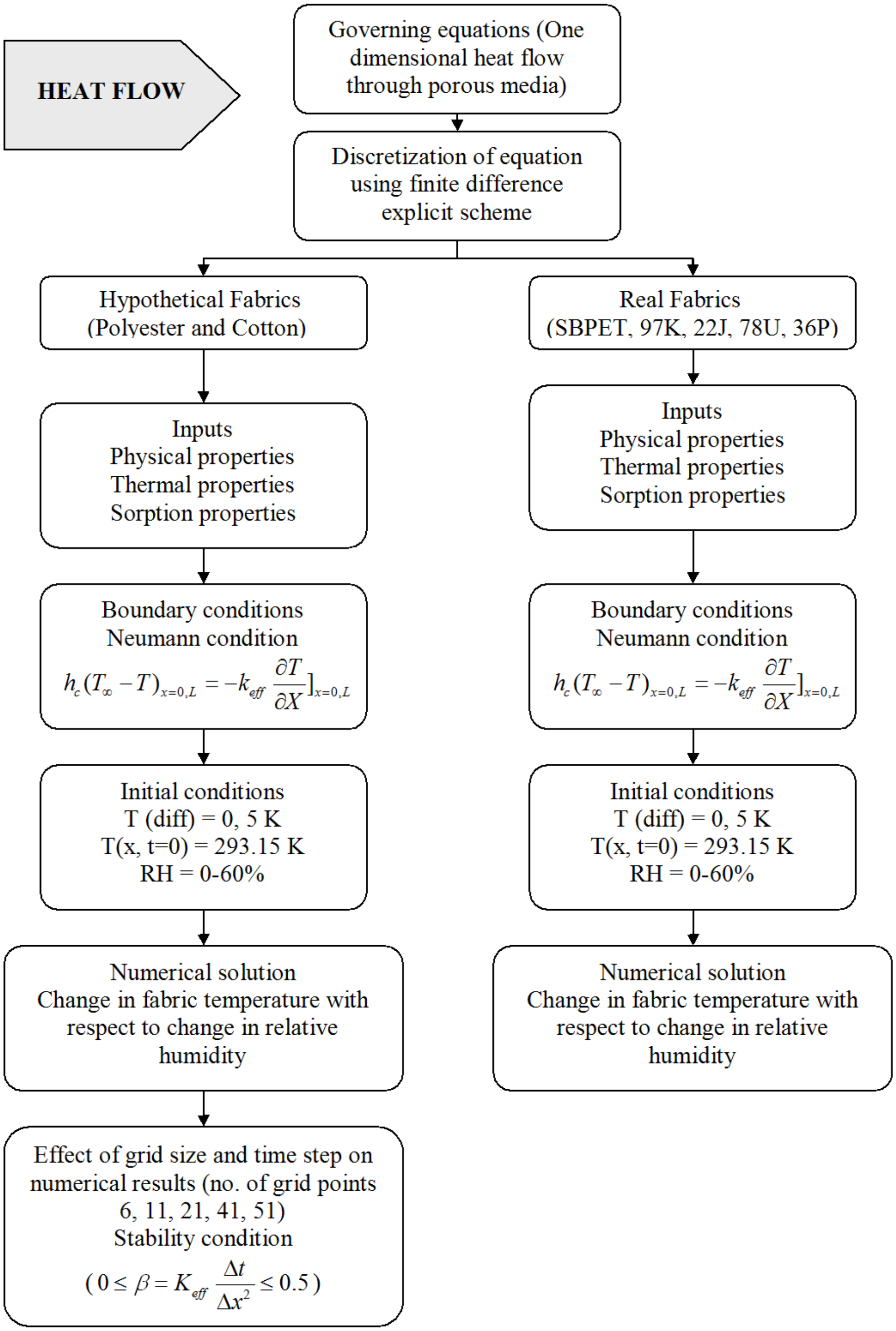


Figure 3. Flowchart for Modeling Evaluation of Heat Flow through a Fabric

3.5 Mass Flow Modeling Efforts

Mass or moisture flow through the fabric system can be studied via the flow shown in Figure 4. By the end of this study, mass flow progressed only to the hypothetical fabrics, results of which can be found in the section of this report titled "Heat and Fluid Flow Modeling – Final Results".

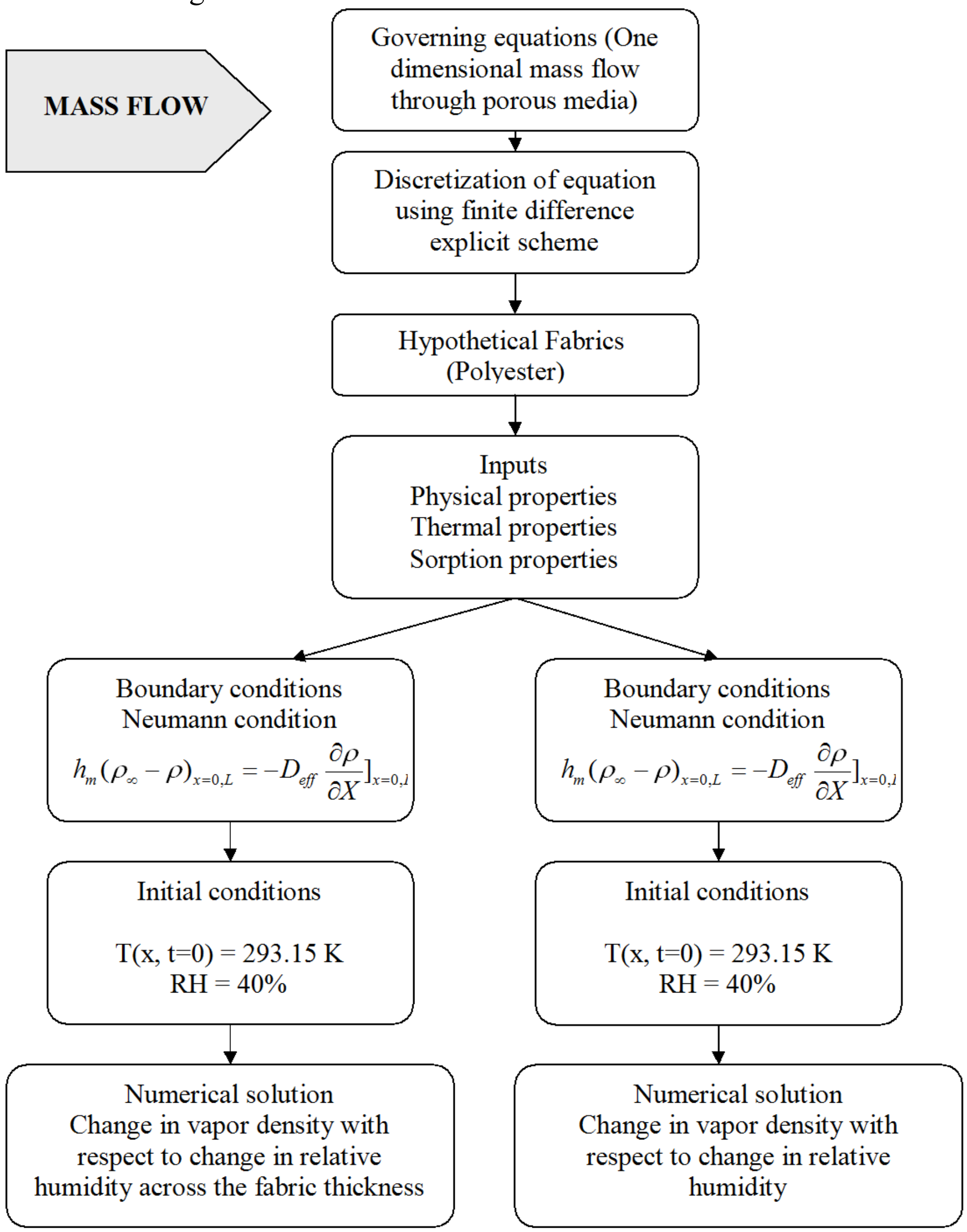


Figure 4. Flowchart for Modeling Evaluation of Mass Flow through a Fabric, Modified [4].

3.6 Modeling Flow Around the Body

In addition to modeling heat and fluid flow through fabrics, this project used CFD to examine flow around the body, particularly tubular components, such as the arms, torso, and legs. The idea here was that environmental conditions, such as wind and temperature, during use of the multilayered textile structures should be taken into account to accurately predict heat and moisture vapor through the garment. For this purpose, a thin cross-section of the tubular objects was evaluated, which can be considered thin enough to not have any thickness, and thus can be modeled as a two-dimensional object. Only the middle of the body was evaluated, which comprises sections of the torso and two arms, using Fluent version 6.

The only parameter studied was airflow over these objects without considering the heat production rate caused by metabolic processes within the body. An air velocity of 2 meters per second (m/s), considered to be a laminar flow, was used. The air exhausted into ambient atmosphere, which was considered to have a pressure of 1atm. Air density and viscosity were kept at 1.225 kg/m^3 and 1.79e-05 respectively. A triangular mesh, depicted in Figure 5, was used for this study.

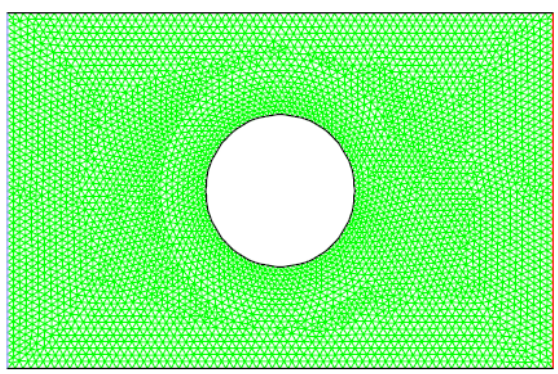


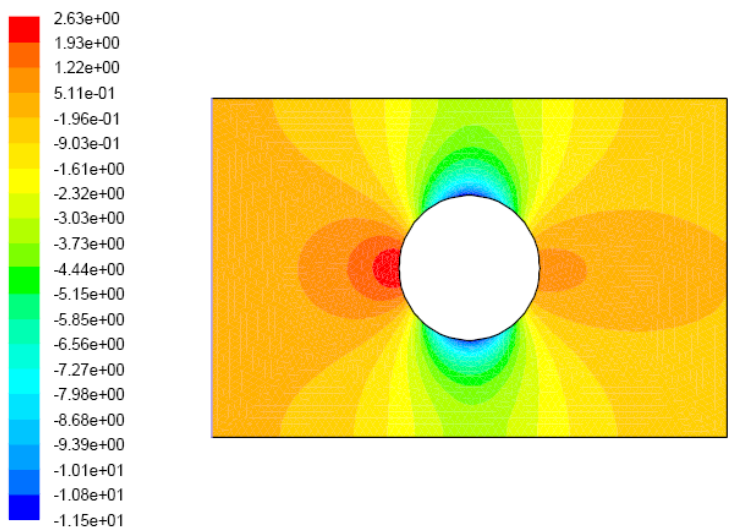
Figure 5. Computational Domain with Mesh for Flow Around Circular Surface

4. Results and Discussion

4.1 CFD Body Modeling

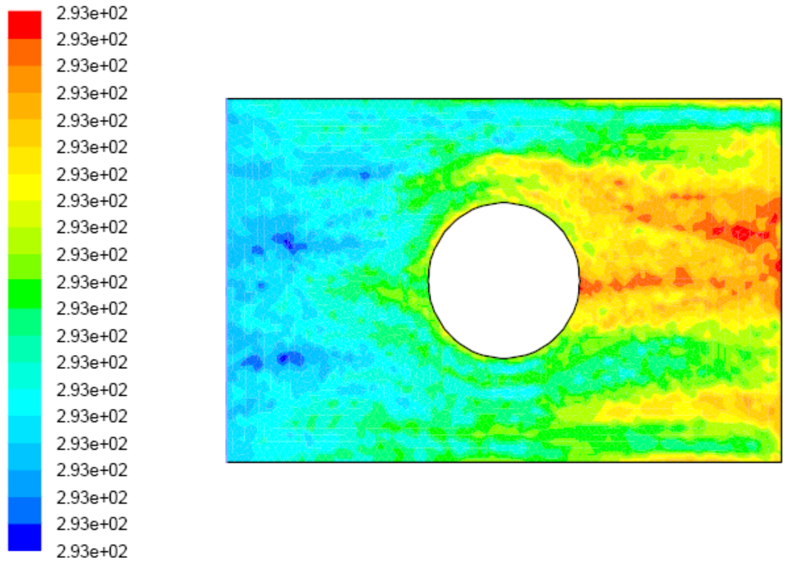
Initial modeling focused on modeling airflow around the body, which can be considered to be a set of tubular structures, with the legs and torso comprising one structure, while the arms are separated structures apart from the leg and torso structure, because the arms are generally held apart from the body in many situations.

The convergence of solution is obtained at 72nd iteration and the values of residuals are plotted against number of iterations. Figures 6 and 7 show the pressure and temperature distribution around the cylindrical surface. This analysis is made to compare the results and the effect of arm structures of the human body on the fluid flow characteristics.



Static pressure scale

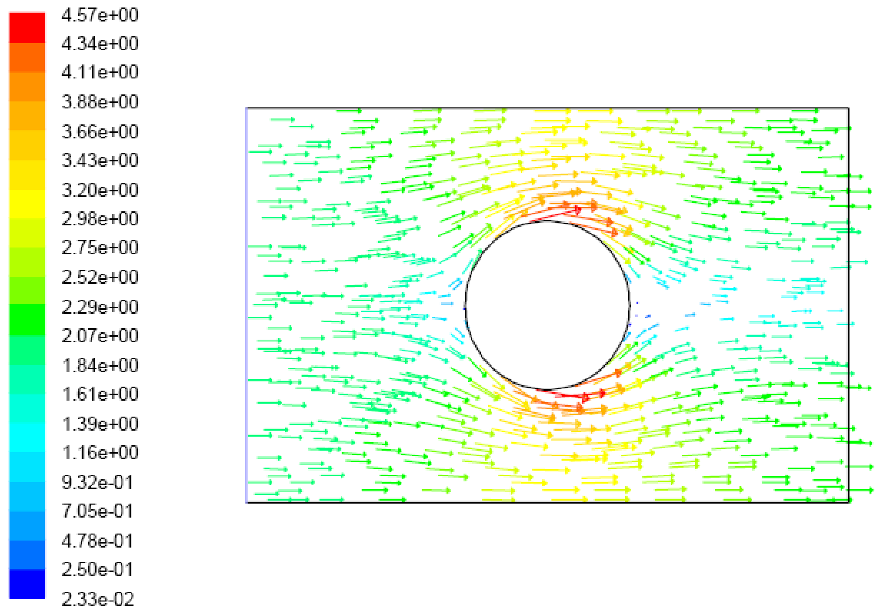
Figure 6. Contours of Static Pressure (Pascals)



Static temperature scale

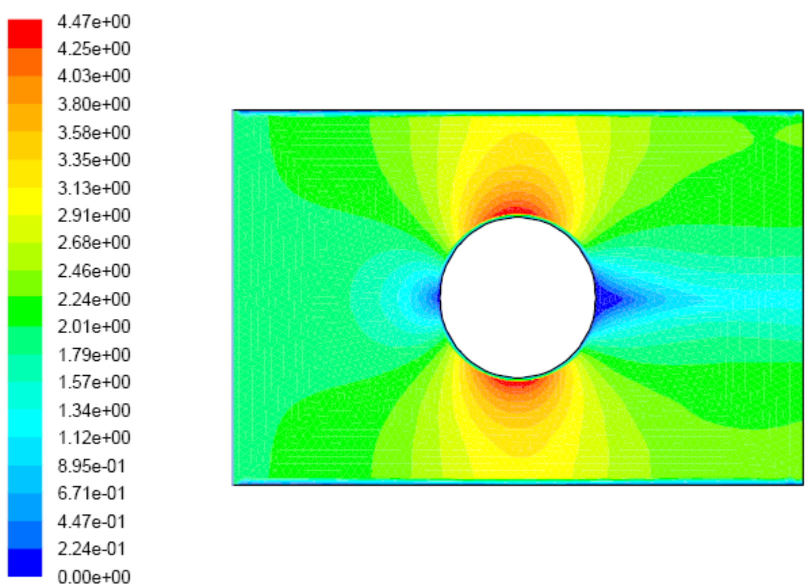
Figure 7, Contours of Static Temperature (K)

The velocity vectors depict how the flow develops downstream of the cylinder. The contours of velocity are colored according to their magnitude. The velocity magnitude of flow around a cylinder surface is highest at the parallel flow, as shown in Figure 8. Figure 9 is an alternative view of Figure 8, depicting contours rather than vectors of velocity magnitude.



Velocity Magnitude scale

Figure 8: Velocity Vectors Colored by Velocity Magnitude (m/s)



Velocity Magnitude scale

Figure 9. Contours of Velocity Magnitude (m/s)

The above flow modeling has given a general idea of airflow over two-dimensional bodies. The following work shows the flow modeling of

2-D human body cross section across the girth measurement. Figure 10 also depicts the mesh used to determine flows. Figure 11 depicts the scaled residuals as a function of the number of iterations processed. Clearly, a greater number of iterations results in decreased residuals.

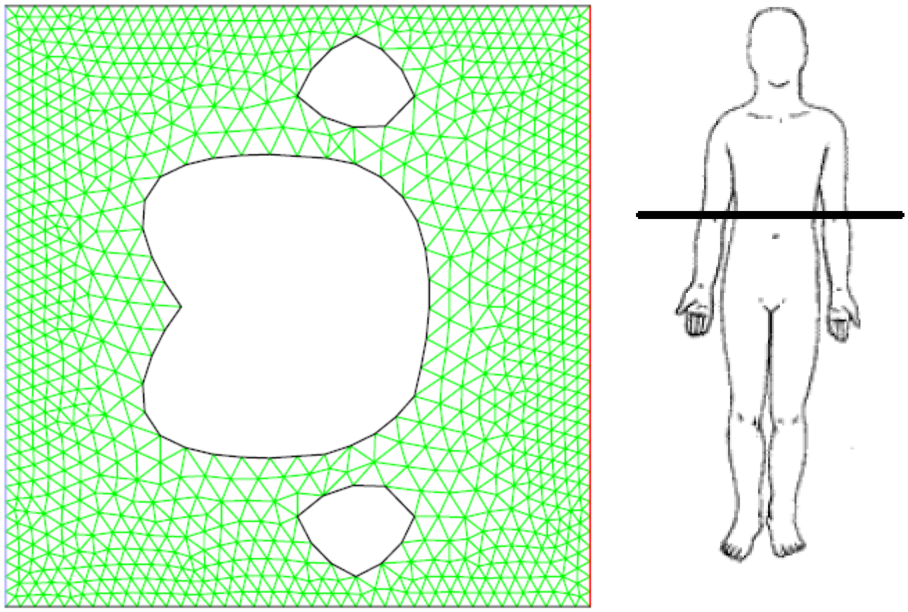


Figure 10: Computational Domain with Mesh for 2-D Human Body Structure

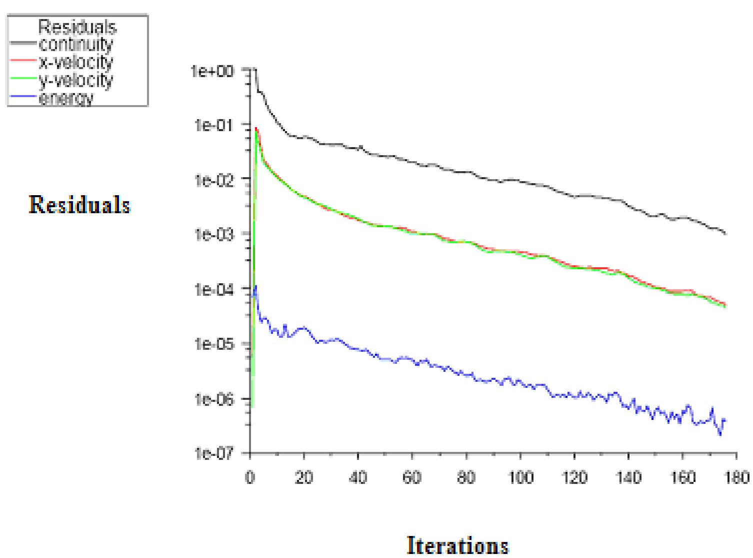
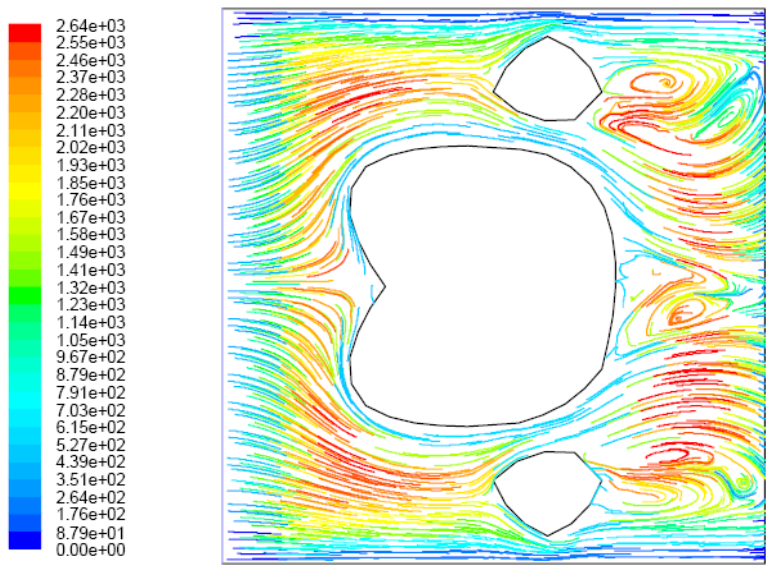


Figure 11. Scaled Residuals in the Converging Range

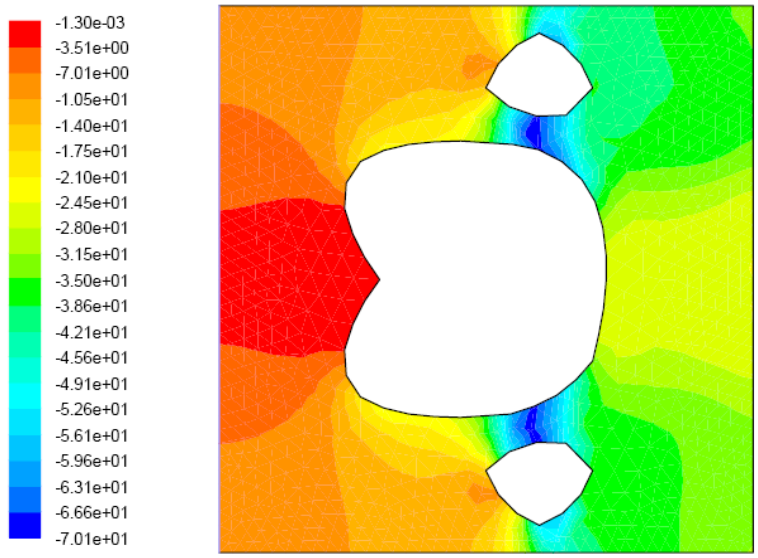
The path lines in Figure 12 specify the flow field with respect to particle positions, the torso and arms, in space.



Particle reference scale

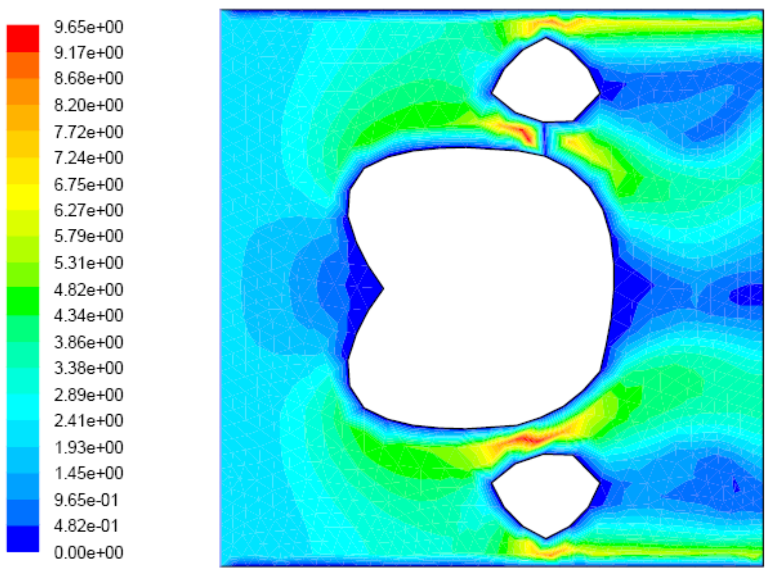
Figure 12: Path Lines Colored by Particle ID

From the above picture it is clear that eddies are created at the back end of the flow structure. Pressure distribution around the surfaces, depicted in Figure 13, point out the low and high pressure areas between the arm and body structure, while Figure 14 depicts the variations in velocity as air flows around the body. These figures will give proper guidance to design future protective garments suitably to allow for effective cooling.



Static pressure scale

Figure 13: Contours of Static Pressure (Pascal)



Velocity Magnitude scale

Figure 14: Contours of Velocity Magnitude (m/s).

These efforts were modeled for an air temperature of 20 °C and air velocity of 2 m/s. The above results display the high velocity point developed in between the body and arms. The velocity profile and path line are the important CFD simulations that show the factors that influence flow for garment design. Understanding and knowledge of this phenomenon can be used in future iterations of protective garments developed at Philadelphia University to provide greater cooling capabilities.

4.2 Thermal Resistance Modeling

Based on the above experiments, thermal resistance of two fabric systems from the Universe of Fabrics was evaluated. The fabrics, 98H and 10R, were considered to be tubular structures similar to a pant leg or shirt sleeve, and covered a heat-generating cylinder. Both tightly and loosely fitting structures were modeled under different external air flows, approximating various wind conditions. Loose fitting meant that there was a space of 0.01 m between the heat generating cylinder and the fabric, while tight fitting indicated no air space between the cylinder and the fabric.

Figures 15 and 16 show the overall thermal resistance of fabric covered cylinders at various air speeds. The green line represents fabric 98H; the red line represents fabric 10R. As wind speed increases the thermal resistance of the fabric systems decreases, due to convection. Loose fitting garments seem to provide more thermal resistance than tighter fitting garments, most likely due to the air space between body and garment, which allows for more heat accumulation.

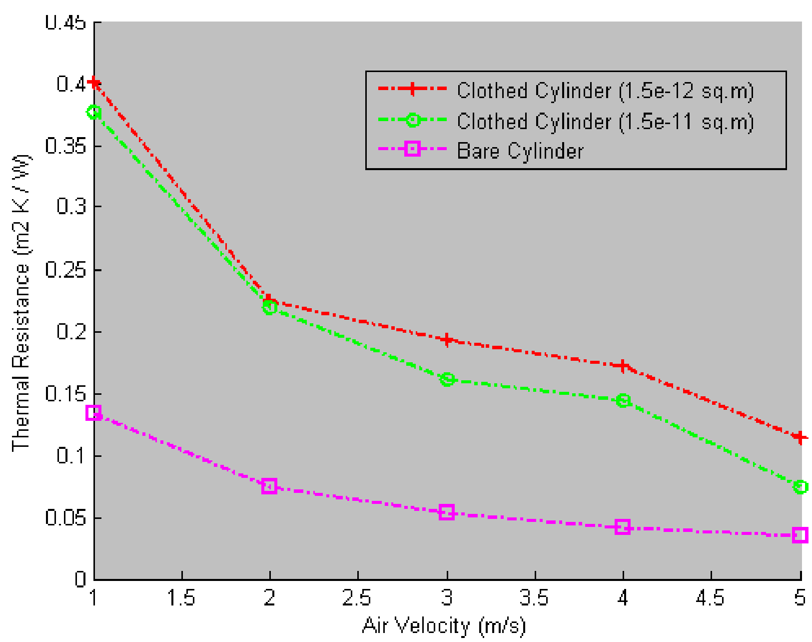


Figure 15. Overall Thermal Resistance of Fabric-Covered Cylinders at Various Air Speeds – Loosely Fitted Garments

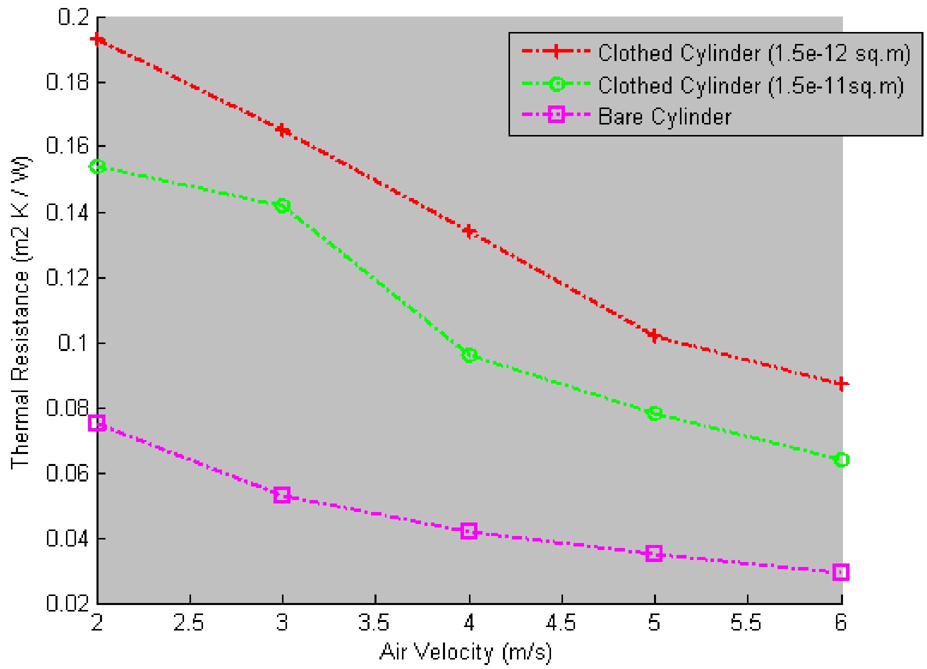


Figure 16: Overall Thermal Resistance of Fabric-Covered Cylinders at Various Air Speeds – Tightly Fitted Garments

4.3 Heat and Fluid Flow Modeling – Preliminary Results

Several fabrics were considered for initial modeling efforts: SBPET, 36P, 61S, 73R, 46E, 54Q, and two semi-permeable membranes supplied by Deerfield Polyurethane: M1 and M2.

However, several of these fabrics, 73R, a spunbond polypropylene fabric supplied by Kappler; 46E, a nonwoven containing a microporous film, supplied by DuPont; and 54Q, a spunbond and thermally bonded polypropylene fabric supplied by Kappler; and both membranes, M1 and M2, were discovered to be relatively "impermeable." Because of their small pore size in the membranes M1 and M2, as well as the membranes in 73R, 46E, and 54Q, no results could be obtained via the air permeability evaluation equipment at Philadelphia University. Therefore, these three fabric systems and both membranes were not further considered for modeling purposes.

In contrast to the above fabrics, the nonwoven fabrics, SBPET, 36P, and 61S were too porous for accurate air permeability results to be obtained using the equipment at Philadelphia University.

To determine if airflow direction would dramatically alter the results of air permeability evaluations for multi-component systems, a three-layer nonwoven fabric system containing an inner layer of SBPET, middle layer of 36P, and an outer layer of 61S was created. SBPET is a spunbond and overall thermally bonded polyester fabric. 36P refers to a spunbond and thermally bonded polypropylene fabric provided by Kappler. 61S is a spunbond, thermally bonded polyester fabric supplied by DuPont.

The results are depicted graphically in Figure 17, which shows little difference in air-flow properties regardless of flow direction evaluations.

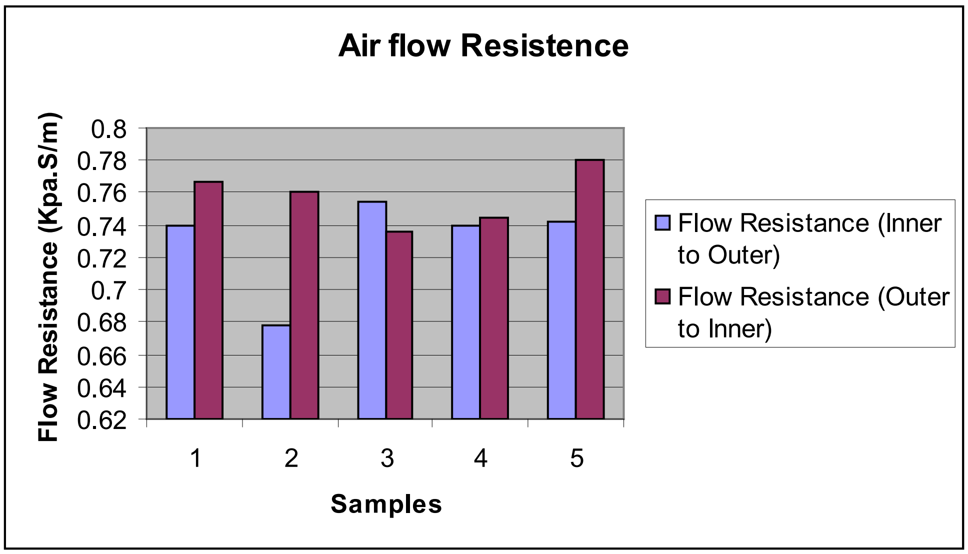


Figure 17: Influence of Layer Assembly in Multilayer Air Flow

A T-test value at a 95% confidence limit shows that there is no significant difference between two-way air flows. Since the T-calculated value is less than T-actual, the null hypothesis is accepted. This shows that the consideration of airflow in two-way flow characteristic analysis is not significant in modeling compared to heat and moisture vapor transfer. However, if a fabric system is being modeled on a person, then the direction of flow must be taken into account.

T-test (95% confidence limit)

Accepting Null hypothesis – There is no significant difference	
T_{cal}	1.594
T_{act}	2.132

Figure 18. T-Test Results for Determining If There Is a Significant Difference in Direction of Air Flow through Multi-Layer Fabric Systems during Air-Permeability Testing.

After gaining experience with modeling flow through a single layer of SBPET, efforts moved on to a three-layer SBPET fabric system to further explore modeling. It was found that there is a difference between simply stacking the different layers and bonding them together; see Figure 19. When the fabric layers are stacked they often touch only at discrete points. As a result, the fabrics have layers of air separating them. As air is one of the best known insulators, stacking of the fabrics results in lower thermal conductivity values than fabric systems that have adhesive between the layers, which eliminates the insulating air layer.

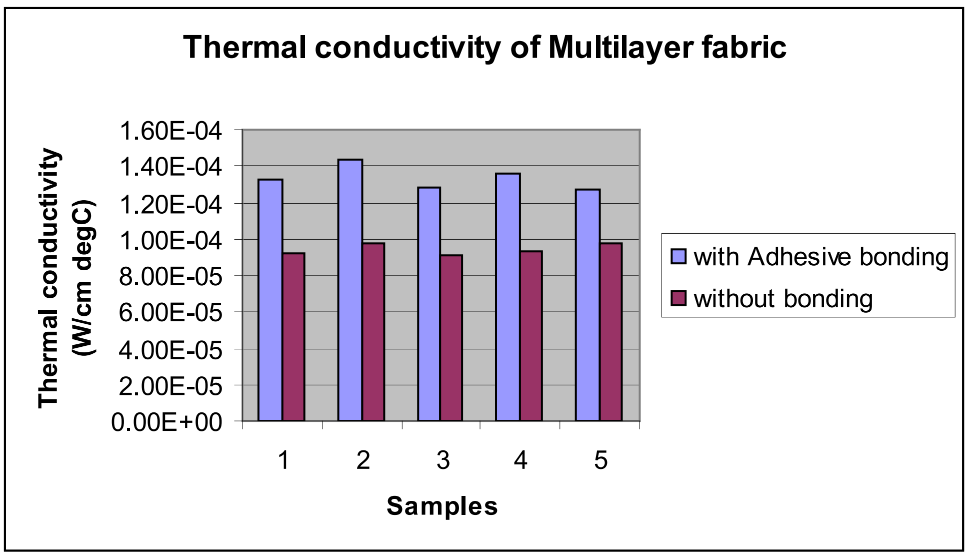


Figure 19. Influence of Interlayer Adhesive Bonding in Multilayer Thermal Flow

A T-test, depicted in Figure 20, shows that there is a significant difference between the thermal conductivity of stacked fabrics versus bonded fabrics. However, if adhesive or other bonding between the layers is used, its presence may affect the fit between the model and actual results. This should be studied further in the future.

T-test (95% confidence limit)

Rejecting Null hypothesis – There is a significant difference	
T_{cal}	13.635
T_{act}	2.132

Figure 20. T-Test Results for Determining If There Is a Significant Difference Between Stacked Fabrics and Bonded Fabrics in Thermal Conductivity of the Fabric System

This difference is evident when a circuit model is used in an attempt to model thermal conductivity of the three layer SBPET system. A circuit model has the form of:

$$\frac{\lambda}{K_{t(cond)}} = \frac{L_1}{K_{1(comp)}} + \frac{L_2}{K_{2(comp)}} + \ldots\ldots + \frac{L_n}{K_{n(comp)}}$$

where:

λ refers to total thickness of the multilayer assembly,
L refers to the single fabric layer thickness, and
K is the thermal conductivity [15].

This model assumes that each fabric is touching the next layer with no air between layers. Each layer of the SBPET has a thickness of 0.025cm, a basis weight of 0.004706 g/cm^2, and a solid volume fraction of 0.144.

As depicted in Figure 21, the circuit model fails to predict the thermal conductivity of the three-layer SBPET system consisting of stacked fabrics. This model also does not consider thermal diffusivity, which could also lead to the lack of agreement with measured values.

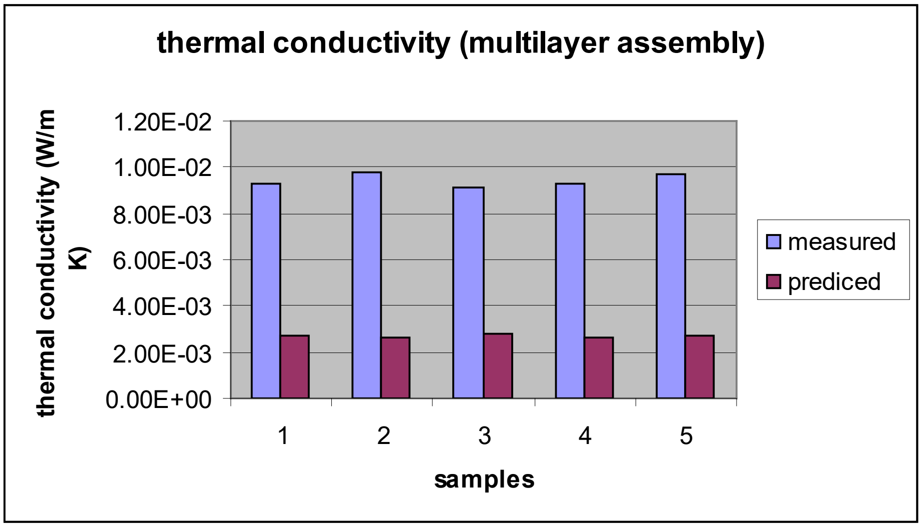


Figure 21. Thermal Conductivity of Three-Layer SBPET Assembly

However, the circuit model does predict air permeability of layered SBPET fabric systems more reliably than it does thermal conductivity. When a two-layer SBPET system was modeled the results obtained were in somewhat close agreement with the test results, as depicted in Figure 22.

However, when a third layer was added, the agreement between measured and predicted values decreased somewhat, as depicted in Figure 23. This decrease could be due to variability in the fabric specimens, such as thickness or basis weight, rather than a modeling issue. More fabric assemblies would need to be evaluated and modeled to determine the cause of this lower level of agreement.

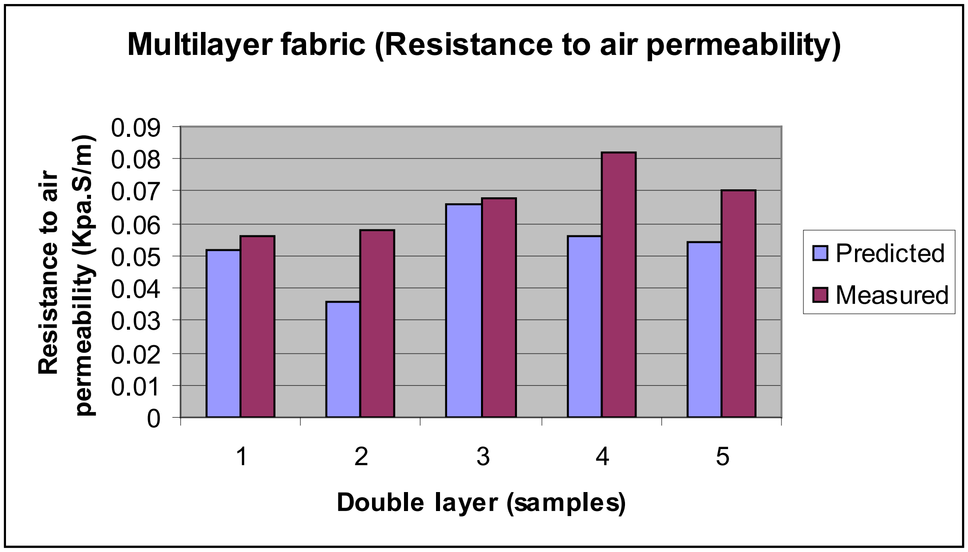


Figure 22. Agreement Between Measured and Modeled Air-Permeability Results of Two-Layer SBPET Assembly.

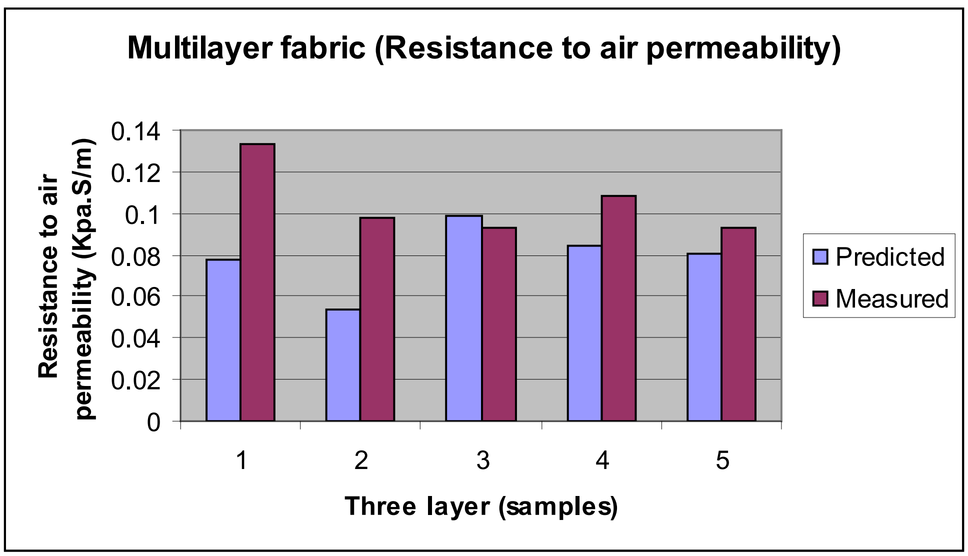
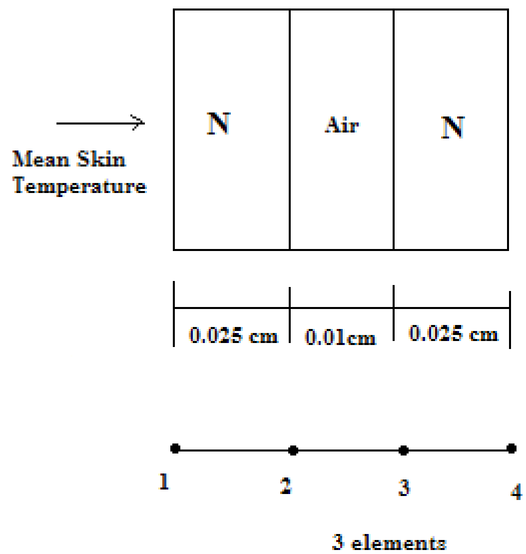


Figure 23. Agreement Between Measured and Modeled Air-Permeability Results of Three-Layer SBPET Assembly

Other models, however, do take this air layer between fabric layers into account. Most of these models are finite-element models that consider fabric systems between the skin and the outer environment. Gibson [14] has proposed the following:



where N represents a SB PET nonwoven fabric with the mathematical model of

$$K_x \frac{d^2T}{dx} = \frac{hP}{A}(T - T_a)$$

where:
h is the convection coefficient.
P is the peripheral dimension.
A is the cross-sectional area.
Ta is the ambient fluid temperature.
T is the temperature of the body surface.

Others have considered models that factor in phase change of the liquid, surface characteristics of the fabric, such as surface profile, surface tension, and air space between layers, and coupled heat and moisture transfer. However, these models consist of sets of equations and become complicated to solve since parameters such as diffusion flux between the layers might become variable depending on the properties of each layer. Generally, these models are solved through the use of software such as computational fluid dynamics.

To better understand thermal flow through the selected fabric systems it is necessary to use thermocouples on each fabric in order to accurately measure the temperature of each fabric and determine whether the layers in the system are touching or if they are separated by air. This might result in better correlation between the models and the results garnered during evaluation. If this is accomplished, a further goal can be to correlate these models with results obtained from the sweating guarded hotplate. Although this has been done for single layer fabrics, it has yet to be reported for multi-layer fabric systems.

4.4 Heat and Fluid Flow Modeling – Final Results

The charts in Figure 24 provide the inputs used in the modeling of heat and fluid flow through fabrics for the efforts made prior to project termination. The hypothetical fabric inputs were provided by Phil Gibson of the U.S. Army Natick Soldier Research, Development & Engineering Center, but can also be found in Appendix A of reference 4. Real fabrics were also evaluated to determine if the models developed by Gibson for hypothetical fabrics would be adequate for actual fabrics.

The real fabric parameters were measured in the Grundy Lab at Philadelphia University; see Figure 24. The SBPET and 36P fabrics utilized in the preliminary work were used for this research, as well as some new fabric systems: 97K, 22J, and 78U. The label "S" next to the fabric name in Figure 24 indicates that the fabric is a single layer, while the label "M" refers to a multi-layer textile system. 97K is multi-component system of knit polyester and woven nylon with polyurethane laminated to the fabric. It was supplied by Stedfast and has the commercial name of Stedair II CW Woodland. 22J, supplied by Optimer, and known as Dri-Release, is a modacrylic and rayon blended single jersey knit fabric. The origin of 78U is unknown.

Inputs for hypothetical fabrics

Hypothetical fabrics	Thickness (m)	Areal density (kg/sq.m)	Bulk density (kg/cu.m)	dry solid density (kg/cu.m)	Dry solid volume fraction	Regain at 65% RH	Heat capacity (J/kgK)	Thermal conductivity (J/smK)
Polyester woven	5.89E-04	0.24	407	1390	0.293	0.004	1340	0.14
Cotton woven	3.84E-04	0.2	521	1550	0.336	0.07	1210	0.16

Inputs for real fabrics

Real fabrics	Thickness (m)	Areal density (kg/sq.m)	Bulk density (kg/cu.m)	dry solid density (kg/cu.m)	Dry solid volume fraction	Regain at 65% RH	Heat capacity (J/kgK)	Thermal conductivity (J/smK)
SBPET – S nonwoven	2.50E-04	0.0471	188	1390	0.1353	0.004	1340	0.14
97K – M laminated	4.30E-04	0.236	548	1140	0.4807	0.041	1430	0.25
22J – S knit	5.70E-04	0.1967	346	1418	0.244	0.032	1185	0.191
78U - S	2.29E-04	0.099	432	1345	0.3212	0.056	1320	0.2
36P – S nonwoven	3.32E-04	0.0562	169	1390	0.1216	0.004	1340	0.14

Figure 24. Fabric Parameters Used in Modeling Efforts

Most of the final modeling effort focused on heat flow. One area of study was to determine the effect of change in the relative humidity from 0% to 90% on both sides of the fabric, given a constant temperature of 293K (20 °C) for both sides of the fabric. This change in humidity levels approximates the change of temperature in the fabric due to the increase of humidity. This would be similar to fabric temperature changes due to sweating of a soldier while wearing a garment made of such fabric. This effort approximated Model I contained in Figure 2.

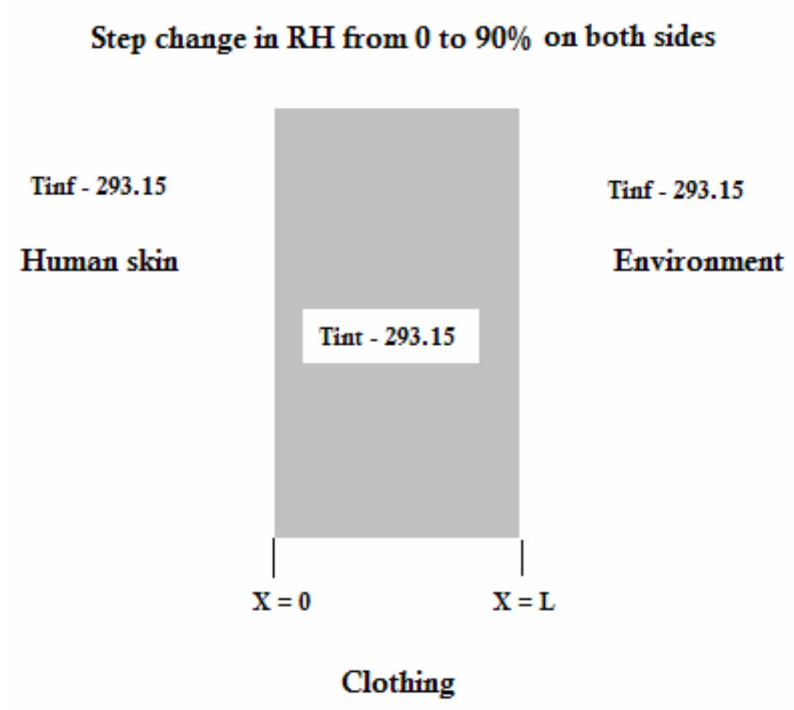


Figure 25. Illustration of Boundaries Utilized in Modeling Fabric Temperature Effects Due to Change of Humidity

Another study varied the relative humidity from 0% to 90% on both sides of the fabric with the fabric conditions maintained at 40% relative humidity and a temperature of 293K (20 °C). This simulates changes in gas phase vapor density and can provide a measure of how gaseous fluid, such as moisture vapor, flows through the fabric as surrounding relative humidity on either side of the fabric changes. This study corresponds with Model II in Figure 2.

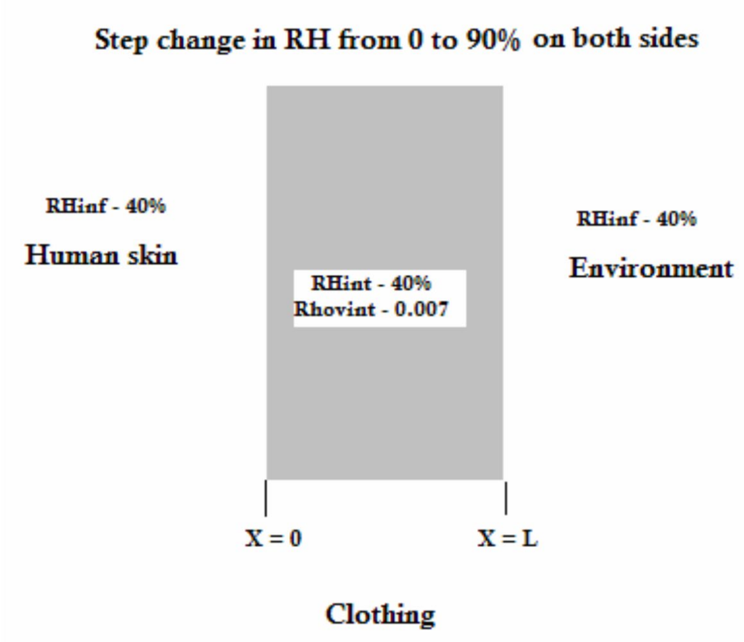


Figure 26. Illustration of Boundaries Utilized in Modeling Gas Vapor Flow Effects in the Fabric Due to Changes in Humidity in the Surrounding Environment

The third model presented in Figure 2 couples the mass and energy equations. This model simulates the effects on the fabric due to sudden changes in temperature and humidity on both sides of the fabric. The first simulation evaluated changes in the fabric due to sudden changes in the surrounding humidity; the second simulation measured the changes in the fabric due to variation in the humidity and temperature levels on either side of the fabric, as illustrated in Figure 27.

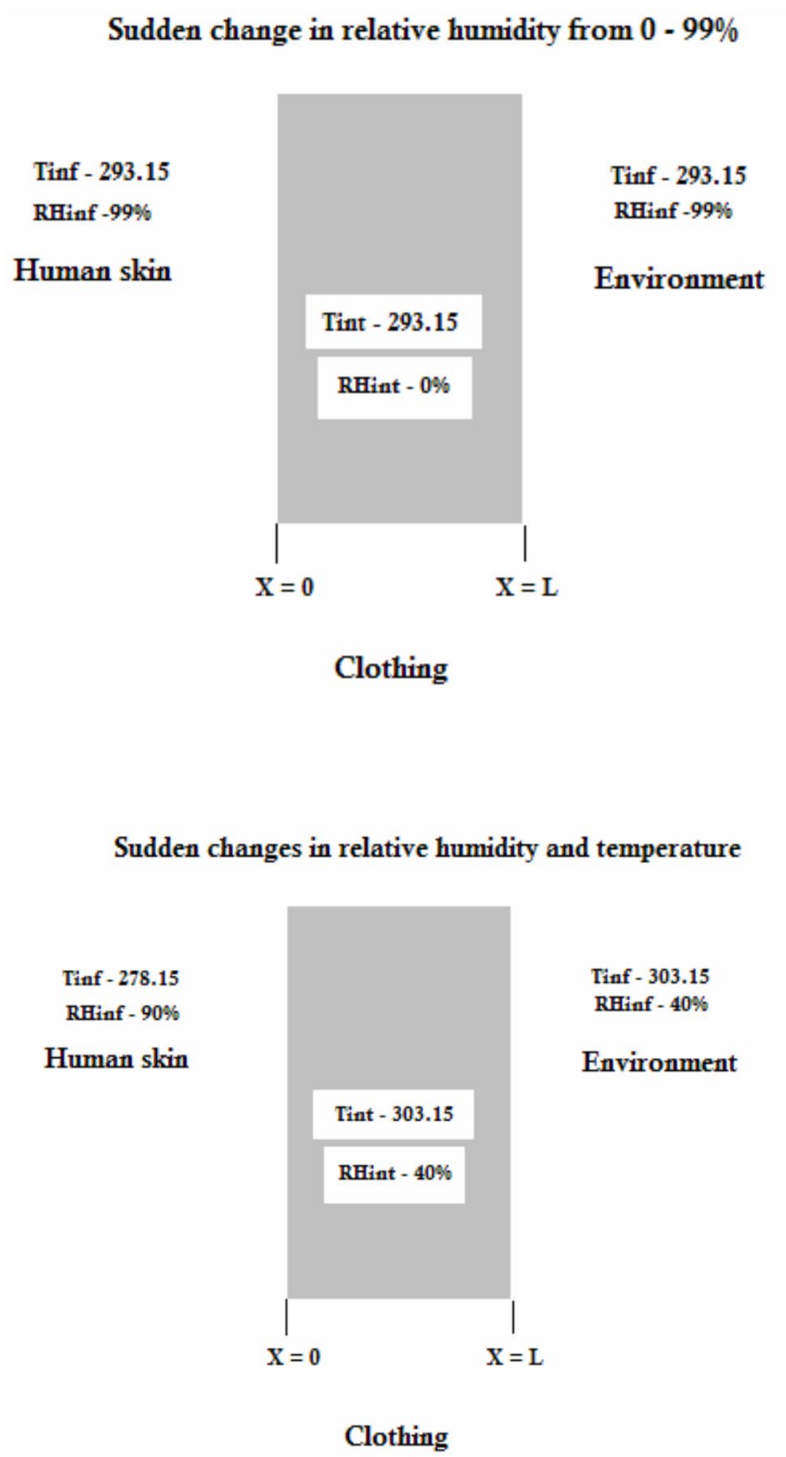


Figure 27: Illustration of Boundaries Used in Coupled Model for Two Different Simulations

Model I, as illustrated in Figure 2, was solved both numerically and analytically.

The analytical solution has the form of:

$$T = T_{\infty} + (Q_l + \Delta h_{vap}) \frac{\dot{m}_{sv}.h^2}{K_{eff}} \left[\frac{\overline{x}^2}{2} - \frac{\overline{x}}{2} - \frac{K_{eff}}{2h.h_c} \right]$$

The values obtained for both solutions were compared as illustrated in Figure 28. Numerical results were obtained with Fluent software.

Effect of grid size on the agreement of the numerical models with the analytical model was also studied at this time, with those results provided in Figure 28. As grid size decreased the numerical model started to mirror the results provided by the analytical solution. This is not surprising, as smaller mesh usually provides more valid results, although the time required for computing these results increases as the mesh size decreases. By using a smaller grid size the software was able to approximate the analytical solution with good results.

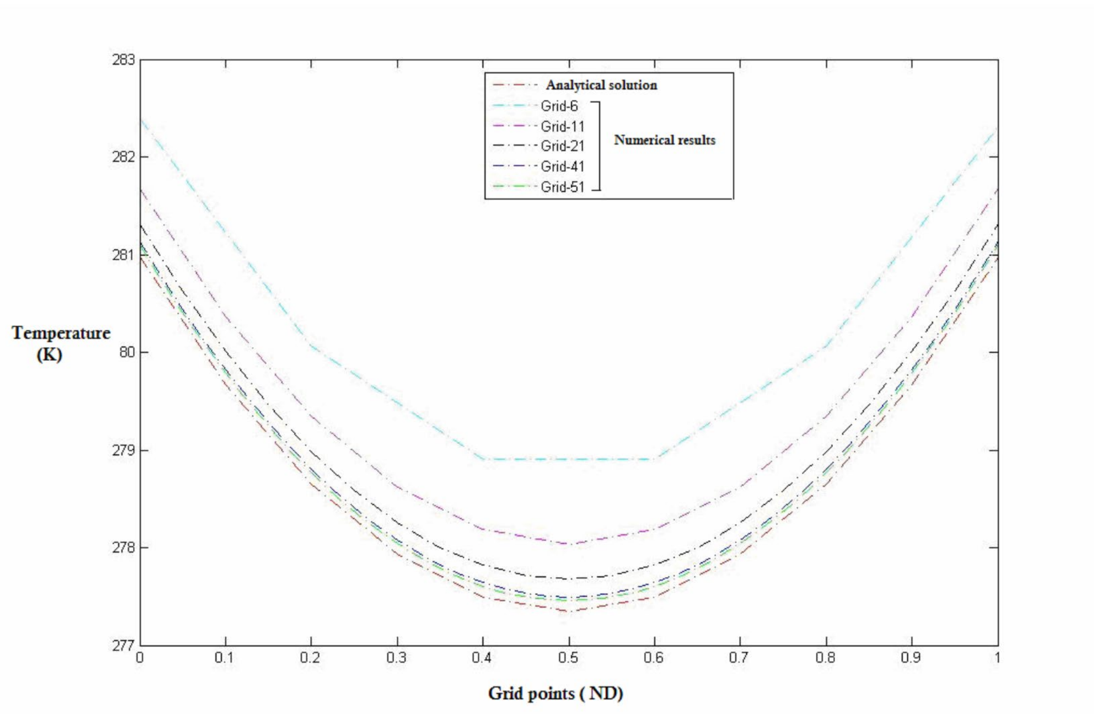


Figure 28: Effect of Grid Size on Numerical Results and Comparison of Analytical Solution with Numerical Solution for Model I.

The numerical results for Model I using the hypothetical polyester fabric are illustrated in Figure 29. This model measured the change in fabric temperature due to step changes in relative humidity. It was assumed that there was no temperature differential between the environment and the fabric surface. Temperature, in Kelvin, is shown on the vertical axis, while relative humidity is shown on the horizontal axis. As can be seen, change in humidity results in a slight increase in fabric temperature, but has the appearance of an asymptotic curve. Hence, it can be concluded that a change in humidity in the environment surrounding the fabric does not result in a large increase in the temperature of the fabric.

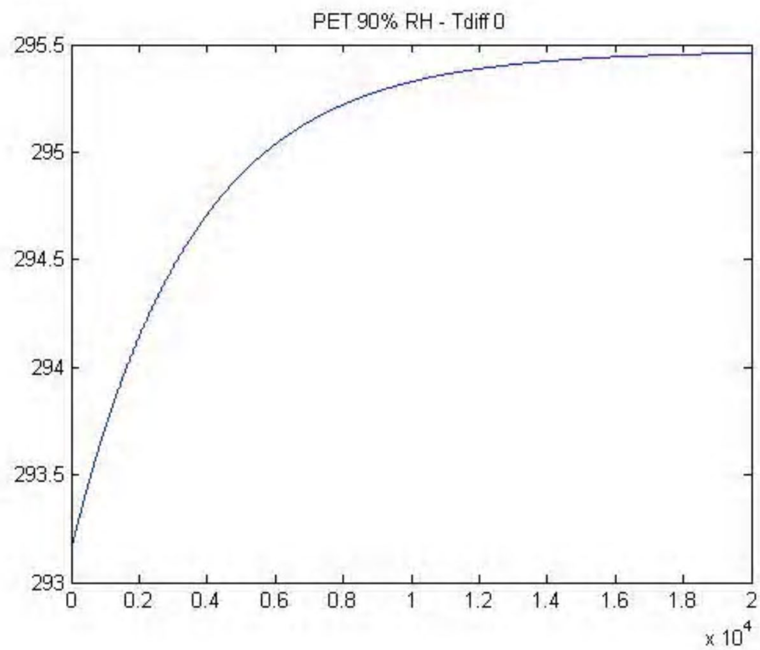


Figure 29. Change in Fabric Temperature for Step Changes in Relative Humidity from 1% to 90%

As depicted in Figure 30, the change in fabric temperature for step changes in relative humidity from 1% to 60% were modeled for the real and hypothetical fabrics detailed previously in Figure 24.

As with the hypothetical polyester, these fabrics displayed asymptotic behavior, with all the fabrics reaching a maximum temperature. There were differences in heat generated by the different fabrics, and the real fabrics did not approximate the modeling results of the hypothetical fabrics, but this is most likely due to differences in fiber, yarn, and fabric parameters. This modeling effort is considered to be successful because the real fabrics have behavior similar to the hypothetical fabrics, indicating successful modeling of their properties.

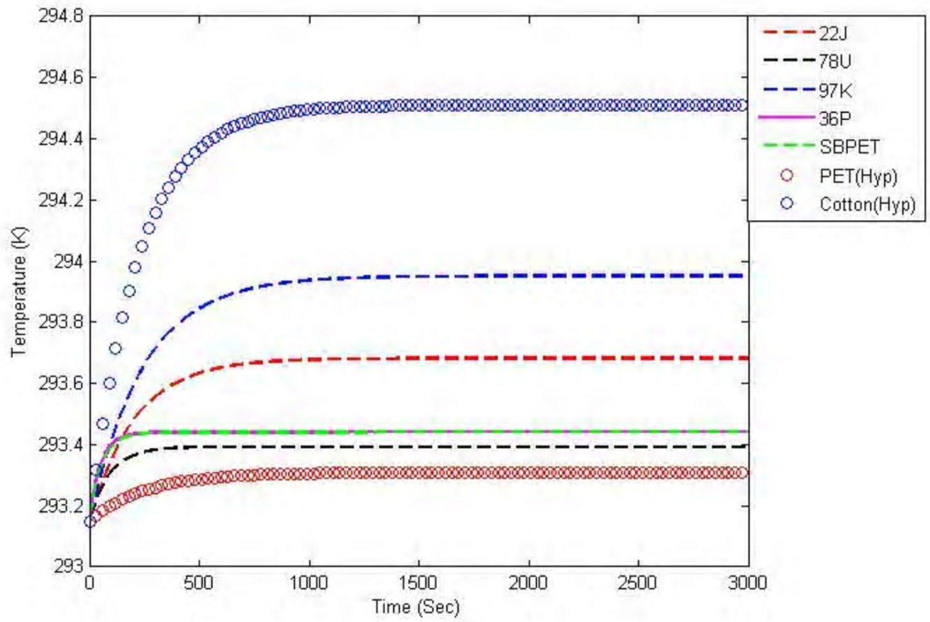


Figure 30. Change in Fabric Temperature for Step Changes in Relative Humidity from 1% to 60% for Both Real and Hypothetical Fabrics

The analytical solution for Model II has the following form:

$$\rho_v = \rho_{v\infty} - \frac{\dot{m}_{sv}.h^2}{D_{eff}}\left[\frac{\overline{x}^2}{2} - \frac{\overline{x}}{2} - \frac{D_{eff}}{2h.h_m}\right]$$

The numerical and analytical solutions for Model II are plotted against one another in Figure 31. As can be seen in this chart, there is good agreement between these two models, indicating success in modeling the changes in moisture flow due to changes in relative humidity outside the fabric.

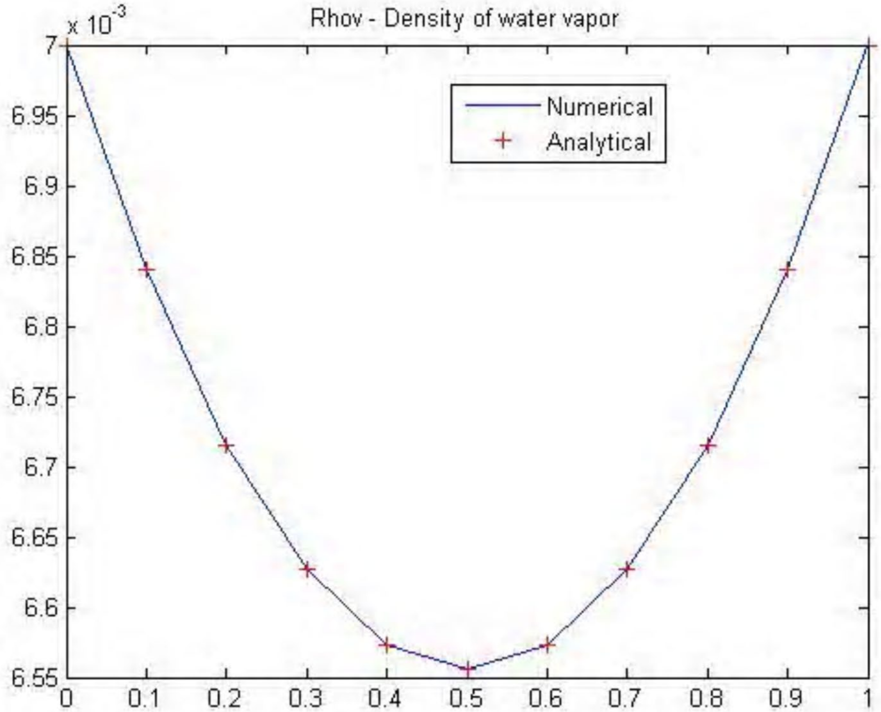


Figure 31. Comparison of Numerical and Analytical Results for Model II, a Measure of Moisture Flow Changes in the Fabric Due to Changes in Humidity in the Areas Surrounding Either Side of the Fabric

The numerical results for Model II are illustrated in Figure 32. This evaluation used the same polyester fabric that was used in the Model I study. In Figure 32 the change in vapor density is on the vertical axis; relative humidity is on the horizontal axis. Once again, asymptotic behavior is noted. In this case, as the relative humidity increases the vapor density decreases, but only slightly, until it reaches an asymptotic minimum.

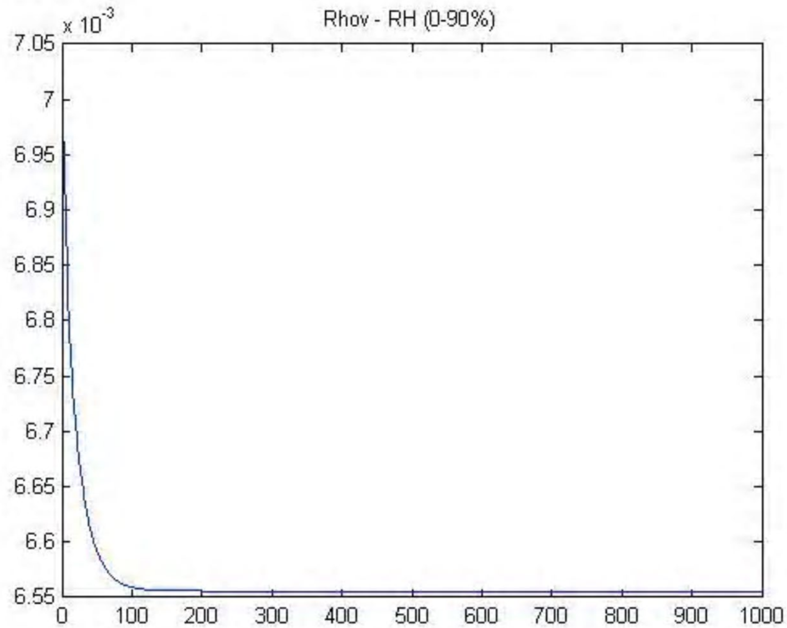


Figure 32. Change in Vapor Density for Step Change in Relative Humidity from 1% to 90%

5. Conclusions

Initial success was achieved in modeling numerical and analytical solutions to heat and fluid flow models for single-layered fabrics. Valid comparisons between the numerical and analytical solutions, as well as between the hypothetical and real fabrics, were realized.

Better understandings of the role of garment fit and thermal insulation were gained, as was understanding of cooling due to wind.

6. Recommendations

Phil Gibson has done a remarkable job on modeling heat and fluid flow through fabrics; it is imperative that this work continue in order to better understand the roles that fibers, yarns, fabrics, and construction of fabric systems play in a comfortable yet protective garment.

Although modeling of heat and fluid flow through fabrics has been discontinued, it is felt that this should be further evaluated in the future as it has the potential to save time and money for LEHP, NSRDEC, and protective apparel producers who must now create fabric systems and evaluate them because there is currently no reliable method of doing this in a virtual manner. Additional efforts should be spent on determining how well the models can predict actual thermal and heat flow of multi-layer textile systems that use adhesives or methods such as seams to join the layers, as well as the fit of systems that utilize hung liners, where fabric layers are not joined together. Further consideration should be given to modeling of multi-layered fabric systems, in order to understand why predicted and measured values do not correlate well. It is thought that this may be due to the method of creating a multi-layered system for this study, but further evaluation is required.

Another area of research to be explored should involve the findings that velocity profile and path line are important factors in cooling capabilities of garments given some air movement around the body. Understanding of this and incorporation of features taking advantage of this phenomenon may provide garments with superior cooling capabilities.

This document reports research undertaken at the U.S. Army Combat Capabilities Development Command Soldier Center, Natick, MA, and has been assigned No. Natick/TR-22/017 in a series of reports approved for publication

7. References

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