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Computational Fluid Dynamic Modeling of Protective Clothing Systems

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ABSTRACT

Protective clothing provides laboratory and hazardous materials workers, fire fighters, military personnel, and others with the means to control their exposure to chemicals, biological materials, and heat sources. Depending on the specific application, the textile materials used in protective clothing must provide high performance in a number of areas, including impermeability to hazardous chemicals, breathability, light weight, low cost, and ruggedness. Models based on computational fluid dynamics (CFD) have been developed to predict the performance of protective clothing materials. Such models complement testing by enabling property data from laboratory material testing to be used in predictions of integrated multilayer garments under varying environmental conditions.

Introduction

Advances in computational fluid dynamics (CFD) have made it possible to create accurate engineering models which can include the irregular shapes of a clothed human, as well as the extremely different length and time scales present in a typical computation (i.e. thin clothing layers over a relatively large human body and irregular air spaces). Body-fitted coordinates or unstructured grids are used to model shapes such as a clothed human arm covered by a permeable clothing layer, or simpler geometries such as a fabric-covered cylinder. This new capability can help to design more comfortable and effective protective clothing. Modern chemical protective garments provide high levels of protection against battlefield chemical threats, yet are often found to impose high levels of heat stress under certain environmental conditions. Accurate modeling and analysis techniques for heat and mass transfer aid in designing more comfortable protective clothing systems.

Air flow, heat transfer, and mass transfer through clothing can be studied on different scales: (i) macroscale of the whole human body in protective clothing, (ii) mesoscale of a single limb covered by clothing material and (iii) microscale, focusing on transport phenomena in the clothing material at the scale of individual fibers. Clothing material properties are important at all of these scales. Transport through the clothing system involves diffusion of heat and moisture, convective airflow, and liquid water capillary wicking. Hygroscopic fibers absorb water in vapor or liquid form and release the heat of sorption within the clothing. Water can condense or evaporate in outer layers of clothing. Many modern protective clothing systems include polymeric membranes, which may be a microporous hydrophobic polymer or a very thin solid layer of a hydrophilic polymer. Modeling the sorption of liquid water or vapor into the membrane, diffusion through the structure, and desorption from the other side, is complicated by the polymer's concentration-dependent permeation properties. Nearly all transport phenomena in clothing systems are time-dependent. Equilibrium does not take place within a matter of seconds, but may require time scales of minutes to hours. Since humans rarely work at a sustained constant level for hours on end, the use of steady-state approximations to determine quantities such as total moisture accumulation within the clothing, or total heat and mass transferred through the clothing, are often inaccurate. Steady-state heat and mass transfer properties do not describe the true situation. With the appropriate assumptions, CFD is useful at both the material and system level in clothing design. CFD provides a framework to model the diffusive and convective transport of heat and gases/vapors; capillary transport of liquids; vapor and liquid sorption phenomena and phase change; and the variable properties of the various clothing layers. It can also model the effects of sweating and humidity transport on the thermal stress imposed on the wearer of the clothing.

Material Modeling

A porous material may be described as a mixture of a solid phase, a liquid phase, and a gaseous phase. In protective clothing the solid phase consists of several materials (usually polymers and carbonaceous adsorbents), plus any bound liquid absorbed in the solid matrix, or on the surface of a solid absorbent (such as activated carbon). Hence, the solid phase density is dependent on the amount of liquid contained in the solid phase. Solid polymer layers, such those present in laminates and membranes, are treated by assuming the gas phase volume fraction for that layer is zero.

The liquid phase consists of the free liquid that may exist within the porous medium. The liquid phase is a pure component, and its density is assumed to be constant. In protective clothing the liquid phases are liquid water (sweat or rain) and liquid chemical agents.

The gaseous phase consists of vapor plus the noncondensable gas (e.g. air). The gas phase density is a function of temperature, pressure, and vapor concentration.

The general governing equations for energy, mass, and momentum transport in porous media are obtained by volume-averaging techniques [1,2], using definitions for intrinsic phase average, phase average, and spatial average for porous media given by Whitaker [3,4]. Material models must account for vapor phase transport (convection and diffusion), liquid phase transport (wicking), heat transfer (convection, conduction, and radiation), liquid evaporation and condensation, and sorption/diffusion of vapor and liquid through the solid phase. Complications due to variable porosity caused by swelling or shrinkage of the porous matrix are accounted for by various source terms in the transport equations.

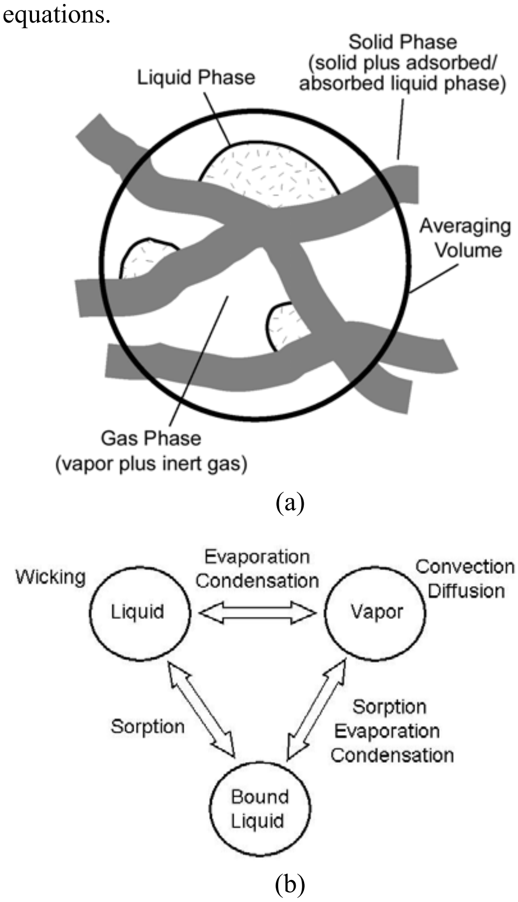


Figure 1. (a) Material Model and (b) Mass Transport Interactions

Material Modeling Example

The two-dimensional system of governing equations may be solved to simulate the case of transient diffusion/sorption. Heat is released as water vapor diffuses through and is absorbed by a bed of hygroscopic fibers. The heat released can be physiologically significant for clothing layers incorporating hygroscopic fibers such as cotton or wool, or polymer membranes such as polyurethane, which are often components in protective clothing systems. This sorption process can also buffer the effect of rapid changes in environmental humidity. CFD methods have been used model this transient sorption process for a variety of hygroscopic clothing materials [5-7], and an example is given as follows.

Experimental results for the transient diffusion/sorption case were obtained using two layers of fabric instrumented with three thermocouples sandwiched between the two layers, to record temperature changes as the fibers absorb or desorb water vapor from a gas stream flowing on the two sides of the fabrics. The sample was initially equilibrated with a dry gas flow on both sides under constant nitrogen flow. The relative humidity was then changed to 100% on both sides, and the temperature rise and fall due to vapor sorption was recorded as a benchmark for the computer simulations. Fig. 2 shows the computed and the experimentally measured temperatures of three fabrics as a function of time. The numerical results match the experimental results, and particularly the fact that there is a difference between the upstream, center, and downstream thermocouples, due to the formation of concentration and temperature boundary layers down the length of the sample.

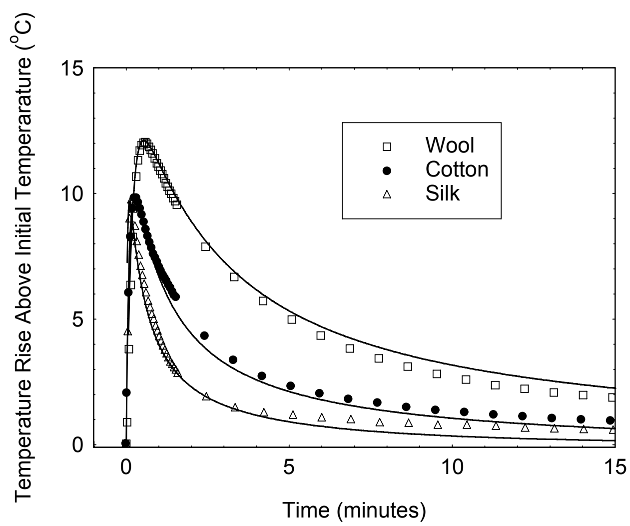


Figure 2. Numerical (solid lines) and experimentally measured (symbols) temperature transients for hygroscopic fabrics subjected to a step change in relative humidity.

Modeling of Fabric-Covered Cylinders

Fabric-covered cylinders provide a convenient geometry to study some of the system-level effects important for clothing systems. The effects of variable air spacing between fabric layers, or between the fabric and the human skin surface, can be important in determining how much heat and mass is transferred into or out of the clothing. In many cases, approximating the human body as an assemblage of fabric-covered cylinders provides sufficiently accurate results for engineering purposes. In general, an external air flow due to wind or body motion impinges on the clothed human, and some air flows around the body, while some air penetrates through the clothing system and into the gap between the clothing and body. This is illustrated in Fig. 3, which is a typical CFD simulation of flow over a cylinder covered by a permeable fabric. For a given external air velocity, the amount of air which flows around the body, and the amount which penetrates through the clothing layer is determined by the air flow resistance (air permeability) of the clothing layer. Materials with a low air flow resistance allow a relatively high flow rate through the fabric, with a correspondingly low pressure drop. Materials with a high air flow resistance allow less flow through the fabric, and have a higher pressure drop across the fabric layer (up to the limit of the stagnation pressure for the particular environmental flow conditions).

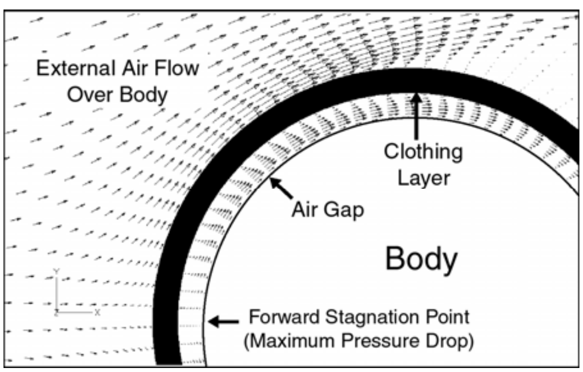


Figure 3. Flow conditions for a fabric-covered body.

The simple flow geometry shown in Fig. 3 is useful for answering some very basic questions about the interaction of the different transport properties characterized individually by laboratory test methods, but which all operate simultaneously in a clothing system. For example, protective clothing systems can be designed to protect from aerosol particles present in the environment. But clothing aerosol barrier performance cannot be measured in the same way that industrial filters are evaluated. Aerosol particle filters are commonly placed in systems that have a well-defined flow rate or pressure drop across the filter material. In clothing systems, however, the aerosol barrier is incorporated into a clothing system covering the human body, and the actual flow rates and pressure drops for a particular set of conditions are dependent on the air flow resistance properties of the fabric layer itself. For a truly valid comparison between aerosol barrier materials which differ in their air permeability properties, it would be desirable to test at a unique volumetric flow rate / filter velocity and pressure drop which corresponds to that produced by a given external air velocity on a typical clothing system. A simple cylinder model is useful in defining a reasonable set of laboratory test conditions for comparing different material candidates for new protective clothing systems [8-14].

Similar questions arise for interactions between the convective properties of air permeability, or convective air flow resistance, and the diffusive property of thermal conductivity/thermal resistance. Laboratory evaluations of individual transport properties yield a variety of material response due to a wide range of thermal resistance and air permeability properties. A CFD simulation of the performance of the materials in the fabric-covered cylinder geometry can help to determine how the total heat and mass transfer coefficients are influenced by a particular combination of fabric properties.

An illustration of typical CFD modeling results for fabric-covered cylinders [15] is shown in Figure 4. A body-fitted mesh is created for a cylindrical geometry. A thermal insulation layer, and an air space, is placed around the cylinder. The air flow resistance property of the insulation layer is varied (while keeping thermal insulation constant). In this particular case the cylinder diameter was 0.187 m (corresponding to the diameter of a human thigh), and the air space between the fabric and the cylinder surface was 0.01 m. The cylinder surface temperature was 35°C (nominal human skin temperature) and the air temperature was 5°C. Simulations were carried out over a range of air flow velocities from 1 to 40 m/s, although only the results up to 10 m/s are shown in Fig 4. The curve for the bare cylinder case in this figure agrees with heat transfer correlations for gas flow over heated cylinders. These types of simulations are useful in efforts to design the proper mix of fabric transport properties to maximize comfort while still providing adequate protection from the environment, and from chemical/biological warfare agents.

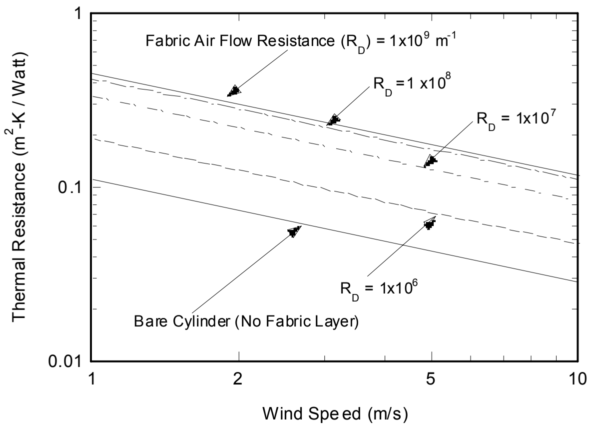


Figure 4. Overall Heat Transfer Resistance of Fabric-Covered Cylinders in Cross-Flow Conditions at Various Wind Speeds.

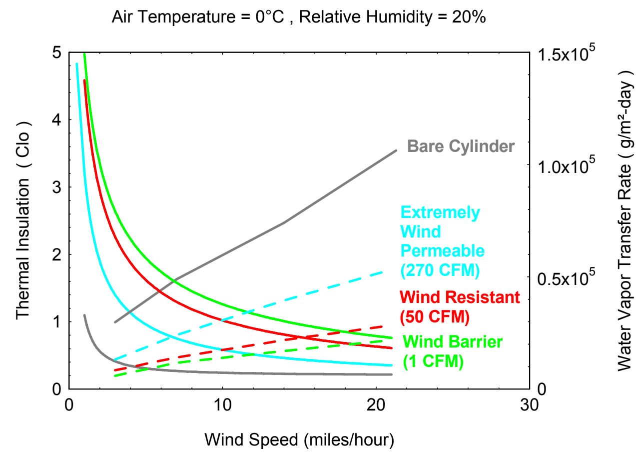


Figure 5. Comparison of Heat Transfer and Water Vapor Flux for Three Varieties of Insulating Fleece. Solid Lines are Thermal Insulation, Dashed Lines are Water Vapor Flux.

These modeling techniques were applied to commercially available knit fleece layers that are under consideration for cold-weather applications [16-17]. Considerable effort is expended to develop clothing that is "breathable" to sweat vapor, yet that will also retain heat even in windy conditions. Modeling simulations were carried out for a variety of new insulating fleece fabrics produced for the outdoor clothing market that address the need for materials which breathe well, but which also keep out enough wind in cold conditions to keep people warm. These fabrics are becoming available in a wide variety of material properties, and it is difficult to rank or evaluate them based on material properties alone. CFD modeling of the behavior of these materials in a simple clothing analog of a fabric-covered cylinder can be helpful in distinguishing significant differences between some of these fabrics.

Thermal resistance, water vapor diffusion resistance, and air permeability were determined on flat samples using laboratory test methods. The material properties were then input into a CFD model of a fabric-covered cylinder, with an air space, under conditions of several different wind speeds. The CFD model provides the ability to go directly from laboratory tests of material properties to a system simulation that approximates real-world conditions. An example comparison for three of the fabrics is shown in Figure 5.

The baseline bare cylinder results are essentially the cooling effect and evaporative heat loss due to "wind chill." The presence of a clothing layer modifies the wind chill effect significantly depending on the air permeability, thermal resistance, and water vapor diffusion resistance of the clothing layer, and the air space between the cylinder surface and the clothing layer. The air permeability of the fabric layer was found to be the most significant parameter affecting the performance of the various materials evaluated. Differences in thermal resistance that seemed important under the stagnant test conditions present in the laboratory tests were much less significant when the materials were compared under moderate wind speeds which produced significant air flow through the model fabric-covered cylinder system.

Of equal importance for military protective clothing systems is the transport of chemical and biological warfare agents into a clothing system. The cylinder model is useful as a starting point for looking at the importance of a property such as fabric air flow resistance on the performance of a particular protective clothing system design.

More systematic studies of flow around fabric-covered cylinders use sophisticated turbulence models incorporating vortex shedding in the wake of the cylinder [18-20]. Experimental measurements conducted in parallel with CFD computations developed single correlations which predict heat and mass transfer properties based on nondimensional scaling relations between fluid flow rate, fabric air flow resistance, and the inner gap between the fabric and the cylinder surface. Scaling rules have been deduced as a function of the Reynolds number, the Darcy number and the Damkohler number, representing the wind speed, clothing permeability, and adsorptivity of poisonous trace gases, respectively. The range of values of the studied parameters was based on applications in heat and mass transfer to a clothed human limb in outdoor wind. For a wide range of conditions, air was found to penetrate the outer porous cylinder in the upstream region, down to an angle of approximately 50 degrees from the front stagnation point. In this region, heat and mass transfer are high. Further downstream, heat and mass transfer are dictated by conduction/diffusion through the air layer in between the two cylinders. For large Reynolds numbers and high fabric air permeability, the flow easily penetrates the porous sheath and heat transfer approaches that of a bare cylinder. For low Reynolds numbers, on the other hand, the boundary layer around the pair of concentric cylinders becomes very thick and limiting for heat transfer, and again heat transfer approaches that of a bare cylinder. The dimensionless parameters for heat transfer and mass transfer can be summarized in a single correlation under a wide range of conditions. Within its range of validity this correlation is accurate within 5 %, compared to the numerical simulations.

A battlefield hazard for the soldier is the presence of droplets of liquid chemical agents that have contaminated the outer surfaces of protective clothing. These droplets evaporate and the vapor can diffuse into the clothing system. The droplets can also be carried into the clothing system by convective air flow due to body motion or an external wind.

Figure 6 is an example of a CFD simulation of a liquid droplet placed onto the outer surface of the fabric-covered cylinder model. All fabric properties are constant with the exception of the fabric air flow resistance. What is interesting about this particular example is that the fabric with the highest air flow resistance does not produce the lowest total exposure to the chemical vapor. The fabric with low air flow resistance provides a standoff of the droplet from the cylinder surface, while the ventilating air flow carries vapor quickly through the system and away from the cylinder. For the case of the fabric with a high air flow resistance, the total vapor exposure is higher. This is due to the fact that although there is little convective flow into the air space under the fabric layer, the vapor is able to diffuse through the clothing and build up to higher concentrations. In this case there is no ventilating air flow to sweep the vapor out of the system, and the total exposure to the vapor is much higher than for the well-ventilated system.

Modeling fabric properties in this simple cylindrical geometry provides much of the information required for system-level decisions about various transport property trade-offs between different material candidates for protective clothing materials. However, there are some situations, particularly those having to do with body movement and motion, as well as interfaces and closures between different clothing system components, where more detailed models are desirable.

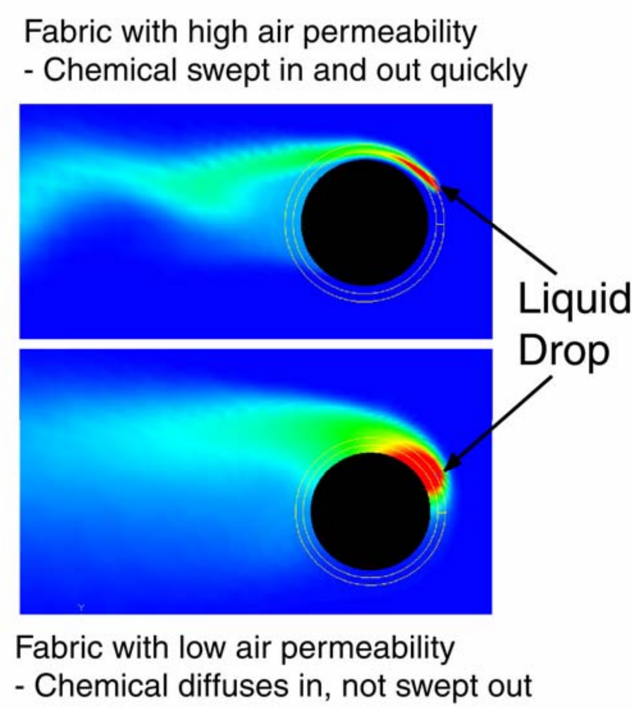


Figure 6. CFD simulation of liquid droplet evaporating on outside surface of an air-permeable fabric layer covering a cylinder (color contours refer to vapor concentration, scale not shown).

A variety of geometric parameters affect the transport of agent vapor from a liquid surface drop [21-22]. These parameters include orientation of the drop relative to the flow direction, gap size between the cylinder and the clothing layer, non-uniform gap size, and multiple clothing layers. The variation in parameters was assessed at two imposed wind speeds of 5 and 20 mph.

Figure 7 shows the base geometry assumed for these two-dimensional transient simulations. The model is that of a cross-section of a 10 cm diameter arm covered with a single 0.5 mm thick clothing layer having a 1.1 cm gap between the surface of the arm and the clothing layer. Fabric permeability was assumed to be a cotton shell (permeability approximately 2.4×10^{-12} m^2). Vapor properties correspond to GB (Sarin) (molecular weight of 140.1 kg/kg-mol, vapor pressure of 2.9 mm Hg, and vapor diffusivity of 7.5×10^{-6} m^2/s). The transient simulations were performed with a time step chosen to resolve the shedding frequency of the vortex street for flow over a circular cylinder.

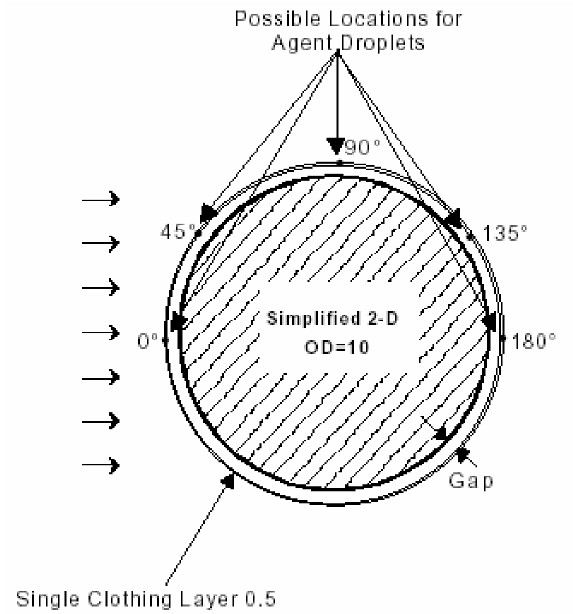


Figure 7. Schematic of Base Geometry for Two-Dimensional Simulations of Evaporating Surface Agent (with Droplet Locations Shown)

The following sets of geometric parameters were considered:

- Base Geometry with an incident wind direction of 0°, 45°, 90°, 135°, and 180° relative to the droplet. A condition of 0° corresponds to the droplet located at stagnation point.
- Wind direction at 0° relative to droplet with single clothing layer having uniform gap spacing of 0.2, 0.6, 1.1, and 2.1 cm.
- Wind direction at 0° relative to the droplet with single clothing layer eccentric to the arm with non-uniform gap spacing of 4.1:1, and 6.8:1 (maximum/minimum of 1.767 cm /0.433 cm and 1.918 cm /0.282 cm, respectively with minimum thickness located at the stagnation point).
- Wind direction at 0° relative to the droplet with two clothing layers having uniform gap spacing. First case: inner surface of inner and outer layers located 0.55 cm and 1.1 cm from arm surface, respectively. Second case: inner surface of inner and outer layers located 1.1 cm and 2.1 cm from arm surface, respectively.

All simulations were run until they reached a stationary oscillatory state in which the solution variables varied with time around a constant asymptotic mean (physical times of approximately 80 seconds and 20 seconds for 5 mph and 20 mph respectively). Once this condition was reached, the agent concentration was assessed at the arm to determine the maximum concentration (mg/cm^3) as a function of time. The area-averaged concentration over the arm surface as a function of time was also computed. For the conditions under consideration here, the amplitudes of the time varying concentrations at the arm were typically small relative to the time average values once the stationary state was reached. The boundary condition for the saturation concentration imposed at the droplet is 2.19x10^4 mg/m^3.

The resulting observed trends are generally consistent with expectations. Droplets located at the stagnation point produce higher exposure than when located at other angles relative to the wind direction. For the 5 mph wind speed, maximum and average concentrations are the same order of magnitude for all orientations. The lowest maximum is observed for the 45° orientation with an increase in maximum concentration as the droplet is moved around to the back of the arm (180°). The average concentration is similar for all orientations other than the stagnation point droplet location indicating that diffusion of agent from the droplet location is of primary importance for these wind and fabric conditions.

For the 20 mph wind speed, the maximum and average concentrations are several orders of magnitude higher for the stagnation point location, with asymptotically decreasing concentrations as the droplet is moved away from this location. For the fabric conditions considered here, the higher velocity increases exposure for stagnation point conditions, but assists in sweeping agent away when the droplet is located away from the stagnation point. There is an increase in maximum concentration as the droplet is moved around to the back of the arm (180°). The average concentration is similar for all orientations other than the stagnation point droplet location indicating that diffusion of agent from the droplet location is of primary importance for these wind and fabric conditions.

For droplets located at the stagnation point, increased gap widths and multiple clothing layers reduce the observed maximum agent concentration at the arm surface. For this flow configuration, the maximum concentration is always directly under the droplet location.

Increasing the distance from the droplet or adding additional resistance to agent transport in the form of an additional clothing layer allows the surrounding air to dilute the agent concentration before reaching the arm surface. The results in Table I also indicate that increased gap widths tend to increase area-averaged agent concentrations at the arm surface. Increasing the distance between the arm and the outer clothing layer has the effect of increasing the resistance to agent diffusion transport out of the gap region and allows higher concentrations to be reached within the gap away from the droplet location.

As an example of the agent concentration results, Figure 8 shows the agent concentration at the surface of the arm for different uniform gap thicknesses. The larger gaps show a lower peak concentration, but higher concentrations over most of the arm surface.

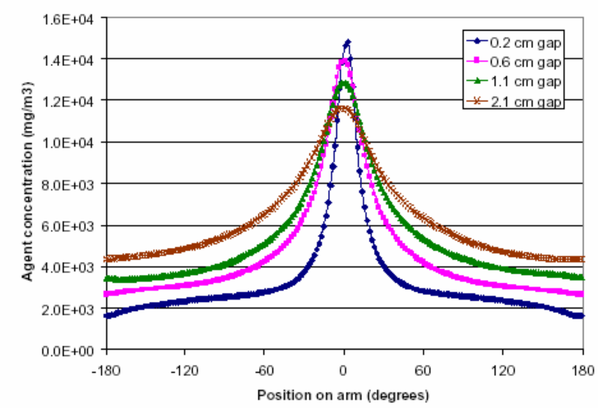


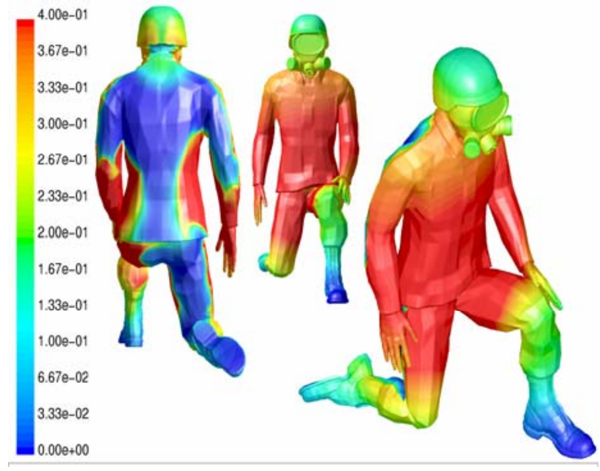
Figure 8. Agent Concentration at the Surface of the Arm using Different Uniform Gap Thicknesses (Wind Speed 20 mph).

Full-Body Modeling

Detailed computational simulations of clothing systems are not necessary at all steps of an analysis. Use of a body that is a solid geometric shape (no porous clothing layers or air spaces) can be useful to define the air flow pattern and pressure field developed over a human form. This information may then be used with the simpler body segment models (such as an arm or torso) to define exposure levels.

Figure 9 shows the geometry of a soldier modeled as a solid body (no porous clothing layers). Two calculations were performed with the model, both for a 4.5 m/s headwind. Figure 9 (a) shows the calculated steady-state flow field around the soldier. The recirculation region immediately behind the soldier is readily visible. In the second calculation (transient), a spherical cloud of tracer gas 1 m in diameter is released at a location 2 m in front of the soldier. Figure 9 displays surface concentrations of gas at 0.5 seconds after release. The results show high concentrations of gas in the soldier's midsection where the cloud is centered.

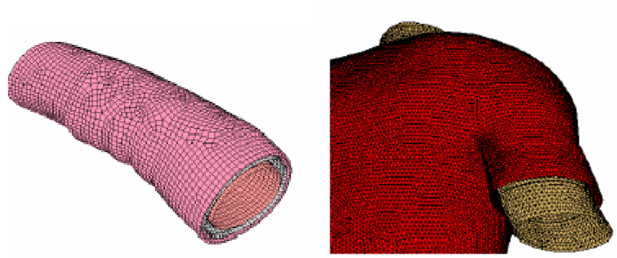
(a)



(b)

Figure 9. (a) Streaklines for 4.5 m/s Headwind (b) Surface Concentrations of Tracer Gas: 0.5 sec after Release of 1 m Spherical Cloud at Location 2 m in Front of Soldier

Figure 10 depicts more complex 3-D models of an arm and torso, respectively. Two layers of fabric clothe the arm. The undulations visible on the inner arm near the elbow are in the outer layer of fabric only. The torso model here is clad in a single fabric layer, a crew-neck T-shirt. Both arm and torso models are based on laser scans of humans. Scanned points are brought into computer-aided design software for creation of the body surface and generation of clothing layers. The geometry is then exported to the CFD software's preprocessor for grid generation. 3-D simulations are generally similar to the 2-D fabric-covered cylinder studies, particularly for the fabric-covered arm segment. Problems arise in the computational requirements for the large number of grid points for a human body, the irregular geometry, and the differences in scale between the size of the human body and the thickness of the mesh required for thin clothing layers.



(a) (b)

Figure 10. (a) 3-D Model of Arm with Two Clothing Layers and (b) Model of Torso (Clad in T-Shirt)

Work is currently underway to develop 3-D models of a human torso having one or more layers of clothing [22]. Results from a preliminary simulation using the computational mesh of Figure 10(b) have been performed under steady state conditions of a 5 mph wind imposed on the front of the torso. Skin conditions are assumed to be a sweat flux of 3×10^{-5} kg/m^2-s and heat flux of 100 W/m^2, while the shirt is modeled as 1 mm thick cotton fabric. Figure 11 shows the temperature at the skin surface and velocity vectors in a plane around the torso for conditions of full closure between the layer of clothing and skin at the bottom of the shirt, ends of the sleeves, and at the neck (i.e., snug fit at neck, sleeves, and waist).

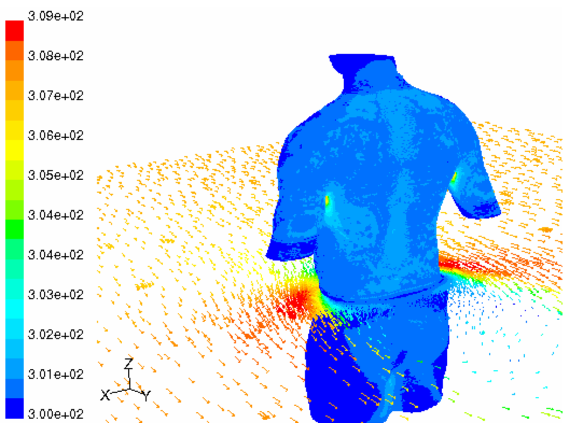


Figure 11. Preliminary Simulation Results of Clothed 3-D Human Torso: Temperatures at skin surface and flow around torso with complete closure (snug fit) at neck, sleeves, and waist.

As might be expected, the highest temperatures are in the vicinity under the arm. Furthermore, the presence of the closures and their effect of limiting the ability of flow from the environment to enter the area under the shirt results in higher temperatures. These results represent a first step in performing simulations of thermal and agent transport in protective clothing on a 3-D human torso model.

Conclusions

Modeling offers a powerful companion to experiments and testing in the development of protective clothing materials and other textiles. Detailed material models for vapor and liquid phase transport within textile fabrics have been developed and integrated with CFD software. Material-level modeling can account for transient processes such as aerosol transport and deposition, liquid wicking, and phase changes due to evaporation, condensation, and sorption/desorption. It is desirable to include these more complicated phenomena in the system-level three-dimensional body modeling efforts.

General nondimensional scaling correlations of heat and mass transfer from cylinders covered with a porous layer are very valuable for application to the problems of clothing comfort and protection from chemical agents. Modeling and experiments for fabric-covered cylinders will continue to be an efficient pathway to understanding the interactions between materials properties and their performance in a protective clothing system. Future modeling applications will involve assessment of thermal comfort/stress on wearers of protective clothing, effects of layering on protective performance, and sensitivity to textile permeability and wicking properties.

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