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Research Article

A Design Tool for Clothing Applications: Wind Resistant Fabric Layers and Permeable Vents

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A computational clothing design tool is used to examine the effects of different clothing design features upon performance. Computational predictions of total heat and mass transfer coefficients of the clothing design tool showed good agreement with experimental measurements obtained using a sweating thermal manikin for four different clothing systems, as well as for the unclothed bare manikin. The specific clothing design features examined in this work are the size and placement of air-permeable fabric vents in a protective suit composed primarily of a fabric-laminated polymer film layer. The air-permeable vents were shown to provide additional ventilation and to significantly decrease both the total thermal insulation and the water vapor resistance of the protective suit.

1. Introduction

Windproof and wind resistant clothing layers are important in applications such as cold weather clothing and military chemical and biological protective ensembles. Completely windproof clothing provides protection from heat loss due to air penetration in cold conditions but can also become very uncomfortable when the wearer is working hard and generating a lot of heat and sweat. The same situation arises in protective clothing—some ventilation through the fabric layers can be very helpful in mitigating heat stress and extending wear time. Design tools that allow simultaneous assessment of factors such as wind penetration, heat transfer, moisture transport, and permeation of toxic substances can assist in developing new clothing systems that strike a good balance between protection and comfort.

We have shown previously that the wind resistance and aerosol filtration properties of clothing layers can be controlled by varying the deposition of electrospun fiber membranes onto textile substrates [1], as shown in Figure 1.

Since nanofiber layers make it possible to control air flow resistance over several orders of magnitude without affecting other clothing properties, we are interested in the resulting consequences of using these materials in new clothing designs. Electrospun elastomeric polyurethane membranes are now used in commercial outerwear fabrics such as "NeoShell" by Polartec, Inc., and take advantage of this ability to "tune" air flow through the fabric without significantly affecting other properties such as thermal insulation or water vapor diffusion (breathability). These materials may be used for either an entire clothing item, such as jacket or pants, or incorporated into permeable "vents," where the more permeable fabric in certain areas of the garment provides increased ventilation.

2. Approach

A protective clothing design tool under development by Creare, Inc., for the U.S. military provides a physics-based computational framework for iterative modification

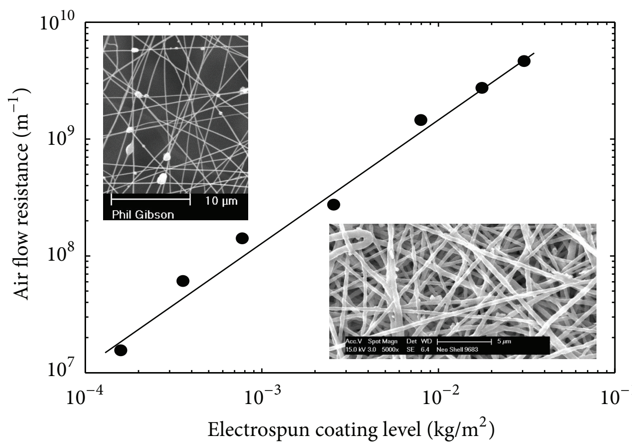


FIGURE 1: Air flow resistance of fabric layer modified by electrospun fiber coating level [1].

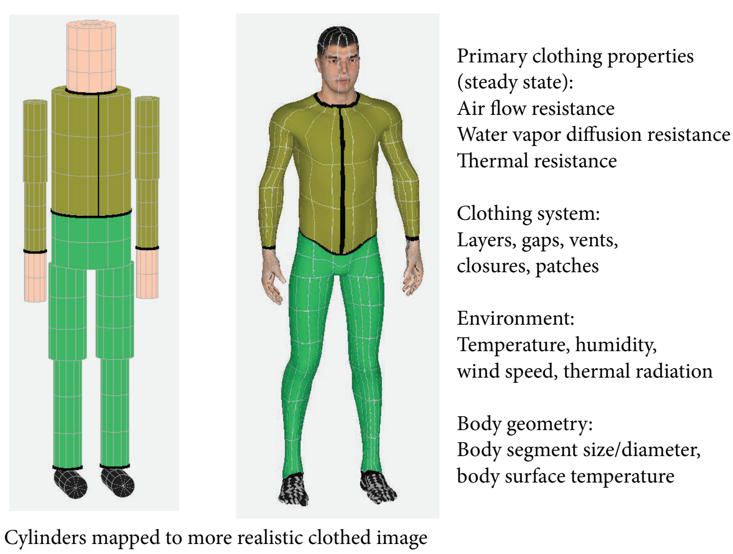


FIGURE 2: Typical IP SPM simulation.

and assessment of protective clothing systems [2]. Creare's Individual Protection System Performance Model (IP SPM) is built on a foundation of advanced computational fluid dynamic and experimental results, but the software itself is purposefully simplified to allow nonexpert users to modify clothing designs and assess the consequences of various clothing aspects such as fit, closures, interfaces, material properties, and layering, upon comfort and protection. The IP SPM model treats the clothed human body as an assemblage of fabric-covered cylinders, although the graphical user interface maps clothing layers onto a more anatomically correct human figure, as shown in Figure 2. Computational models that include more detailed human and clothing geometry are possible [3] and in fact are used as some of the guides for the IP SPM software, but too much detail has been found to add an unneeded level of complexity for a user-friendly design tool, especially for nonexpert users.

In this study we focus upon the use of the IP SPM tool to assess the relative importance of changing the air flow resistance of fabric layers or permeable vent sections upon the calculated total heat transfer resistance of the clothing system. Several recent experimental papers have discussed the trade-offs between fabric air flow resistance, clothing vents, and the interaction with air flow due to external wind or body motion [4–6].

3. Results and Discussion

3.1. Comparison of IP SPM Predictions with Thermal Manikin Measurements. The Creare IP SPM can be configured to simulate a thermal manikin, which is an important tool in clothing comfort research. Figure 3 shows baseline comparison results for the IP SPM thermal manikin calculated overall heat transfer coefficients as compared to some empirical correlations obtained with humans [7] and thermal manikins [8], as well as computational and analytical results from heated cylinders [9].

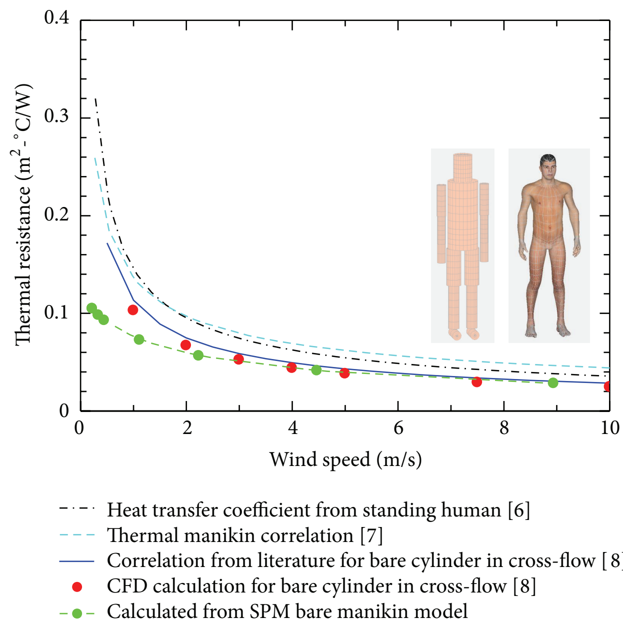
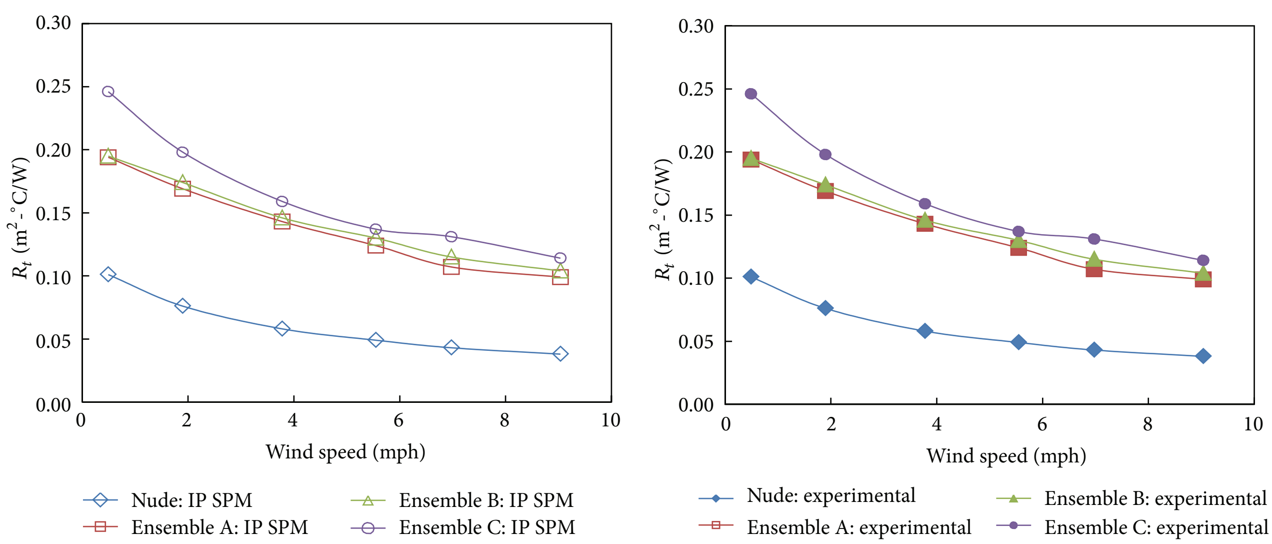


FIGURE 3: Overall heat transfer coefficient of IP SPM thermal manikin as a function of wind speed.



(a) IP SPM

(b) Thermal manikin

FIGURE 4: Comparison of thermal insulation for the nude manikin and three clothing ensembles: (a) IP SPM model results versus (b) experimental thermal manikin results.

Figure 3 shows an underprediction of bare manikin values at low wind speeds when radiative heat transfer is included in the IP SPM model; when this is removed from the calculation (h_{rad} of 4.5 W/m^2-°C), the IP SPM results show good agreement with the convective-only heat transfer calculations from [8] shown in Figure 3.

IP SPM predictions can be compared to experimental thermal manikin results. Inputs to the IP SPM model require clothing thermal resistance, water vapor diffusion resistance, and air flow resistance for the fabric and some information on the fit (space between the fabric and the body surface), tightness of the closures and seams, and the extent of coverage of the fabric over different sections of the body. Figure 4 shows a comparison of IP SPM predictions to experimental results obtained by a thermal manikin [10, 11] for both the bare (nude) condition and for three separate clothing ensembles on the manikin.

As shown in Figure 4, the performance rankings between the ensembles were correctly replicated by the IP SPM predictions, for both the overall thermal resistance (shown

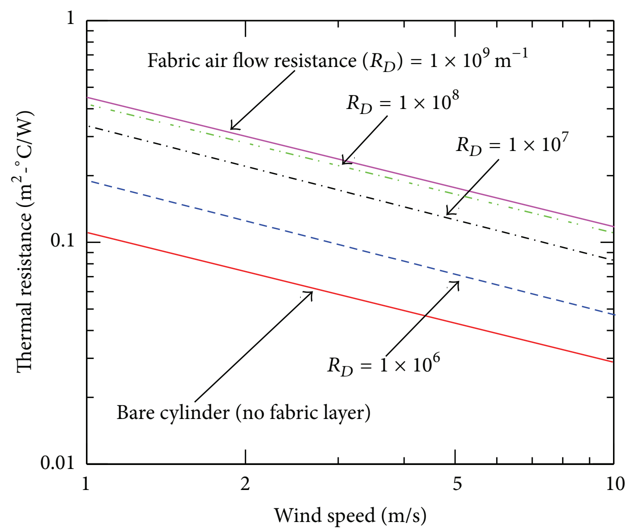


FIGURE 5: Overall heat transfer resistance of fabric-covered cylinders in cross-flow conditions at various wind speeds [9].

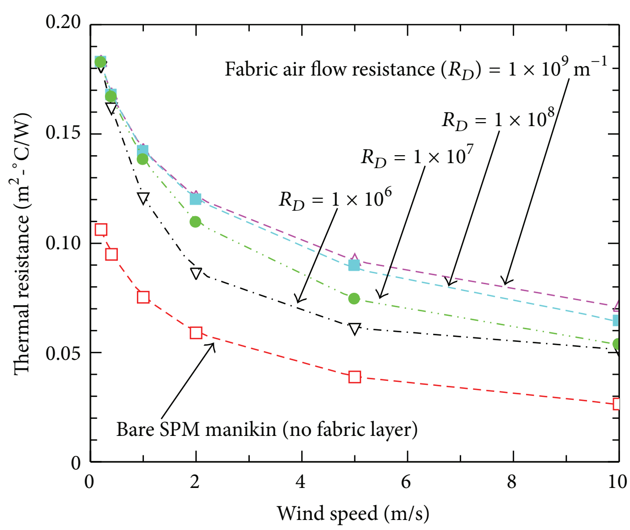


FIGURE 6: Individual protection system performance model (IP SPM) predictions for variable air flow resistance of fabric layer.

in Figure 3) and evaporative resistances (not shown). This is an important result because it indicates that in situations where the exact experimental configurations are not known or defined, the IP SPM can still be used to determine relative garment rankings for thermal performance using nominal configuration values (e.g., for garment fit).

3.2. Effect of Fabric Air Flow Resistance on Clothing System Thermal Resistance. The IP SPM purposefully simplifies the clothing/body model to be an assemblage of fabric-covered cylinders. For a practical design tool, it has been found that faithful reproduction of body geometry, along with details of fabric folds, drape, and fit, can quickly make a computational tool such as this only usable by dedicated experts. Previous computational simulations of fabric-covered cylinders as an analog to the human body [9] examined the effect of varying only the fabric air flow resistance (all other properties kept constant) and calculated the overall heat and mass transfer coefficient, as shown in Figure 5.

The IP SPM allows a very similar computation to be carried out for a more realistic clothing and body geometry. The IP SPM is configured to simulate a set of wind-resistant clothing (jacket and pants) that only varies the single property of air flow resistance. A similar relationship thermal resistance as a function of external wind speed as was shown in Figure 5 is shown in Figure 6 for the IP SPM model. Air flow resistance is more important at high wind speeds, and once the fabric becomes “wind-proof,” any further increase in air flow resistance does not significantly affect heat transfer.

An example of the use of the IP SPM to examine some simple clothing design variations is shown in Figure 7. Suit A and suit B vary only in the air flow resistance of the jacket

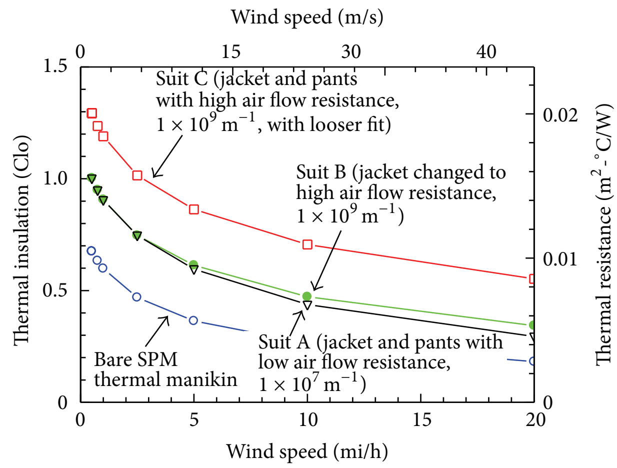


Figure 7: Use of IP SPM to examine effect of fabric air flow resistance on overall thermal insulation.

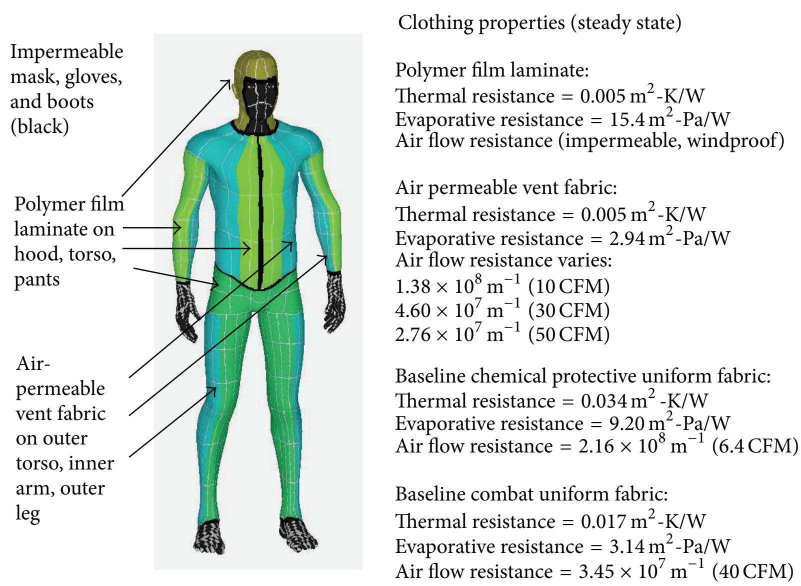


Figure 8: IPM SPM simulation to vary air flow resistance of permeable fabric vents in a membrane suit.

(causing slightly more heat loss at higher air flow conditions for the less-permeable jacket). Suit C is wind-resistant, and also has a much looser fit which traps more air under the clothing, resulting in increased thermal insulation properties for that configuration.

3.3. Effect of Permeable Fabric Vents on Thermal and Water Vapor Resistance. An example of a more detailed design study was performed with the IP SPM to examine the effect of incorporating permeable fabric vents into a chemical-protective suit that is primarily composed of a solid polymer membrane that provides chemical protection, yet allows some water vapor transport for comfort. It is anticipated that such a complete membrane-based suit will not allow enough ventilation by itself but must incorporate a venting strategy of some kind. One solution would be to incorporate separate vent panels composed of a more air-permeable fabric into the membrane-based suit.

Figure 8 shows the basic IP SPM setup for this simulation. Large air-permeable fabric vents are incorporated into the protective suit, and the vent fabric air flow resistance is varied in a systematic way. The suit also incorporates a protective hood, mask, boots, and gloves, which are impermeable to both air and water vapor. For comparison purposes, results are also modeled for the polymer film laminate suit with no vents incorporated into the design and two other baseline cases of a suit made up of a standard chemical protective uniform fabric and a standard combat uniform fabric. The additional case of the nude manikin simulation was also modeled, to provide a reference point for how much each clothing system decreases thermal and evaporative transfer from the human body.

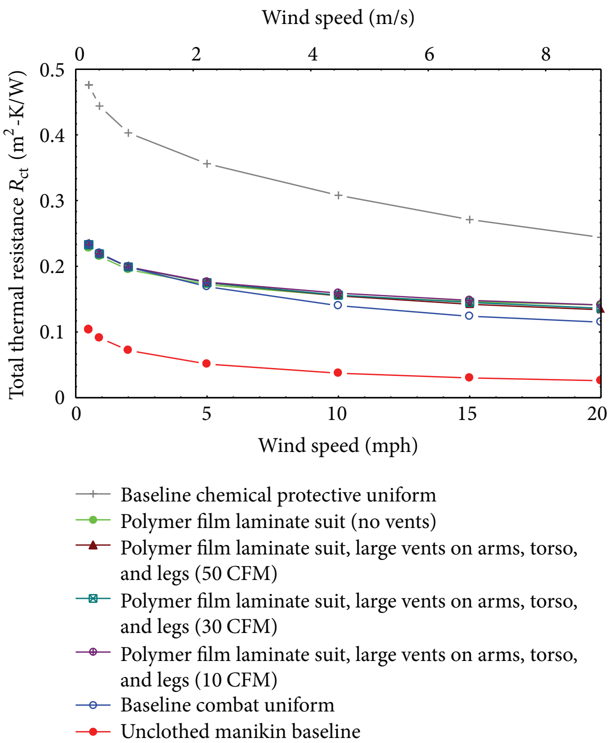


FIGURE 9: Overall IP SPM manikin thermal resistance.

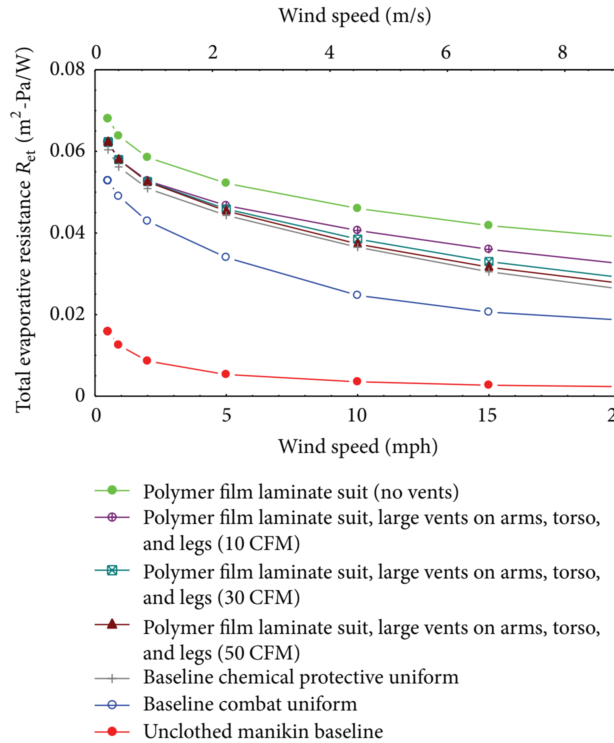


FIGURE 10: Overall IP SPM manikin evaporative resistance.

Figures 9 and 10 show the simulation result for these cases described in Figure 8. Figure 9 shows the overall thermal resistance of the IP SPM thermal manikin, over a range of air flows from 0.5 to 20 mph. For the IP SPM manikin thermal resistance, all the designs incorporating the polymer film laminate (vented or unvented) showed very little differences, since the thermal resistance of the fabric itself is minimal. However, there are large differences between the polymer film laminate suit and the baseline chemical protective uniform, which is a much thicker material, with a higher measured thermal resistance, which impedes dry heat transfer from the body to the environment. The baseline combat uniform shows a lower thermal resistance at higher wind speeds, as a consequence of its lower air flow resistance (higher air permeability), as opposed to the polymer film laminate fabric, which is impermeable to wind. For overall IP SPM manikin thermal resistance, the large air-permeable fabric vents on the arms, torso, and legs do not make an appreciable difference to the thermal comfort of this suit design.

Figure 10 shows the overall evaporative resistance of the IP SPM manikin, over a range of air flows from 0.5 to 20 mph. For the evaporative case, there are significant differences between the different suit designs and fabrics. It is still the case that none of the polymer film laminate suit designs approach the performance of either the baseline combat uniform or the nude manikin, but the incorporation of air-permeable fabric vents does favorably impact the performance of the polymer film laminate suit. The unvented polymer film laminate suit has the highest evaporative resistance of any of the suits modeled. As the vent fabric air permeability increases, the polymer film laminate suit becomes progressively better, and the design incorporating fabric vents with an air flow resistance of $2.8 \times 10^7\ m^{-1}$ (50 CFM) has the best performance, approaching the evaporative resistance of the baseline chemical protective uniform, which is entirely air-permeable.

4. Conclusions

Simplified clothing design tools would greatly enhance our ability to iteratively vary clothing design features and examine the consequences for comfort and protection. Further verification and validation with experimental thermal manikin measurements will be required for a variety of clothing ensembles, so that results predicted with the model can be used as a reliable design tool in the future.

Conflict of Interests

Jerry Bieszczad, John Gagne, and David Fogg are employed by the commercial entity, Creare, Inc., which developed the computational software mentioned in the paper.

Acknowledgment

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