Thermal Manikin Testing and Thermal Model Simulation as Predictors of Total Heat Loss

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Background

- The ability of personal protective clothing and equipment (PPE) (Fig.1) to allow transfer of heat (thermal and evaporative resistance) out of the ensemble to the environment is determined by the sweating hot plate test, assigning a total heat loss (THL) value based on a composite swatch of ensemble material.
- The National Fire Protection Association (NFPA) provides THL requirements in their standards for the certification of various PPE such as ensembles used by first responders, emergency medical staff, and wildland firefighters, but few studies have been done to validate THL values using human subject data.

Objectives

- The overall aim of this project is to assess if the sweating hot plate test-determined THL value is a valid predictor of human thermo-physiological responses to working while wearing PPE ensembles.
- In this sub-task of Phase 1, we compare the results of the sweating hot plate test with two other methodological approaches (sweating thermal manikin and thermal model simulation) using two PPE ensembles with the same design, but made of fabrics with different THL values.

Overall Project Technical Approach

- Three year project consists of three phases to be performed using the sweating hot plate (used to obtain THL), thermal manikin, thermal model simulations, and human subjects.

  Phase 1: Build prototype PPE ensembles using the same design and different materials (with different THL values) and test on a thermal manikin, create thermal model simulation, and test on human subjects. Fig.1 shows the technical approach of this phase.

  Phase 2: Test a representative set of commonly available PPE ensembles across four separate THL ranges on human subjects.

  Phase 3: Evaluate the impact of reinforcements, pockets, visibility marking, linings, and other additional layers on the breathability of the garment through human subject testing.

Methods (Phase 1)

- Two PPE ensembles with the same design but built of materials with different THL values that fall in the NFPA standards extreme ranges (THL <250 W/m^2 and >650 W/m^2) were evaluated.
- The materials were first tested by an independent laboratory to acquire the sweating hot plate THL test value (Table 1).
- The PPE constructed with each of the two materials were tested using a sweating thermal manikin (Fig. 1) to predict THL values (Table 1) based on ASTM test standards.

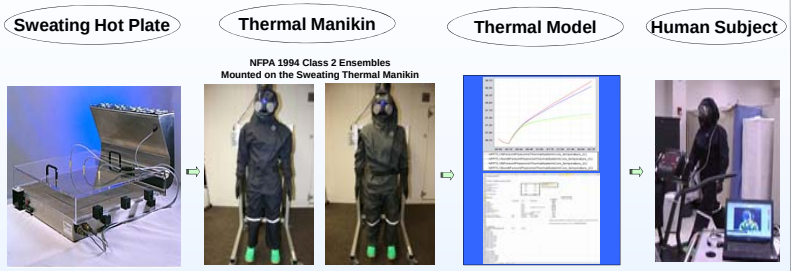

Figure 1. Schematic of Technical Approach for Phase 1

- The clothing values from the manikin testing were used to simulate the thermal responses of humans working while wearing the ensembles, using a thermal model simulation developed by TNO (Lotens, 1993 and Lotens and Havenith, 1991).
- The thermal model simulation predicts heat loss during metabolic work similar to work performed by humans at any environmental condition.

Measurements:
- Thermal Resistance (sweating hot plate and manikin)
- Evaporative Resistance (sweating hot plate and manikin)
- Total Insulation and Permeability Index (manikin)
- Total Heat Loss (sweating hot plate, manikin and thermal model simulation)

Data/Statistical Analysis:
- All measurements were calculated according to the various ASTM standards (F1291, F2370, and F1868)
- Percentages of the differences between the two ensembles were calculated to reflect the variation between the three methodological approaches.

Results and Discussion

- The differences (Table 1) between the two ensembles from the three methodological approaches could be due to several reasons:
  - Sweating hot plate test is performed on a small sample of PPE fabric in a tightly controlled environment.
  - Sweating thermal manikin tests the whole PPE ensemble as it is worn by an individual in which a layer of air is created between the warm surface of the manikin and the clothing that affects the overall heat transfer.
  - Condensation of moisture (sweat) on the outer layer of clothing is another factor that is not tested in the sweating hot plate test but affects heat transfer.
  - The thermal simulation model tries to account for the air layer between the skin and clothing and does incorporate and predict moisture absorption and condensation effects of the clothing layers.
  - Skin temperature varies with changing conditions in the thermal model simulation, whereas the manikin maintains overall skin temperature at 35°C.

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Table 1. Thermal characteristics of two experimental PPE ensembles

Test Method	Suit A	Suit B	THL difference (%)
Sweating Hot Plate Test			
Intrinsic thermal resistance (R_{ct}) [K·m^2/W]	0.019	0.005	
Intrinsic evaporative resistance (R_{et}^A) [kPa·m^2/W]	0.170	0.003	
Total heat loss (Q_t) [W/m^2]:	191.3	909.4	718.1 (78.9%)
Sweating Thermal Manikin Test			
Intrinsic thermal resistance (R_{cl}) [°C·m^2/W]	0.150	0.134	
Intrinsic evaporative resistance (R_{ecl}) [kPa·m^2/W]	0.478	0.041	
Total insulation (It) [clo]	1.270	1.170	
Permeability index (i_m) [0-1][a]	0.025	0.227	
Heat loss potential (Q_p) [W/m^2][b]	81.5	150.0	68.5 (45.6%)
Predicted heat loss potential ($Q_{predicted}$) [W/m^2][c]	58.2	128.6	70.4 (54.8%)
Thermal Model Simulation			
Total heat loss (Q_t) [W/m^2][c]:	88	123	35 (28.4%)

[a]: Woodcock moisture permeability index (0: totally impermeable – 1:totally permeable); [b]: the total amount of heat that can be transferred from the manikin to the ambient environment combined from evaporative and dry heat transfer that were separately measured in 35°C, 40%RH and 20°C, 40-60%RH, respectively; [c]: the predicted amount of heat that can be transferred from the manikin to the ambient environment for a specified condition of 25°C, 65%RH identical to the test condition of total heat loss (Q_t) sweating hot plate testing and the thermal model simulation.

Conclusions

- Suit B consistently shows higher THL values across all test methods.
- The magnitudes of THL differences between the two ensembles are most likely due to differences in the test methods, but showing less magnitude as the test method is more similar to human testing.
- Further validation is required, but these preliminary results suggest that THL values given by the sweating thermal manikin and thermal model simulation should be taken into account when assessing THL numbers for PPE ensembles.

References

Lotens, W.A. (1993). *Heat transfer from humans wearing clothing*. PhD thesis, Technical University Delft, February 1997, Delft.

Lotens, W.A. Havenith, G. (1991). *Calculation of clothing insulation and vapour resistance. Ergonomics 34, 233-254*

Partners

- TNO
- Lion Apparel
- NFPA
- North Carolina State University
- Underwriters Laboratories (UL)
- ASTM

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