Heat Transfer Model for Validation of a Heat Loss Test Method in Non-Isothermal Conditions

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Abstract: Heat transfer through clothing systems can mean the difference between life or death for first responders, such as firefighters, who perform intense physical activity in extreme environmental conditions. Total Heat Loss (THL) is a fabric level test method required by the National Fire Protection Association (NFPA) to assess the thermal burden imposed by materials in the construction of turnout clothing. This methodology, however, does not account for garment fit, construction, or air layers that develop within the clothing. Instead, thermal manikins may be used to measure the THL of entire clothing systems according to ASTM test methods. Environmental test conditions between the two standard methods (fabric versus manikin) differ, creating the need for an adapted heat transfer model for manikin THL comparisons in similar environmental conditions (Ross, Barker, & Deaton, 2012). Therefore, the purpose of this research was to validate the assumptions of the heat transfer model for its accuracy in predicting manikin THL in non-isothermal test conditions. Three protective clothing systems with varying levels of clothing insulation were tested for THL in both isothermal and non-isothermal conditions, as well as on the sweating guarded hot plate. Predictive calculations using Ross’s heat transfer model, adapted from the original THL hot plate calculation in ASTM F 1868, were correlated to the actual measurements taken in the isothermal conditions to determine if there is any bias present in the current model.

Introduction
A major objective of this research project was to validate the assumptions of Ross’s (2012) heat transfer model for measuring heat loss on the garment level in non-isothermal conditions, using a sweating thermal manikin, versus the fabric level measurements in isothermal conditions, using a sweating guarded hot plate. On the fabric level, thermal insulation (R<sub>t</sub>) and evaporative resistance (R<sub>et</sub>) are measured in the same, isothermal conditions for both dry and wet heat loss. For structural firefighter turnout suits specifically, the National Fire Protection Association (NFPA) 1971 Standard on Protective Ensembles for Structural Firefighting specifies test conditions for fabric THL of 25°C/65% relative humidity (RH). While NFPA 1971 only requires total heat loss (THL) testing on the material level, understanding heat loss properties of a three-dimensional garment when worn on the human body in realistic conditions is essential. Therefore, thermal manikin evaluations in dry and wet conditions may be conducted to determine thermal insulation (R<sub>t</sub>) and evaporative resistance (R<sub>et</sub>).

Garment level THL measurements differ in that thermal insulation and evaporative resistance measurements are conducted in non-isothermal conditions according to ASTM F 1291 and ASTM F 2370, respectively. The environmental test conditions for these tests include 20°C/50% RH for thermal insulation and 35°C/40% RH for evaporative resistance. In order to compare manikin THL results in other environmental conditions, predicted manikin performance in the same 25°C/65% RH environment may be calculated according to Ross’s (2012) heat transfer model. This model, however, includes some assumptions, such as condensation and absorption are negligible and that fabric is independent of environmental conditions. Therefore, the purpose
of this research was to validate the assumptions of the heat transfer model for its accuracy in predicting manikin THL in isothermal test conditions according to the following research objectives:

1. To validate the condensation, absorption, and fabric independency assumptions of the heat transfer model for predicted manikin heat loss measurements.
2. To determine the effect of an impermeable membrane and multi-layer clothing system on the heat transfer model assumptions in isothermal conditions.
3. To analyze and conclude if any inherent bias or error is present in the current heat transfer model.

**Methodology**

*Sample:*
Three protective clothing systems with varying levels of clothing insulation were tested for manikin THL in both isothermal and non-isothermal conditions, as well as on the sweating guarded hot plate for fabric THL. These garments included a multi-layer structural firefighter turnout ensemble, a single layer urban search and rescue (USAR) garment, and a stationwear uniform shirt and pants. These garments were chosen as clothing systems representative of the fire service industry with varying levels of clothing insulation and permeability. The structural firefighter turnout suit consisted of three layers: an outer shell, semi-permeable moisture barrier, and thermal liner. The USAR system consisted of a single layer, PBI/Nomex blend outer shell material while the stationwear uniform was constructed of 100% cotton. Figure 1 illustrates the structural turnout suit, USAR system, and stationwear uniform.

*Procedures:*
All three garments were tested on a static sweating thermal manikin, standing, with a still air speed of 0.4 m/s. The structural firefighter turnout suit and USAR system were both tested assuming a vehicle extrication scenario with the manikin wearing a helmet, gloves, and boots, but no SCBA. The manikin was first dressed with a cotton t-shirt, athletic shorts, and socks as base layers. For the stationwear uniform, no helmet or gloves were donned and tennis shoes were worn in place of boots. No base layers were worn underneath the stationwear uniform. The head, hands, and foot zones were removed from the manikin THL calculations to ensure consistency between garments. Three repetitions were completed for each garment configuration.
Initial testing included performing the dry and wet heat loss tests for thermal insulation and evaporative resistance under the conditions specified in ASTM F 1291 and ASTM F 2370. According to these standards, dry thermal resistance is tested in a 20°C/50% RH environment and wet evaporative resistance is measured in isothermal conditions at 35°C/40% RH, with ambient air temperature equivalent to skin temperature of the manikin (35°C). From these results, a "predicted" manikin THL may be calculated, according to Equation 1. Manikin THL was predicted in a 25°C/65% RH environment as specified by NFPA 1971 for measuring fabric THL on the sweating guarded hot plate. Predicting manikin THL in these conditions allows for comparisons to be made with fabric level THL on the sweating guarded hot plate which is conducted for both dry and wet heat loss at 25°C/65% RH. Therefore, fabric THL for each clothing system was also conducted according to ASTM F 1868 Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate.

\[
Q_t(\text{predicted, } T, \text{RH}) = \left(\frac{T_s - T_a}{R_t}\right) + \left(\frac{P_s - P_a}{R_{etA}}\right)
\]

where:

- \(Q_t(\text{predicted, } T, \text{RH})\) = predicted manikin THL for specified environmental conditions (W/m²),
- \(T\) = specified temperature condition (°C),
- \(RH\) = specified relative humidity (%),
- \(T_s\) = specified temperature at the manikin surface (°C),
- \(T_a\) = specified temperature of the local environment (°C),
- \(P_s\) = calculated water vapor pressure at the surface of the manikin (kPa),
- \(P_a\) = calculated water vapor pressure in the specified local environment (kPa),
- \(R_t\) = total thermal resistance of the clothing ensemble and surface air layer (°C·m²/W),
- \(R_{etA}\) = apparent total evaporative resistance of the test ensemble and surface air layer (kPa·m²/W) (McCullough, Jones, & Huck, 1985; Ross et al., 2012).
The heat transfer model used to predict manikin THL in other environmental conditions assumes that condensation and absorption are negligible and that results are independent of fabric type. These assumptions, however, have not been validated. Therefore, additional sweating thermal manikin testing was conducted for each of the three garments in an actual 25°C/65% RH environment, for both dry and wet heat loss. Thermal and evaporative resistance occurred in modified, isothermal conditions as opposed to the standard non-isothermal conditions in ASTM F 1291 and ASTM F 2370. The manikin THL calculated from this data was not predictive and was correlated back to the predicted manikin THL for the same environment.

Results

**Predicted versus Measured Manikin THL**

The predicted manikin THL results, in a 25°C/65% RH environment, for each of the three clothing configurations are given in Table 1 below. These results were measured according to ASTM F 1271 (20°C/50%RH) and ASTM F 2370 (35°C/40%RH) standard test conditions for thermal insulation ($R_t$) and evaporative resistance ($R_{etA}$), respectively. The overall manikin THL, as well as the dry ($Q_{dry}$) and wet ($Q_{wet}$) heat loss is presented.

<table>
<thead>
<tr>
<th>Garment</th>
<th>$R_t$</th>
<th>$R_{etA}$</th>
<th>Dry Heat Loss ($Q_{dry}$)</th>
<th>Wet Heat Loss ($Q_{wet}$)</th>
<th>THL ($Q_t$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationwear</td>
<td>0.220</td>
<td>0.031</td>
<td>45.5</td>
<td>115.3</td>
<td>160.8</td>
</tr>
<tr>
<td>USAR</td>
<td>0.292</td>
<td>0.060</td>
<td>34.2</td>
<td>59.6</td>
<td>93.9</td>
</tr>
<tr>
<td>Structural Turnout</td>
<td>0.426</td>
<td>0.088</td>
<td>23.5</td>
<td>40.5</td>
<td>64.0</td>
</tr>
</tbody>
</table>

The major objective of this study was to validate Ross’s current heat transfer model by comparing non-isothermal test condition results (Table 1) that are predicted in a standard environment to those isothermal test condition results actually measured in the standard environment (Table 2). The measured thermal insulation, evaporative resistance, and THL of the three clothing configurations measured in a 25°C/65% RH environment are included in Table 2 below.

<table>
<thead>
<tr>
<th>Garment</th>
<th>$R_t$</th>
<th>$R_{etA}$</th>
<th>Dry Heat Loss ($Q_{dry}$)</th>
<th>Wet Heat Loss ($Q_{wet}$)</th>
<th>THL ($Q_t$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationwear</td>
<td>0.213</td>
<td>0.032</td>
<td>47.0</td>
<td>112.4</td>
<td>159.4</td>
</tr>
<tr>
<td>USAR</td>
<td>0.296</td>
<td>0.051</td>
<td>33.8</td>
<td>72.3</td>
<td>106.1</td>
</tr>
<tr>
<td>Structural Turnout</td>
<td>0.427</td>
<td>0.079</td>
<td>23.4</td>
<td>45.3</td>
<td>68.7</td>
</tr>
</tbody>
</table>

By comparing the results in Tables 1 and 2 for each clothing system, minimal differences are noted. Statistical analysis revealed more variation exists between the $R_{etA}$, $Q_{wet}$, and $Q_t$ values for the structural turnout suit and USAR system. The overall predicted manikin THL aligns closely to the measured manikin THL for each suit except for the USAR. There is a 12.2 W/m² difference between the predicted and measured manikin THL for the USAR suit demonstrating
the garment had a higher heat loss value than was predicted according to Ross’ heat transfer model. Differences in $Q_t$ for the stationwear (-1.4 W/m$^2$) were small and may be due to test instrument variation. For the structural turnout suit, the differences (+4.7 W/m$^2$) were significant ($p < 0.05$ for $Q_{wet}$ and $R_{et}$). These results show slightly increased evaporative heat loss in the measured conditions but, this difference was still small and may be less relevant under practical conditions. The USAR garment showed a stronger, significant effect ($p < 0.05$, paired t-test); a lower $R_{et}$, and higher $Q_{wet}$ and $Q_t$ values when measured versus predicted. These differences are in line with the literature that has also shown higher measured (evaporative) heat loss under cooler conditions due to condensation within the suit. It may still be uncertain if at this temperature the differences would be meaningfully significant to the wearer, but the trend suggests that this effect becomes stronger at lower temperatures, enhancing evaporative heat loss under cooler conditions.

**Fabric THL versus Manikin THL**

While the focus of this study was to validate Ross’ heat transfer model, his original intention was to predict manikin THL in the same environment as fabric THL was measured in isothermal conditions on a sweating guarded hot plate. Unfortunately, many more variables exist between thermal and evaporative resistance measurements when comparing fabric and garment level results. Table 3 below gives the fabric THL results for each garment configuration.

<table>
<thead>
<tr>
<th>Garment</th>
<th>$R_{ct}$</th>
<th>$R_{ct}^{A}$</th>
<th>Dry Heat Loss ($Q_{dry}$)</th>
<th>Wet Heat Loss ($Q_{wet}$)</th>
<th>THL ($Q_t$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationwear</td>
<td>0.098</td>
<td>0.009</td>
<td>142.5</td>
<td>488.0</td>
<td>630.9</td>
</tr>
<tr>
<td>USAR</td>
<td>0.091</td>
<td>0.012</td>
<td>164.9</td>
<td>357.8</td>
<td>522.7</td>
</tr>
<tr>
<td>Structural Turnout</td>
<td>0.161</td>
<td>0.021</td>
<td>76.7</td>
<td>186.7</td>
<td>263.4</td>
</tr>
</tbody>
</table>

The structural firefighter turnout suit base composite (outer shell, moisture barrier, and thermal liner) was measured as a multi-layer system on the fabric level. For the USAR system, the single layer outer shell fabric was measured. The cotton stationwear shirt was also assessed. When comparing these results to those in Table 1 which were predicted using Ross’s model in the same 25°C/65%RH environment, it is obvious the values are much different. The same is true if comparing with the results in Table 2 that were actually measured in the same conditions as the fabric THL.

**Discussion**

There were multiple outcomes determined from the statistical analysis and manikin THL comparisons. The first of which indicated that between the predicted and measured values, there were small but significant differences, especially in the garments with higher levels of insulation. This outcome demonstrates limitations to Ross’ heat transfer model and the assumptions that condensation, absorption, and fabric differences are negligible. The model was found to be a fairly good estimate, but not entirely accurate for the multi-layer structural turnout clothing system and USAR garment in the dry conditions ($R_t$ and $Q_{dry}$). For the single layer stationwear garment, no significant or relevant differences were found. It should be noted that all garments were tested without a helmet, boot, gloves, or base layers. This may have influenced the results...
and is a limitation of the study, as garments were tested with end use ensemble accessories that differed.

Secondly, the obtained variations, although determined to be statistically significant, may not be meaningful to the wearer at this temperature (25°C, 65% rh) but at lower temperatures the differences are expected to increase. These findings could indicate that condensation and absorption may not be negligible in the heat transfer model when assessing a multi-layer clothing system with semi-permeable barrier materials as the evaporative resistance and wet heat loss were more affected. This also challenges the fabric independency assumption. In order to validate these conclusions, however, further research should be conducted with a broader scope and larger sample size.

Ultimately, the difference between measuring evaporative resistance in an isothermal condition (skin temperature and ambient temperature are the same) according to ASTM F 2370 and measuring it in non-isothermal conditions (skin temperature at 35°C; ambient temperature at 25°C) resulted in significant differences in wet heat loss and manikin THL for the USAR system, compared to the structural turnout suit and station-wear.

The comparison between fabric THL and manikin THL illustrates the limitation of testing heat loss on the fabric level which neglects garment fit, construction, additional reinforcements, and air layers that develop within the clothing when worn on the three-dimensional human form as has been shown in the literature, as well. This research, along with future studies, should be conducted and disseminated to justify the addition of manikin level assessments at the standards level for protective and functional clothing, including structural firefighter turnout suits.

Conclusions
Overall, the thermal insulation for all suits demonstrated strong correlations between the predicted and measured test conditions with limited absolute differences. This is most likely due to the similar test conditions. Predicted measurements were taken according to the test conditions specified in ASTM F 1291 (20°C/50%RH) which are not drastically different from the actual measured condition (25°C/65%RH). Taking measurements in non-isothermal conditions in which the temperature of the manikin “skin” and the ambient environmental temperature were not the same led to larger variations in the data and weaker correlations for evaporative heat loss. The measured conditions of 25°C/65%RH are quite different from the standard ASTM F 2370 conditions of 35°C/40%RH.

In conclusion, the results from this study show limitations of Ross’ heat transfer model assumptions that condensation and absorption are negligible and that fabric insulation is independent of environmental conditions. Some variation occurred that indicated statistically significant differences, but correlations between these results remained strong. The largest difference (12.7 W/m²) between the predicted and measured results was found when determining wet heat loss for the USAR suit. This research demonstrates that Ross’ computational model may be useful when temperatures around 25°C are considered. As condensation conditions seemed to be present it is not clear if the approach would still be valid for lower environmental temperatures. Any presence of inherent bias or error in the model was not found in this study.
References


Faculty Mentor Assessment

As faculty mentor I can state that Meredith has accomplished a great deal in her work around the development of novel concepts for structural turnout gear. In that process she has also developed a strong affinity to the testing of fabrics and garments for thermal comfort as this work demonstrates. The complications and subtleties of dry and evaporative heat loss and all physical factors influences the heat and mass transport properties are often elusive to researchers and users of firefighter PPE and Meredith has demonstrated an ability to master the major topics and conduct solid scientific studies in this area. This is a welcome addition to the small groups of experts that work in the area of thermal comfort testing and evaluation of protective clothing. As such this work has been most valuable as it attempted to, and succeeded in, studying current standard ASTM test methods and enhance knowledge and understanding around these test methods and provide scientific data to answer questions that have been raised in ASTM (and NFPA) working groups around these issues. Although this limited study may not provide all answers the data are in line with other studies on very different types of clothing that have been conducted in the past. Meredith’s work provides a key piece to the discussions around assessment of thermal comfort and thermal strain of protective clothing and opened up some interesting additional questions. Having achieved this with minimal means alongside the huge endeavor of her PhD work is a great accomplishment and I am looking forward to more contributions from her in this area.