Empirical Equations for Intrinsic and Effective Evaporative Resistances of Multi-layer Clothing Ensembles

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Empirical equations for intrinsic and effective evaporative resistance of multi-layer clothing ensembles

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Clothing total thermal and evaporative resistances are the two most important parameters for thermal comfort and human heat balance models. Total clothing evaporative resistance \( R_e \) is the combined resistance provided by clothing \( R_{cl} \) (clothing intrinsic evaporative resistance) and the surrounding layer of air \( R_{ea} \) (evaporative resistance of the air layer). This relationship can be mathematically described as:

\[
R_e = R_{cl} + R_{ea} \quad (1)
\]

Values for \( R_e \) and \( R_{ea} \) can be measured from variations of the standard tests for clothing thermal resistance by using either a sweating guarded hot plate or a sweating thermal manikin. The intrinsic clothing evaporative resistance \( R_{cl} \) and effective clothing evaporative resistance \( R_{ele} \) are calculated from the following equations:

\[
R_{cl} = R_e - \frac{R_{ea}}{f_{cl}} \quad (2)
\]

\[
R_{ele} = R_e + R_{ea} \quad (3)
\]

where:

- \( f_{cl} \) is the clothing area factor, the ratio outer surface area of a clothed person and a nude person.
- This can be measured by photographic or 3D whole body scanning methods. The surface area increased resulted from wearing clothing depends on the thickness of the clothing, which is relate to the clothing thermal resistance. The clothing area factor may also be estimated from the equation proposed by McCullough and Jones in 1984:

\[
f_{cl} = 1 + 0.31 f_{cl} \quad (4)
\]

where:

- \( f_{cl} \) is the clothing intrinsic thermal resistance, clo.

Although ISO 9920 provides a database on the clothing area factor and intrinsic clothing thermal resistances of many western, Gulf region and Korean clothing ensembles, it is still a challenge to accurately measure the clothing area factor. Moreover, the empirical equation regarding clothing evaporative resistance values of multi-layer clothing ensembles based on individual garments hasn’t reported yet. It is necessary to develop empirical equations to estimate the intrinsic and effective evaporative resistances of clothing ensembles by using the summation of individual garment. Additionally, the empirical equations are expected to be used for clothing manufacture companies and consumers for rough estimations. In this paper, we used a fabric sweating thermal manikin Walter to investigate the relationship between clothing ensemble’s evaporative resistances (intrinsic and effective evaporative resistances) and the summation of the evaporative resistance of individual garments. Two empirical equations for estimation of clothing effective and intrinsic evaporative resistances were also developed.

METHODS
Clothing ensembles tested
Two kinds of knitted underwear (U1 and U2), three different middle-layer garments (M1, M2 and M3), a nylon/cotton Gore-Tex jacket (O) and a pair of long trousers (T) were used in this study. With these sets of clothing, nineteen different clothing combinations were selected.
at random for the tests. The details of all clothing ensembles are listed in table 1.

**Thermal manikin**

A fabric sweating thermal manikin Walter (fig. 1) was used to test the thermal and evaporative resistances of these garments. With this manikin, the total thermal resistance can be measured and calculated by using the following equations:

\[
R_t = \frac{A}{H_t} \quad (5)
\]

\[
H = H_d + H_e \quad (6)
\]

\[
R_e = \frac{A}{E} \frac{(P_{ea} - P_e)}{P_{sa} \cdot RH_s + P_{ad} \cdot RH_a} \quad (7)
\]

where:
- \(R_t\) is the total thermal resistance of a garment, m²·°C/W;
- \(A\) – the body surface area, m²;
- \(t_s, t_a\) – the skin and ambient temperature respectively, °C;
- \(H, H_d, H_e\) – the total, dry and evaporative heat loss, W;
- \(E\) – the latent heat of evaporation of water at the skin temperature, W·h/g;
- \(Q\) – the sweating rate, g/h.

The total evaporative resistance of a garment can be calculated by:

\[
R_e = \frac{A}{E} \frac{(P_{ea} - P_e)}{P_{sa} \cdot RH_s + P_{ad} \cdot RH_a} \quad (8)
\]

where:
- \(R_e\) is the evaporative resistance, Pa · m²/W;
- \(P_{ea}, P_a\) – the water vapor pressure at the skin and the ambient temperature, Pa;
- \(P_{sa}, P_{sa}\) – the saturated water vapor pressure at the skin temperature and ambient temperature, Pa;

\(RH_s, RH_a\) – relative humidity at the skin surface and the ambient respectively, %.

**Test conditions**

The core temperature of thermal manikin Walter was controlled at 37°C. The area of the climatic chamber is 4.0·2.5·2.1 m and all tests were conducted at an ambient temperature of 8 ± 0.5°C, relative humidity of 50 ± 5% and an air velocity of 0.3 ± 0.1 m/s. Two Pt-100 RTD stainless steel temperature sensors, two Honeywell humidity sensors (HIH-3610) and an air velocity sensor (Testo 435, Germany) were used in the climatic chamber. Fifteen RTD temperature sensors were attached using a flat elastic webbing belt at different body parts (head, chest, back, tummy, hip, right upper arm, tight lower arm, left upper arm, left lower arm, right anterior thigh, right posterior thigh, left anterior thigh, left posterior thigh, right shin, left shin) of the manikin surface skin to measure the skin surface temperatures. An average temperature value of these 15 points was used as the mean skin surface temperature. All clothing ensembles were put inside the climatic chamber where the conditioned air temperature 20°C and 50% RH for 24 hours before the measurement to stabilize. Each of the tests at one condition was repeated three times and the mean values were used for the final analysis. The recordings were considered good and correct if the coefficient of variance of all values measured for each clothing ensemble stayed below 10%. Finally, all the tests were strictly conducted according to ISO 15831, clothing physiological effects-measurement of thermal insulation by means of a thermal manikin, and ASTM F 2370, standard test method for measuring the evaporative resistance of clothing using a sweating manikin.

**RESULTS AND DISCUSSION**

A computer automatically records the manikin skin surface temperature – \(T_s\), the ambient temperature – \(T_a\), ambient relative humidity – \(H_a\), total heat loss value – \(E\), and the sweating rate – \(Q\). The thermal resistance – \(R_t\) and evaporative resistance – \(R_e\) of the clothing.
ensembles can also be calculated by the LabVIEW program (National Instrument, USA). All measured and calculated parameters are listed in table 2. Since the same pair of trousers were used for all tests, the thermal and evaporative resistances when the manikin only wearing the trousers could be deemed as the basic thermal and evaporative resistances of the air layer. As a result, the thermal and evaporative resistances of the air layer are 0.135°C m²/W and 16.63 Pa m²/W.

The calculated intrinsic, effective clothing evaporative resistances and clothing area factor of all 18 possible clothing combinations (exclude the clothing combination T) are listed in table 3. It can be clearly seen that the effective evaporative resistance of a clothing combination is larger than its intrinsic evaporative resistance. Hence it is demonstrated that the clothing area factor is larger than 1 due to the thickness of the added clothing. The calculated clothing area factor of all 18 clothing ensembles by equation (4) ranges from 1.139 to 1.560.

The accumulated effective evaporative resistance $\Sigma R_{cl,e}$ of the clothing ensemble can be achieved by adding up the effective evaporative resistance of individual garment. Similarly, the accumulated intrinsic evaporative resistance $\Sigma R_{cl}$ of individual clothing in a multi-layer clothing ensemble can be also easily acquired. According to the data of effective and intrinsic evaporative resistances for 18 clothing ensembles presented in table 3, the relation between accumulated intrinsic (or effective) evaporative resistances and total intrinsic (or effective) evaporative resistance of multi-layer garments could be developed using origin software â OriginLab Corporation, Version 8.0, USA (fig. 2). The empirical equations are listed as follows:

$$R_{cl,e} = 0.60 \Sigma R_{cl,e} + 5.89 \quad (9)$$

<table>
<thead>
<tr>
<th>Clothing combinations</th>
<th>$T_1$ °C</th>
<th>$T_2$ °C</th>
<th>$H_r$ %</th>
<th>$E_r$ W</th>
<th>$Q_r$ g/h</th>
<th>$R_t$ °C m²/W</th>
<th>$R_e$ Pa m²/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>31.5</td>
<td>8.4</td>
<td>55</td>
<td>601</td>
<td>422</td>
<td>0.135</td>
<td>16.6</td>
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<tr>
<td>$U_1T$</td>
<td>32.9</td>
<td>8.5</td>
<td>55</td>
<td>456</td>
<td>326</td>
<td>0.190</td>
<td>27.3</td>
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<tr>
<td>$U_2T$</td>
<td>32.8</td>
<td>8.1</td>
<td>55</td>
<td>490</td>
<td>364</td>
<td>0.189</td>
<td>23.5</td>
</tr>
<tr>
<td>$M_1T$</td>
<td>34.1</td>
<td>8.2</td>
<td>45</td>
<td>381</td>
<td>283</td>
<td>0.254</td>
<td>37.9</td>
</tr>
<tr>
<td>$M_2T$</td>
<td>33.1</td>
<td>8.1</td>
<td>45</td>
<td>422</td>
<td>324</td>
<td>0.229</td>
<td>29.0</td>
</tr>
<tr>
<td>$M_3T$</td>
<td>33.2</td>
<td>8.3</td>
<td>46</td>
<td>415</td>
<td>308</td>
<td>0.225</td>
<td>31.2</td>
</tr>
<tr>
<td>$OT$</td>
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<td>8.5</td>
<td>53</td>
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<td>282</td>
<td>0.246</td>
<td>36.2</td>
</tr>
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<td>$U_1M_1T$</td>
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<td>361</td>
<td>268</td>
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<td>40.4</td>
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<td>34.6</td>
<td>8.2</td>
<td>48</td>
<td>341</td>
<td>250</td>
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<tr>
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<td>46</td>
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<td>39.7</td>
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<tr>
<td>$U_3M_2T$</td>
<td>34.1</td>
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<td>49</td>
<td>333</td>
<td>251</td>
<td>0.282</td>
<td>42.1</td>
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<tr>
<td>$U_3M_3T$</td>
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<tr>
<td>$U_3M_4T$</td>
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<td>8.2</td>
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<td>0.255</td>
<td>37.9</td>
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<td>327</td>
<td>258</td>
<td>0.335</td>
<td>43.6</td>
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<td>34.9</td>
<td>8.4</td>
<td>45</td>
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<td>236</td>
<td>0.334</td>
<td>49.9</td>
</tr>
<tr>
<td>$U_3M_8T$</td>
<td>34.2</td>
<td>8.2</td>
<td>46</td>
<td>292</td>
<td>229</td>
<td>0.354</td>
<td>48.5</td>
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<tr>
<td>$U_3M_9T$</td>
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<td>7.9</td>
<td>45</td>
<td>318</td>
<td>254</td>
<td>0.344</td>
<td>44.0</td>
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<td>7.9</td>
<td>47</td>
<td>307</td>
<td>229</td>
<td>0.330</td>
<td>51.5</td>
</tr>
</tbody>
</table>

Fig. 2. Relations between accumulated clothing effective/intrinsic evaporative resistance and clothing effective/intrinsic evaporative resistance: a – intrinsic evaporative resistance of clothing ensembles and sum of intrinsic evaporative resistance of individual garment; b – effective evaporative resistance of clothing ensembles and sum of effective evaporative resistance of individual garment
It can be deduced from figure 2a that there is a good linear relationship between the accumulated clothing intrinsic evaporative resistance $\Sigma R_{\text{ec}}$ and the intrinsic evaporative resistance $R_{\text{ec}}$ of the clothing ensemble. Hence, we can use accumulated clothing evaporative resistance of individual garment to predict the total evaporative resistance of a multi-layer clothing ensemble. Since thermal manikin tests are costly, using such an empirical equation could rapidly estimate clothing total evaporative resistance by using the value of the individual garment. Similarly, the effective clothing evaporative resistance of a specific multi-layer clothing ensemble can also be predicted using the equation presented in figure 2b. Furthermore, we can use clothing effective evaporative resistance to replace clothing intrinsic evaporative resistance for rough estimation due to the fact that the measurement of the clothing area factor is difficult and time-consuming.

In this paper, we only investigated the two static evaporative resistances (intrinsic and effective) of winter garments due to the fact that heat pumping effect resulted from walking and air speeds is small for thick clothing ensembles. It would be more useful to consider effects of both the air velocity and walking speed on the resultant evaporative resistance for both thick and thin clothing ensembles. Further studies will be focused on the effects of walking and air velocity on the resultant evaporative resistance of various clothing, especially one-layer light summer series clothing.

**CONCLUSIONS**

In this paper, a fabric sweating thermal manikin Walter was used to develop the relation between total intrinsic evaporative resistance of a multi-layer clothing ensemble and the accumulated intrinsic evaporative resistance of the individual garment. Two empirical equations on ensemble evaporative resistance based on summation of individual garments were also developed. Some of the novel findings in this study are summarized as follows:

- The two empirical equations for clothing intrinsic and effective evaporative resistances are:

$$R_{\text{ec}} = 0.60 \sum R_{\text{ec}} + 5.89$$

$$R_{\text{ec}} = 0.60 \sum R_{\text{ec}} + 4.42$$

- It is useful to use accumulated intrinsic evaporative resistance of individual garment to predict the total intrinsic evaporative resistance of a multi-layer clothing ensemble. On the other hand, the effective evaporative resistance could be also used to estimate the clothing intrinsic evaporative resistance for a rough estimation due to the difficulty of measuring clothing area factor.

**BIBLIOGRAPHY**


Cea de-a VIII-a ediţie a celui mai important târg comercial internaţional de materiale pentru amenajări interioare, perdele şi draperii – PROPOSTE, s-a desfăşurat în perioada 5–7 mai 2010, la Villa Erba/Cernobbio.

Din cei 103 expozaţii europeni, 53 au fost din Italia. Numărul total de vizitatori profesionişti a scăzut cu 2,5%, faţă de anul 2009. Totuşi s-a înregistrat un număr de 6 553 de vizitatori – dintre care 2 698 (41%) italieni şi 3 855 din alte 70 de ări – la care s-au adăugat 442 de jurnalişti şi invitaţi. În topul ărilor cu prezenţa cea mai mare s-a aflat Germania, Marea Britanie, Franţa, Statele Unite ale Americii şi Rusia.

Interesant este faptul că s-a înregistrat o creştere a participării din partea Americii (+29%), Rusiei (+11%) şi Arabiei Saudit (+46%), în timp ce, așa cum era de aşteptat, numărul de vizitatori din Grecia şi Portugalia a scăzut.

Cele 11 oficii ţinute pentru presă au guzdit 20 de companii editoriale, ce au reprezentat un total de 56 de publicaţii.

Contrar unor asteptări pesimiste, bazate pe efectele crizei financiare pe care o traversăm, rezultatele excelente ale PROPOSTE 2010, au demonstrat că cererea de produse inovatoare, de altă calitate, continuă să fie ridicată pe pieţele internaţionale. Pe durata celor trei zile ale evenimentului, un colectiv de jurnalişti şi stilişti au făcut o evaluare a colecţiilor expuse la târg, într-un număr special „Made in Europe Trends at Proposte 2010” publicat pe website la adresa: www.propostefair.it.

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