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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REZUMAT – ABSTRACT – INHALTSANGABE

Ecuaţii empirice de determinare a rezistenţelor intrinseci şi efective la evaporare ale ansamblurilor vestimentare multistratificate

Pentru a determina valorile rezistenţei intrinseci şi ale celei efective la evaporare, atât la îmbrăcămintea individuală, cât şi la ansamblurile vestimentare multistrat destinate sezonului rece, s-a folosit manechinul termic Walter. Pornind de la testările efectuate asupra îmbrăcămintei individuale, au fost dezvoltate două ecuaţii empirice de estimare a acestor rezistenţe, ele fiind utile atât producătorilor de îmbrăcăminte – pentru o estimare globală a rezistenţei intrinseci/efective la evaporare, cât şi utilizatorilor – pentru asigurarea unui confort termic optim.

Cuvinte-cheie: rezistenţă la evaporare, manechin termic, ecuaţie empirică, ansambluri vestimentare

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

To determine the intrinsic and effective clothing evaporative resistances, both in the individual clothing, and in the multi-layer clothing ensembles meant for the winter season, a fabric sweating thermal manikin Walter was used. Based on the tests performed on the individual garments, two empirical equations were developed for the estimation of these resistances, useful either to clothing manufacturers – to roughly estimate the clothing intrinsic/effective evaporative resistance, or to consumers – to assure them an optimal thermal comfort.

Key-words: evaporative resistance, thermal manikin, empirical equation, clothing ensembles

Empirische Gleichungen für die Bestimmung des eigentlichen und effektiven Verdunstwiderstandes der Multi-Schicht Bekleidungsensembles

Um die Werte des eigentlichen und effektiven Verdunstwiderstandes zu bestimmen, sowohl bei der individuellen Bekleidung, als auch bei der Multi-Schicht Bekleidung für den kalten Saison, wurde das thermische Mannequin Walter verwendet. Aufgrund der Teste, durchgeführt auf individueller Bekleidung, wurden zwei empirische Gleichungen für die Schätzung dieser Widerstände entwickelt, indem sie sowohl den Bekleidungsproduzenten – für eine globale Schätzung des eigentlichen/effektiven Verdunstwiderstandes als auch den Endverbrauchern – für die Sicherung eines optimalen thermischen Komfortes, wertvoll sind.

Schlusswörter: Verdunstwiderstand, thermisches Mannequin, empirische Gleichung, Bekleidungsensembles

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_{ecl} (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:

$$R_e = R_{ecl} + R_{ea} \quad (1)$$

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_{ecl} and effective clothing evaporative resistance R_{ecle} are calculated from the following equations:

$$R_{ecl} = R_e - \frac{R_{ea}}{f_{cl}} \quad (2)$$

$$R_{ecle} = R_e + R_{ea} \quad (3)$$

where:

f_{el} 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:

$$f_{cl} = 1 + 0.31 I_{cl} \quad (4)$$

where:

I_{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 (U_1 and U_2), three different middle-layer garments (M_1, M_2 and M_3), 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

Table 1

Sample code	Component	Blend ratio, %	Weight, g	Descriptions
U_1	Polyester/spandex	93/7	112	Coolmax fabric
U_2	Cotton	100	103	Plain weave fabric, knit
M_1	Fabric: Nylon taffeta (70D x 70D) Filling: white duckling down/PET	90/10	343	Average weight: 0.839 mg/block White duck down length of a fibril: 5–30 mm Average diameter of fibrils: 21.0 μm
M_2	Fabric: Nylon taffeta (70D x 70D) Filling: polyester 100%	100	367	PET wedding
M_3	Fabric: Nylon taffeta (70D x 70D) Filling: polyester 100%	100	354	High isulating porous
O	Nylon/cotton	67/33	802	Plain weave fabric laminated with Gore-tex membrane, windproof jacket
T	Nylon	100	416	Moisture management fabric

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:

$$R_t = \frac{A \cdot (t_s - t_a)}{H_d} \quad (5)$$

$$H = H_d + H_e \quad (6)$$

$$H_e = E \cdot Q \quad (7)$$

where:

R_t is the total thermal resistance of a garment, m^2 · ^{o}C/W;

A – the body surface area, m^2;

t_s, t_a – the skin and ambient temperature respectively, ^{o}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:

$$R_e = \frac{A \cdot (p_s - p_a)}{H_e} = \frac{A \cdot (p_{sf} \cdot RH_s - p_{ef} \cdot RH_a)}{E \cdot Q} \quad (8)$$

where:

R_e is the evaporative resistance, Pa · m^2/W;

p_s, p_a – the water vapor pressure at the skin and the ambient temperature, Pa;

p_{sf}, p_{af} – the saturated water vapor pressure at the skin temperature and ambient temperature, Pa;

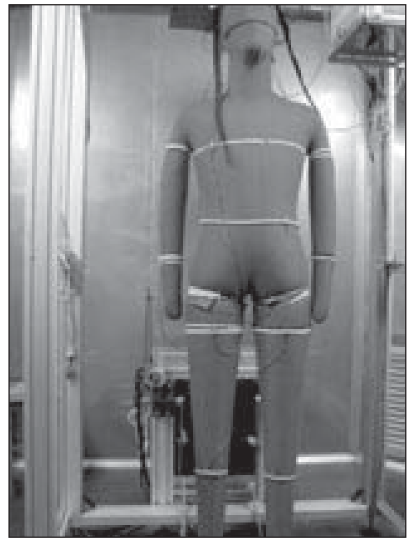


Fig. 1. The sweating fabric thermal manikin Walter

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^{o}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^{o}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^{o}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_e, ambient relative humidity – *He*, total heat loss value – *E*, and the sweating rate – *Q*. The thermal resistance – R_t and evaporative resistance – R_e of the clothing

Table 2

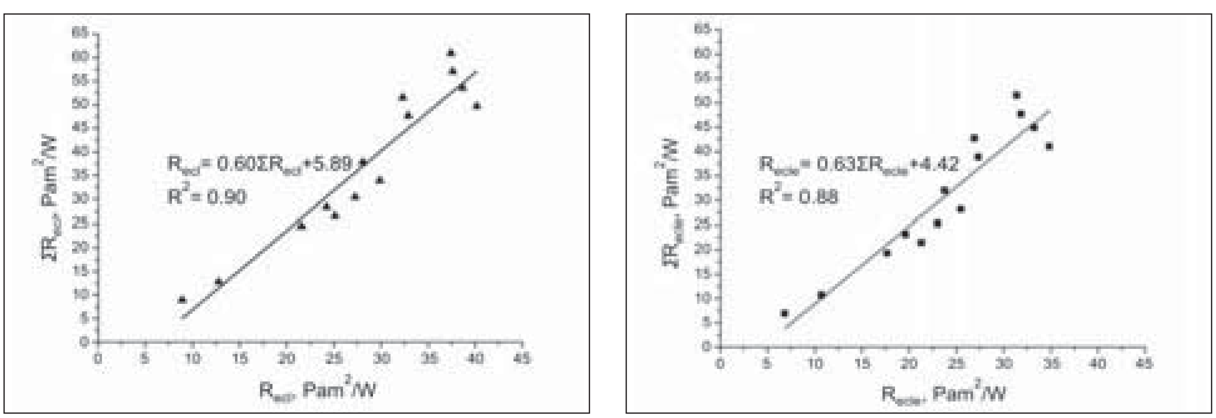
Clothing combinations	T_s, °C	T_e, °C	H_e, %	E, W	Q, g/h	R_t, °C · m²/W	R_e, Pa · m²/W
T	31.5	8.4	55	601	422	0.135	16.6
U_1T	32.9	8.5	55	456	326	0.190	27.3
U_2T	32.8	8.1	55	490	364	0.189	23.5
M_1T	34.1	8.2	45	381	283	0.254	37.9
M_2T	33.1	8.1	45	422	324	0.229	29.0
M_3T	33.2	8.3	46	415	308	0.225	31.2
OT	34.0	8.5	53	383	282	0.246	36.2
U_1M_1T	34.2	7.5	46	361	268	0.278	40.4
U_1M_2T	34.6	8.2	48	341	250	0.288	36.3
U_1M_3T	34.2	7.8	46	364	272	0.274	39.7
U_2M_1T	34.1	8.3	49	333	251	0.282	42.1
U_2M_2T	33.9	8.5	54	377	289	0.257	34.3
U_2M_3T	34.2	8.2	47	387	281	0.255	37.9
U_1M_1OT	34.4	8.0	45	294	235	0.371	48.1
U_1M_2OT	34.6	8.2	45	327	258	0.335	43.6
U_1M_3OT	34.9	8.4	45	308	236	0.334	49.9
U_2M_1OT	34.2	8.2	46	292	229	0.354	48.5
U_2M_2OT	34.5	7.9	45	318	254	0.344	44.0
U_2M_3OT	34.9	7.9	47	307	229	0.330	51.5

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 ΣR_{cle} of the clothing ensemble can be achieved by adding up the effective evaporative resistance of individual garment. Similarly, the accumulated intrinsic evaporative resistance ΣR_{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 – OriginLab Corporation, Version 8.0, USA (fig. 2). The empirical equations are listed as follows:

$$R_{ecl} = 0.60 \sum R_{ecl} + 5.89 \qquad (9)$$



a *b*

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

Table 3

Clothing combinations	R_{cl} Pa · m²/W	R_{cle} Pa · m²/W	f_{cl}
U_1	10.7	12.8	1.14
U_2	6.9	8.9	1.14
M_1	21.2	25.0	1.30
M_2	12.4	15.6	1.24
M_3	14.6	17.6	1.23
O_1	19.6	23.2	1.28
U_1M_1	23.8	28.1	1.35
U_1M_2	19.7	24.2	1.37
U_1M_3	23.0	27.3	1.34
U_2M_1	25.5	29.9	1.36
U_2M_2	17.7	21.6	1.30
U_2M_3	21.3	25.1	1.30
U_1M_1O	31.4	37.4	1.56
U_1M_2O	26.9	32.3	1.48
U_1M_3O	33.3	38.6	1.48
U_2M_1O	31.9	37.6	1.52
U_2M_2O	27.3	32.9	1.50
U_2M_3O	34.8	40.2	1.47

$$R_{ecle} = 0.60\sum R_{ecle} + 4.42 \quad (10)$$

Or, with slightly reduce the accuracy, we can get the following two empirical equations:

$$R_{ecl} = 0.60\sum R_{ecl} \quad (11)$$

$$R_{ecle} = 0.63\sum R_{ecle} \quad (12)$$

It can be deduced from figure 2*a* that there is a good linear relationship between the accumulated clothing intrinsic evaporative resistance ΣR_{ecl} and the intrinsic evaporative resistance R_{ecl} 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 2*b*. 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:

$$R_{ecl} = 0.60\sum R_{ecl} + 5.89$$
$$R_{ecle} = 0.60\sum R_{ecle} + 4.42$$

- 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.

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CRONICĂ

PROPOSTE 2010

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 expozanţi 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 ţări – la care s-au adăugat 442 de jurnalişti şi invitaţi.

În topul ţărilor 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 Saudite (+46%), în timp ce, aşa cum era de aşteptat, numărul de vizitatori din Grecia şi Portugalia a scăzut.

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

Contrar unor aşteptări pesimiste, bazate pe efectele crizei financiare pe care o traversăm, rezultatele excelente ale *PROPOSTE 2010*, au demonstrat că cererea de produse inovatoare, de înaltă 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, dintr-o perspectivă mondială „premiere“, iar tendinţele în domeniul textilelor destinate amenajărilor interioare vor fi prezentate, în curând, într-un număr special *„Made in Europe Trends at Proposte 2010*“ publicat pe website la adresa: www.propostefair.it.

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