A Database of Static Clothing Thermal Insulation and Vapor Permeability Values of Non-Western Ensembles for Use in ASHRAE Standard 55, ISO 7730, and ISO 9920

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ABSTRACT

Four different thermal manikins (male and female shapes) in three different laboratories (UK, Sweden, and China) were used to determine the clothing thermal insulation values of 52 non-Western, mainly indoor clothing ensembles in order to expand the existing clothing database for use with ANSI/ ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy (ASHRAE 2013a), ISO Standard 7730-2005, Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria (ISO 2005), and ISO Standard 9920-2009,Ergonomics of the Thermal Environment—Estimation of Thermal Insulation and Water Vapour Resistance of a Clothing Ensemble (ISO 2009). Insulation values varied over manikins, which is attributed to their different shapes and the different fit of the clothing. The mean value over three manikins is reported (with standard deviation) to include this potential real-life variation in the results. The relation of the clothing surface area factor to intrinsic clothing insulation was found to be different from that published for Western clothing. Prediction equations for the clothing surface area factor f_{cl} *based on the new data had only limited predictive power, which, however, was also the case for those obtained in the past for Western clothing. This issue seems to be commonly overlooked, as the use of these prediction equations is widespread. It has to be concluded that reliable* f_{cl} *values can only be obtained when they are actually measured, as in the present work. However, we suggest that the concept of the* f_{cl} *factor for the non-Western clothing may not be appropriate and may require further attention in research, as wide-falling-robes and gowns do not match the cylindrical clothing and air layer model on which the* f_{cl} *concept is based.*

In summary, the results provide an extensive database of insulation values of non-Western clothing that is expected to be a valuable addition to ASHRAE Standard 55-2013 (ASHRAE 2013a), ISO Standard 7730-2005 (ISO 2005), and ISO Standard 9920-2009 (ISO 2009).

INTRODUCTION

An often-heard criticism of methodologies developed in the Western world by those applying them in other areas of the world is that they do not consider the special local circumstances. Predictions of human thermal comfort sensations (in terms of the predicted mean vote [PMV] and percentage dissatisfied [PPD], ASHRAE Standard 55-2013, ISO Standard 7730-2005) require information on the value of the clothing insulation as worn by occupants (Havenith et al. 2012). Comprehensive data on clothing insulation values are available in the literature and standards (ASHRAE Standard 55-2013; ISO Standard 7730-2005; ISO Standard 9920-2009; McCullough, 1984; McCullough et al. 1985; Olesen and Nielsen 1983; Seppanen et al. 1972). However, the vast majority of these data are for Western-style clothing ensembles only, with comparatively little information available on non-Western ensembles (Al-Ajmi et al. 2008; Al-Rashidi et al. 2012). Clothing insulation is a crucial parameter in the assessment of thermal comfort (Fanger 1972; Havenith et al. 2002; Havenith 2002, 2005a, 2005b; Al-Rashidi et al. 2009a, 2009b, 2010; ASHRAE 2013b) and is therefore important for

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the optimal design of heating, ventilating, and air-conditioning (HVAC) systems to achieve thermal comfort for the building occupants (Ahmad and Ibrahim 2003; Cheong et al. 2003; Kwok and Chun 2003). Furthermore, given the growing energy needs of nations such as India, China, and Pakistan, with often different clothing behavior from the West, precise knowledge of the clothing insulation parameters is essential in optimizing the ventilation and HVAC systems and indoor environmental conditions for these countries and to improve sustainability.

In order to fill this gap in knowledge, ASHRAE commissioned a research project, "Extension of the Clothing Insulation Database for Standard 55 and ISO 7730 to Provide Data for, Mainly Indoor, Non-Western Clothing Ensembles, Including Data on the Effect of Posture and Air Movement on that Insulation" under code 1504-RP. The work was commissioned to a consortium of three research laboratories: Loughborough University, UK; Environmental Ergonomics Research Centre, Lund University, Sweden, Department of Design Sciences, EAT; and Hong Kong Polytechnic University, Institute of Textiles and Clothing, Hong Kong.

The information gathered through this research will constitute an important new addition to the data in building comfort standards. This additional information will enable users of ASHRAE Standard 55-2013 (ASHRAE 2013a), *ASHRAE Handbook—Fundamentals* (ASHRAE 2013b), ISO Standard 7730-2005 (ISO 2005), and ISO Standard 9920-2009 (ISO 2009) to make more accurate thermal comfort predictions under realistic conditions for people clothed in non-Western attire as applicable for buildings, aircraft, rail, and road vehicles. These more accurate data, mainly focussing on indoor clothing, should allow a better analysis of the indoor climatic conditions in non-Western countries, contributing to the tools for improved energy-efficient design.

Results for the static thermal insulation and vapor resistance values will be reported in this paper. Data on the effects of movement, posture, and air movement on the thermal insulation values of non-Western clothing will be reported in a subsequent paper.

METHODS

A survey was conducted of commonly worn everyday clothing, and from this a selection was made of a total of 52 ensemble configurations based on 27 basic ensembles from seven countries. The clothing is shown in Figures 1, 2, and 3. The detailed composition of the clothing ensembles, together with the country in which the ensemble is commonly worn, is shown in the appendix. The experimental work was performed using thermal manikins in three separate laboratories: Loughborough University, Lund University, and Hong Kong Polytechnic University. Each laboratory used different thermal manikins (Figure 4). Dry-heat resistances only were determined in Loughborough and Lund. Dry and evaporative resistances were determined in Hong Kong. Due to the different technology underpinning the Hong Kong manikin versus the other manikins, different equations were used for dry-heat resistance calculation. These are shown in Equations 1 and 4 for the dry manikins and the Hong Kong manikin, respectively.

EERC, Design School, Loughborough University, UK

Female ensembles were tested using a female-shaped thermal manikin, Victoria (PT Teknik 2014), which has 20 independently controlled zones. Male ensembles were tested with male-shaped manikin, Newton (MTNW 2014), consisting of 32 independently controlled zones.

For both manikins, heat input or temperature can be controlled and measured. With the skin temperature of the manikin controlled at 34°C (93.2°F), and for a fixed environmental temperature the measured heat loss rate can be used to calculate dry-heat resistance of the clothing worn. This measurement technique is described extensively in ISO Standard 15831-2004 (ISO 2004) and ISO Standard 9920-2009 (ISO 2009), to which the reader is referred for full detail. Procedures described in this standard were followed unless specifically stated otherwise. Each ensemble was measured at least twice to ensure accuracy, with the mean values being taken. If the discrepancy between measurements was >4%, a third measurement was taken (ISO 2004).

Dry-heat-resistance values of the ensembles were determined in a 21°C (69.8°F) environment at 50% relative humidity (any variations were recorded and calculations of results accounted for these). Mean radiant temperature was equal to air temperature (confirmed by black globe measurement). Static insulation was defined as the thermal insulation in a standing-up posture at 0.2 $m \cdot s^{-1}$ (0.66 $ft \cdot s^{-1}$) air velocity.

Air temperatures, humidity, and air velocity were measured using a Testo 454/350 unit (Testo AG, Testostraße 1, 79853 Lenzkirch, Germany) with vane (unidirectional) and hot-wire (multidirectional) sensors. The manikin system includes two PT100 sensors (Betatherm 30K5A1B) for air temperature at 0.3 and 1.4 meters (1 and 4.6 ft) height and a Vaisala Humidity sensor (HUMITTER 50U).

The manikin was calibrated according to the procedure described in the ASTM Standard F1291-10 (ASTM 2010) and ISO STandard 15831 (ISO 2004). Manikin skin zone sensors were calibrated with the manikin, (heating deactivated), placed horizontal in a climatic chamber in a turbulent high air velocity (>>4 $m \cdot s^{-1}$ [>>13.1 $ft \cdot s^{-1}$]) using the certified Testo high precision sensors as reference.

EAT, Department of Design Sciences, Lund University, Sweden

The walking male-shaped thermal manikin, Tore, is made of plastic with a metal frame inside to support the body parts and joints. Tore is divided into 17 individually controlled zones: head, chest, back, stomach, buttocks, left and right upper arm, left and right lower arm, left and right hand, left and right thigh, left and right leg, and left and right foot. The surface temperature of the manikin's zones was controlled at 34°C (93.2°F).

Figure 1 *Overview of tested ensemble configurations A to I. See the appendix for details of component clothing items and the country where the clothing is commonly worn.*

Figure 2 *Overview of tested ensemble configurations J to T. See the appendix for details of component clothing items and country where commonly worn.*

Figure 3 *Overview of tested ensemble configurations U to Z. See the appendix for details of component clothing items and the country where the clothing is commonly worn. The face cover in V1–V3 is not part of the clothing, but part of the manikin skin.*

Air velocity was measured with a Swema Air 3000d logger with SWA03 sensor, Swema AB, Sweden. Ambient air temperature was continuously monitored using three sensors (PT 100, Pico Technology Ltd., UK) positioned adjacent to the ankles, the midtrunk, and the head (vertical heights of 0.1, 1.1, and 1.7 m [0.3, 3.6, and 5.6 ft] from the soles of the manikin). The air temperature in the chamber was set to 22.2°C ± 0.1°C (72°F). The mean radiant temperature was equal to the air temperature. The air velocity in the chamber was 0.21 ± 0.07 $m{\cdot}s^{-1}$ (0.67 $ft{\cdot}s^{-1}$). The temperatures and heat losses were recorded at ten second intervals. A minimum of 20 minutes stability was required.

Offset calibration of the manikin's surface temperature sensors was carried out in the homogenous conditions (34°C [93.2°F]) in a warm chamber with the same Pico equipment as stated above.

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The male-shaped manikin, Walter, differs from the others in that it is made of a semipermeable membrane, which is filled with water, rather than a hard shell, like the others. For full details, the reader is directed to detailed publications on this point (Qian and Fan 2006, 2009). All tests were conducted in the Walter lab's climatic chamber at the environmental temperature of 20°C ± 1°C (68°F) and humidity of 40% ± 5%. For technical reasons, air velocity for the Walter testing was 0.4 $m{\cdot}s^{-1}$ (1.32 $ft{\cdot}s^{-1}$) (with the manikin in standing position), and measured in front of the manikin. Data obtained were corrected for this deviation in air movement using the equations provided by Havenith et al. (1990a,1990b), Havenith and Nilsson (2004,

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2005), Holmér et al. (1999), and those in ISO Standard 9920-2009 (ISO 2009), which are based on the cited papers.

The climate conditions were set at air temperature 20°C (68°F), relative humidity 40%, and air velocity 0.4 $m \cdot s^{-1}$ (1.32 $ft \cdot s^{-1}$). Sensors used for the air velocity measurement were by Digitron (Anemometer AF210).

General Methods

Clothing surface area factor measurement, f_{cl}. The procedure follows advice from the literature (Seppanen et al. 1972; Sprague and Munson, 1974; McCullough et al. 2005) and uses the analysis of photographs of clothed and nude manikins. Pictures were taken at a 0° and 90° angle, and the surface areas of the clothed or the nude manikin were determined by analyzing the projection of the areas in Adobe Photoshop. The value for f_{cl} was then calculated as the ratio between clothed and nude projection areas. This measurement is discussed later in more detail.

Air insulation, I_a. In all laboratories, the thermal insulation of the nude manikin was determined as the value of the surface air insulation thermal resistance (I_a).

Calculations for I_T and I_{cl}. For the dry manikins (Loughborough and Lund Universities), the dry heat insulation I_T was determined as follows (Havenith et al. 2002, 2005; Kuklane et al. 2007, 2012).

$$I_T = \text{Dry-heat insulation (resistance)} = \frac{T_{skin} - T_{ambient}}{\text{Dry heat loss}}$$
$$\left(\frac{\text{square meter} \cdot \text{Kelvin}}{\text{Watt}} = m^2 \cdot K \cdot W^{-1}\right) \tag{1}$$

The intrinsic clothing insulation I_{cl} was determined as:

$$I_{cl} = I_T - \frac{I_a}{f_{cl}}$$
$$\left(\frac{\text{square meter} \cdot \text{Kelvin}}{\text{Watt}} = m^2 \cdot K \cdot W^{-1}\right) \tag{2}$$

Conversion from SI units to Clo units can be performed by:

$$I(\text{clo}) = \frac{I(\text{SI units})}{0.155} \tag{3}$$

As the wet manikin (Walter, Hong Kong) measures dry and wet heat transfer at the same time, the equation for Walter for dry heat resistance is different from Equation 1. In this case, the thermal insulation (I_T) and moisture vapor resistance ($R_{e,T}$) of clothing were calculated on the same physics principles as in Equation 1, but correcting for evaporative heat loss present in this case by using the following formulae as described by Wu et al. (2009). Assuming that no interaction of wet and dry heat transfer occurs (no condensation in the clothing, steady state), this will provide identical results to Equation 1.

Figure 4 *Four different manikins were used in the study. From left to right: female-shaped thermal manikin used at Loughborough University (Victoria); male-shaped thermal manikin used at Loughborough University (Newton); male-shaped thermal manikin used at Lund University (Tore), and male-shaped thermal manikin (Walter) used at Hong Kong Polytechnic University.*

$$I_T = \frac{A_s(\overline{T}_s - T_a)}{H_s + H_p - H_e} \tag{4}$$

with

$$H_e = \lambda \times Q \tag{5}$$

$$R_{e,T} = \frac{A_s(P_s^* - RH_a P_a^*)}{H_e} - R_{es} \tag{6}$$

where

A_s = the total surface area of the manikin, m^2

$\overline{T}_s$ = the area weighted mean skin temperature, °C

T_a	=	the mean temperature of the environment, °C
H_s	=	the rate of heat supplied to the manikin or the heat generated by the heaters, W
H_p	=	the rate of heat generated by the pumps inside the manikin body, hp = 18.7 W
H_e	=	the evaporative heat loss rate from the water evaporation, W
λ	=	the heat of evaporation of water at the skin temperature, l = 2430 J/g at 34°C
Q	=	the perspiration rate or water loss per unit time, which is measured automatically through the electronic balance, g/s
P_s^*	=	the saturated water vapor pressure at the skin temperature, Pa
RH_a	=	the relative humidity of the surrounding environment, %
P_a^*	=	the saturated water vapor pressure at the surrounding environment, Pa
R_{es}	=	the moisture vapor resistance of the skin. R_{es} is a predetermined constant and equals 8.6 m^2 Pa/W
I_T	=	for the final results, measurements of the static insulation were averaged over the three manikins used for testing each ensemble. For the female garment that would be an average of Victoria, Tore, and Walter and for the male garments would be an average of Newton, Tore, and Walter

Calculations for $\boldsymbol{i_m}$**.** Rather than presenting the $R_{e,T}$ values, it was decided to present the values for the vapor permeability index i_m, as this allows an easier comparison between garments. The observed values for $R_{e,T}$ and I_T were used to calculate the clothing vapor permeability index i_m:

$$i_m = \frac{I_T}{L \cdot R_{e,T}} \tag{7}$$

where L = Lewis constant = 0.0165°C·Pa^{-1}.

RESULTS/DISCUSSION

Averaged Data for Ensembles

The final data for the different ensembles for total and intrinsic clothing insulation and for the clothing permeability index i_m, averaged over all tests with all manikins used, are presented in Tables 1 and 2.

Manikin Comparison

In order to get an impression of the effect of using different manikins for the testing, data obtained on the individual manikins are presented in relation to the mean insulation value over all manikins for that ensemble (following the basic concept behind Bland Altman plots) used for comparing measurements from different instruments (lacking a gold standard). The results indicate a higher than average value for garments measured on the female shape, Victoria (Figure 5). Those for Newton, Tore, and Walter (Figure 6, 7, and 8) are close to the line of identity, with outliers only for the two highest insulative ensembles (including a coat), while the values for Newton are lower than the average and those for Walter are higher than the average. These data points were extensively checked and the data are considered valid, suggesting different effects of the coat on the fit of the clothing between the two manikins.

The higher values for Victoria (8.9% higher on average than Tore and 7.8% higher than Walter) are consistent with earlier studies comparing a female Victoria shape to the male Tore (Kuklane et al. 2004). In that study, insulation values from the female-shaped manikin were 14% to 17% higher for the same ensemble. Tight clothing showed less difference than loose clothing. The presently tested clothing is predominantly loose.

Using different manikins to replicate the tests resulted in a range of values for each ensemble. Originally, the use of the ASTM calibration ensemble was considered to align the results for the different manikins, however, this was reconsidered as the differences between the manikins actually represent a variation that has real-life value. The manikin shape is considered to be the main factor in this variation, with the female shape manikin (Victoria), consistent with literature (Kuklane et al. 2004), providing slightly higher values than the other manikins. Also, the local conditions in the different climatic chambers may have contributed somewhat to the variability. Accounting for the expected variability in body shapes of wearers of the ensembles in real life, having this variability is considered to be a better representation of the variability that is expected when these garments are worn in real-life conditions, rather than if only a single manikin were used. Thus, while defining insulations for commercial purposes may require an adjustment of the individual manikin's value using a calibration ensemble, for the present purpose this is not the case.

Clothing Surface Area Factor

As mentioned earlier, clothing surface area measurements were based on the photographic method using a frontal and a side picture. A projection of the area factor was used and analyzed in graphics editing software. In general, the procedure follows advice from the literature (Seppanen et al. 1972; Sprague and Munson 1974; McCullough et al. 2005). In the past, several projects have looked at the area factors determined using different numbers of pictures and comparing those area factors with other methods like body scanning. The latter method is laborious (folds in the clothing require manual corrections to the data sets). McCullough et al. (2005) showed that for protective clothing, taking a single photograph from the front provided the same information as the more elaborate measurement via six pictures from different angles (r^2 = 0.99, mean square error = 0.015). Given the perhaps different style of the clothing tested here, it was decided to use both the front and the side picture.

Table 1. Means of Three Laboratories

Ensemble	Country	Gender	I_T, m²·K/W	I_T, clo	% SD I_T	I_a, m²·K/W	I_a, clo	f_{cl}, n.d.	I_{cl}, m²·K/W	I_{cl}, clo	i_m Value, 0.2 m/s (n.d.)
Measured/ Calculated			*M*	*M*	*M*	*M*	*M*	*M*	*C*	*C*	*C*
Nude		F	0.099	0.6	3.58	0.099	0.64	1.00	0.00	0.00	
ASTM	USA	F	0.203	1.3	10.82	0.099	0.64	1.23	0.12	0.79	0.28
A1	Pakistan	F	0.187	1.2	4.45	0.099	0.64	1.43	0.12	0.76	0.31
A2	India	F	0.210	1.4	9.08	0.099	0.64	1.48	0.14	0.92	0.36
B1	India	F	0.163	1.1	7.80	0.099	0.64	1.33	0.09	0.57	0.32
B2	India	F	0.187	1.2	5.07	0.099	0.64	1.37	0.11	0.74	0.37
D1	Pakistan	F	0.170	1.1	3.18	0.099	0.64	1.39	0.10	0.64	0.31
D2	Pakistan	F	0.177	1.1	1.32	0.099	0.64	1.41	0.11	0.69	0.32
F1	Pakistan	F	0.273	1.8	6.43	0.099	0.64	1.67	0.21	1.38	0.31
F2	Pakistan	F	0.269	1.7	7.01	0.099	0.64	1.60	0.21	1.33	0.33
F3	Pakistan	F	0.271	1.7	7.88	0.099	0.64	1.66	0.21	1.36	0.29
F4	Pakistan	F	0.248	1.6	13.61	0.099	0.64	1.65	0.19	1.21	0.27
F5	Pakistan	F	0.259	1.7	8.63	0.099	0.64	1.63	0.20	1.28	0.33
F6	Pakistan	F	0.275	1.8	7.96	0.099	0.64	1.61	0.21	1.38	0.33
G1	Indonesia	F	0.211	1.4	10.02	0.099	0.64	1.22	0.13	0.84	0.30
G2	Indonesia	F	0.226	1.5	10.68	0.099	0.64	1.27	0.15	0.95	0.30
G3	Indonesia	F	0.188	1.2	7.87	0.099	0.64	1.25	0.11	0.70	0.29
H1	Indonesia	F	0.198	1.3	4.35	0.099	0.64	1.37	0.13	0.81	0.29
H2	Indonesia	F	0.220	1.4	3.77	0.099	0.64	1.43	0.15	0.97	0.31
L1	Kuwait	F	0.184	1.2	12.00	0.099	0.64	1.23	0.10	0.67	0.32
L2	Kuwait	F	0.198	1.3	10.32	0.099	0.64	1.23	0.12	0.76	0.35
L3	Kuwait	F	0.270	1.7	17.70	0.099	0.64	1.33	0.20	1.26	0.29
M-S1	Kuwait	F	0.231	1.5	8.38	0.099	0.64	1.56	0.17	1.08	0.35
M-S2	Kuwait	F	0.257	1.7	3.87	0.099	0.64	1.65	0.20	1.27	0.33
M-W1	Kuwait	F	0.245	1.6	12.47	0.099	0.64	1.59	0.18	1.18	0.30
M-W2	Kuwait	F	0.299	1.9	4.69	0.099	0.64	1.64	0.24	1.54	0.35
N	Nigeria/Ghana	F	0.168	1.1	2.88	0.099	0.64	1.49	0.10	0.65	0.33
O	Nigeria/Ghana	F	0.190	1.2	1.15	0.099	0.64	1.47	0.12	0.79	0.33
S	Nigeria/Ghana	F	0.194	1.3	6.88	0.099	0.64	1.35	0.12	0.78	0.40
W	China	F	0.141	0.9	2.90	0.099	0.64	1.31	0.06	0.42	0.40
X1	India	F	0.167	1.1	6.23	0.099	0.64	1.28	0.09	0.58	0.36
X2	India	F	0.192	1.2	4.86	0.099	0.64	1.28	0.11	0.74	0.32
Y1	India	F	0.182	1.2	7.28	0.099	0.64	1.46	0.11	0.74	0.33
Y2	India	F	0.216	1.4	7.80	0.099	0.64	1.48	0.15	0.96	0.30

Note: Average values for female clothing insulation (total and intrinsic) and f_{cl}, as well as standard deviation (%) over the three laboratories (minimum two replications in each laboratory). The standard deviation represents the range of insulation values found due to variations in body size and shape for the three different manikins. The f_{cl} values were measured using a photographic method as described in the text. I_{cl} was calculated using I_T and f_{cl} values according to Equation 2. For this female clothing the manikins used were: Victoria, Tore, and Walter. *M* = measured, *C* = calculated.

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Table 2. Means of Three Laboratories

Ensemble	Country	Gender	I_T, $m^2 \cdot K/W$	I_T, clo	% SD I_T	I_a, $m^2 \cdot K/W$	I_a, clo	f_{cl}, n.d.	I_{cl}, $m^2 \cdot K/W$	I_{cl}, clo	i_m Value, 0.2 m/s (n.d)
Measured/ Calculated			*M*	*M*	*M*	*M*	*M*	*M*	*C*	*C*	*C*
Nude		M	0.098	0.6	3.14	0.098	0.63	1.00	0.00	0.00	
ASTM	USA	M	0.192	1.2	5.59	0.098	0.63	1.25	0.11	0.74	0.28
C	Pakistan	M	0.205	1.3	7.93	0.098	0.63	1.36	0.13	0.86	0.35
E	India	M	0.222	1.4	11.32	0.098	0.63	1.45	0.15	0.99	0.35
I	Indonesia	M	0.174	1.1	6.23	0.098	0.63	1.24	0.09	0.61	0.35
J1	Kuwait	M	0.237	1.5	7.72	0.098	0.63	1.47	0.17	1.10	0.28
J2	Kuwait	M	0.263	1.7	10.11	0.098	0.63	1.58	0.20	1.30	0.26
J3	Kuwait	M	0.333	2.2	20.41	0.098	0.63	1.55	0.27	1.74	0.30
K1	Kuwait	M	0.230	1.5	8.27	0.098	0.63	1.53	0.17	1.07	0.29
K2	Kuwait	M	0.269	1.7	14.32	0.098	0.63	1.66	0.21	1.36	0.30
K3	Kuwait	M	0.334	2.2	23.41	0.098	0.63	1.58	0.27	1.76	0.34
P	Nigeria/Ghana	M	0.177	1.1	1.96	0.098	0.63	1.25	0.10	0.64	0.28
Q	Nigeria/Ghana	M	0.171	1.1	3.42	0.098	0.63	1.26	0.09	0.61	0.31
R	Nigeria/Ghana	M	0.267	1.7	9.82	0.098	0.63	1.96	0.22	1.40	0.42
T	Nigeria/Ghana	M	0.152	1.0	11.05	0.098	0.63	1.19	0.07	0.45	0.54
U	Nigeria/Ghana	M	0.198	1.3	12.83	0.098	0.63	1.45	0.13	0.84	0.39
V1	Pakistan	M	0.210	1.4	5.65	0.098	0.63	1.40	0.14	0.90	0.34
V2	Pakistan	M	0.234	1.5	0.42	0.098	0.63	1.39	0.16	1.06	0.31
V3	Pakistan	M	0.261	1.7	4.54	0.098	0.63	1.40	0.19	1.23	0.27
Z	India	M	0.173	1.1	2.53	0.098	0.63	1.25	0.09	0.61	0.32

Note: Average values for male clothing insulation (total and intrinsic) and f_{cl} as well as standard deviation (%) over the three laboratories (minimum two replications in each laboratory). The standard deviation represents the range of insulation values found due to variations in body size and shape for the three different manikins. The f_{cl} values were measured using a photographic method as described in the text. I_{cl} was calculated using I_T and f_{cl} values according to Equation 2. For this male clothing the manikins used were: Newton, Tore, and Walter. *M* = measured, *C* = calculated.

The f_{cl} values were used in the established way to calculate the intrinsic clothing insulation I_{cl}. This model of intrinsic and surface air boundary layer insulation is based on a cylindrical model of clothing (Figure 9) which is typical for Western style clothing with all clothing worn as cylinders around the torso and limbs. Considering the loose fit and the long robe/dress style of many of the garments tested here, this cylindrical model may not be an appropriate model for what is really happening. For example, for the wide *kameez* and *abaya* garments, reaching to the knee or ankle, one would expect air movement underneath these garments, and the still surface air layer may be around the legs rather than all around these outer garments. Creating a physical model of intrinsic and surface layer insulations for such garment styles may therefore not be easy. Also, this would then require different models for ASHRAE Standard 55-2013 (ASHRAE 2013a), which is impractical.

Calculating the I_{cl} values for these ensembles in the traditional way may not be physically correct, but these can nevertheless be used in Standard 55-2013, as the calculations there use the same method to reconstruct total resistance from I_{cl} and I_a. It is important to ensure that the methods used to calculate I_{cl} from I_T are consistent with those used for calculating heat losses in any models or in the standard. Then, despite the

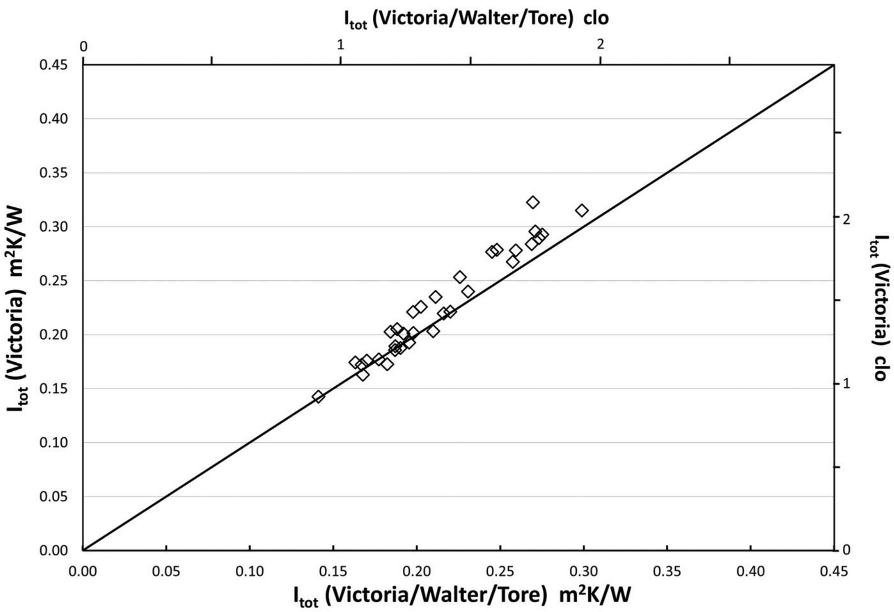

Figure 5 *Comparison of female data for total clothing insulation I_T measured on Victoria to the mean of three manikins (Victoria, Walter, and Tore) on which the same ensemble was measured.*

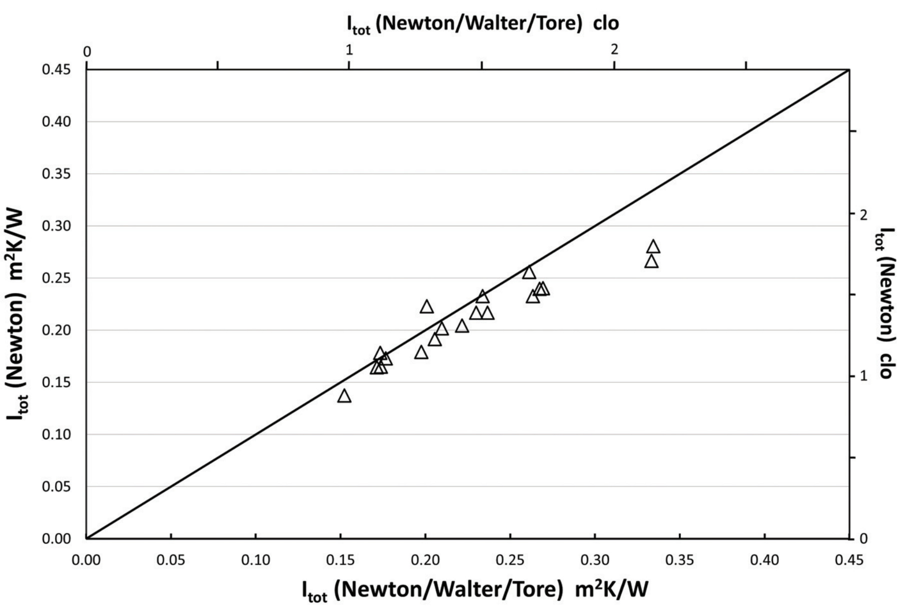

Figure 6 *Comparison of male data for total clothing insulation I_T measured on Newton to the mean of three manikins (Newton, Walter, and Tore) on which the same ensemble was measured.*

calculations not being physically correct, this will have no bearing on the results.

In the various clothing publications dealing with the f_{cl} factor, prediction equations for f_{cl} are provided. These are based on Western clothing. The equation listed in ISO Standard 9920-2009 (ISO 2009), based on work by McCullough et al. (1985), reads

If I_{cl} is expressed in m^2·°C·W:

$$f_{cl} = 1.00 + 1.97 I_{cl} \quad (8)$$

If I_{cl} is expressed in clo:

$$f_{cl} = 1.00 + 0.31 I_{cl} \quad (9)$$

The application range for which these relations were tested is between 0.2 and 1.7 clo.

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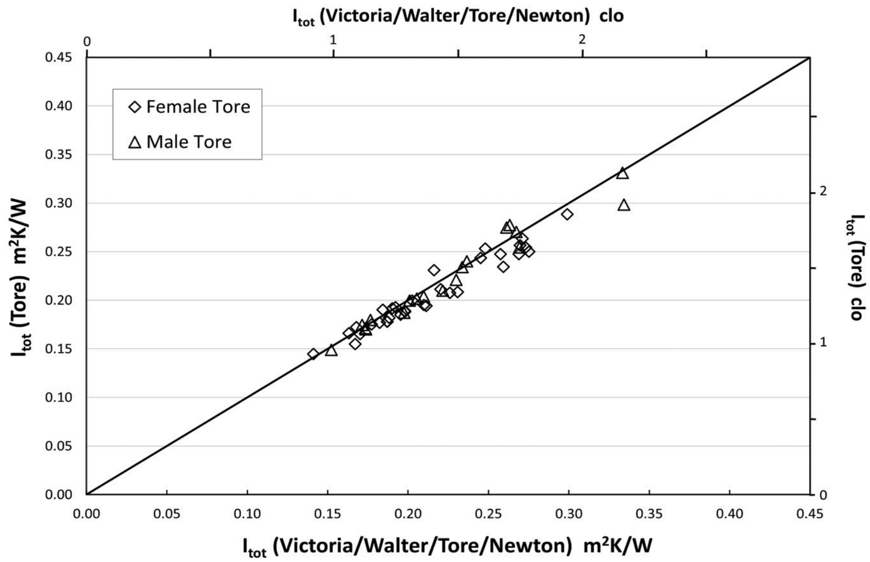

Figure 7 *Comparison of data for total clothing insulation I_T measured on Tore to the mean of three manikins (Victoria or Newton, and Walter and Tore) on which the same ensemble was measured.*

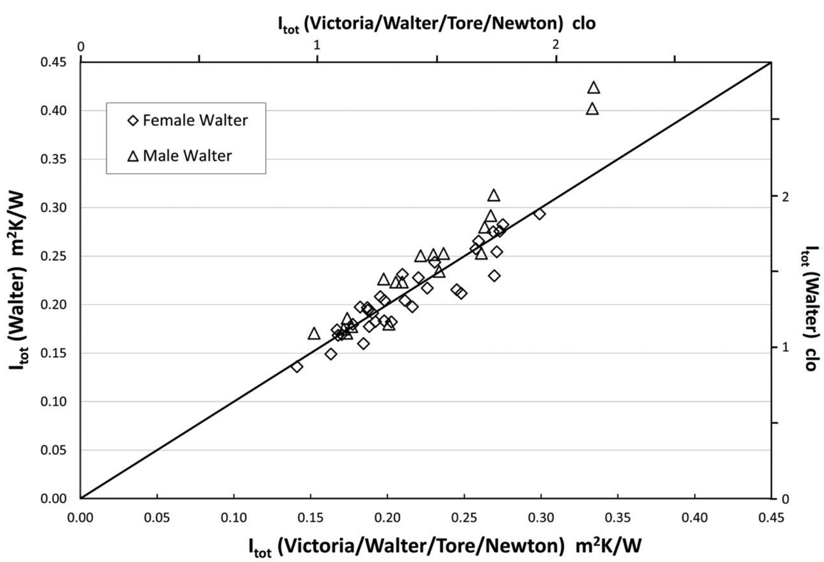

Figure 8 *Comparison of data for total clothing insulation I_T measured on Walter (corrected to 0.2 m/s air speed) to the mean of three manikins (either Victoria or Newton, and Walter and Tore) on which the same ensemble was measured.*

For the non-Western clothing (Figure 10) studied in this project the equations (one with constant fixed to 1.0, the other with a constant allowed to vary from one) would read as follows:

If I_{cl} is expressed in $m^2 \cdot °C \cdot W^{-1}$:

$$f_{cl} = 1.00 + 2.886 I_{cl} \quad (10)$$

or

$$f_{cl} = 1.08 + 2.414 I_{cl} \quad (11)$$

If I_{cl} is expressed in clo:

$$f_{cl} = 1.00 + 0.447 I_{cl} \quad (12)$$

or

$$f_{cl} = 1.074 + 0.379 I_{cl} \quad (13)$$

both with an adjusted r^2 value of 0.60 (with intercept forced to 1.0, the adjusted r^2 rises to 0.95, though this is equivalent to deleting the constant, thus providing a different type of r^2), see Figure 10.

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The standard error of the estimate (SEE) for f_{cl} is 0.106 for these regressions. The application range for which these relations were tested is between 0.4 and 1.74 clo.

Given the quite low r^2 value and high SEE, the authors do not deem this to be a reliable approach, and thus it is questionable whether such equations should be added to ASHRAE Standard 55-2013 (ASHRAE 2013a) or ISO Standard 9920-2009 (ISO 2009). However, revisiting the report by McCullough and McCullough et al. (1984; 1985) for Western clothing, from which the currently used equation in ISO Standard 9920-2009 (ISO 2009) is taken, it appears that the uncertainty in those is equivalent to what is found here. For the equation with a constant (i.e., not forced through 1.0 at $I_{cl} = 0$), the adjusted r^2 equals 0.55, and for the equation without a constant equals 0.95 (again, these r^2 values cannot be compared as they are not based on an equivalent calculation). The SEE is between 0.06 and 0.07, which is better than for the current data set (McCullough et al. 2005). Given the low r^2, it is somewhat surprising that this equation is in such widespread use, though as McCullough et al. (1984) remarks, there are no real alternatives. Nevertheless, this issue should be discussed in the ISO committee dealing with ISO Standard 9920-2009 (ISO 2009), as no caveat is presented with those equations there.

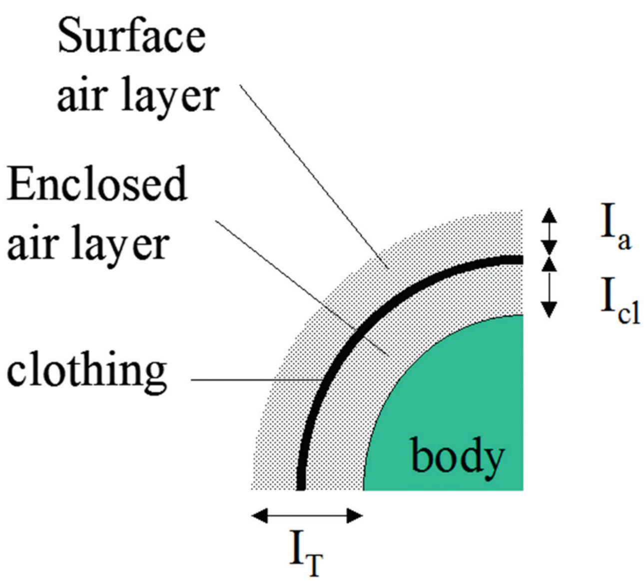

Figure 9 *Cylindrical model of total and intrinsic clothing insulation.*

CONCLUSION

Four different manikins in three different laboratories, were used to determine the clothing thermal insulation values of 52 non-Western clothing configurations. Male clothing was tested on the manikins Newton, Tore, and Walter. Female ensembles were tested on the manikins Victoria, Tore, and Walter. Using different manikins to replicate these tests resulted in a range of values for each ensemble reflecting variations in body size and shape for the different manikins. The manikin shape is considered to be the main factor in this variation. The female shape manikin (Victoria) provides slightly higher (8%) values than the other manikins. Also, the local conditions in the different climatic chambers may have contributed to the variability. Having this variability is considered to be a better representation of the variability to be expected when these garments are worn in real-life conditions, rather than if only a single mani-

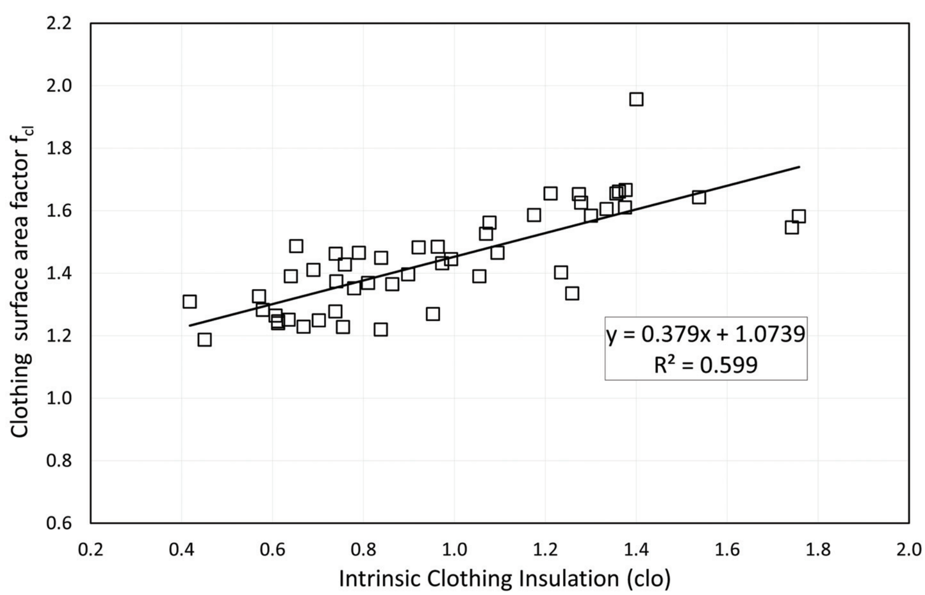

Figure 10 *Relationship between clothing area factor* f_{cl} *and intrinsic clothing insulation* I_{cl} *calculated using this* f_{cl} *value (see Equation 2).*

kin were used, given the expected variability in body shapes of wearers of the ensembles in real life. This was one of the reasons to use a multimanikin approach.

Results indicate that substantial differences in insulation are observed for the different manikin shapes and sizes. These shapes interact with the clothing fit and drape and because of this, affect the air layers in and on the clothing.

Values observed for the vapor permeability index i_m were on average 0.34 ± 0.05 (n.d.).

The relation of the clothing surface area factor to intrinsic clothing insulation was different from that published for Western clothing. Using the new data for validation, the reliability of surface area prediction based on clothing insulation values was considered low, which, however, was also the case for those obtained in the past for Western clothing. This seems to be overlooked, as its use is widespread. It has to be concluded that reliable f_{cl} values can only be obtained when these are actually measured. Having said this, the concept of the f_{cl} factor for the non-Western clothing may not be entirely appropriate, as the wide-falling robes and gowns do not match the clothing and air layer model (Figure 9) on which the f_{cl} concept is based.

In summary, the results provide an extensive database of non-Western clothing styles in different wear configurations. As such, this is expected to be a valuable addition to ASHRAE Standard 55-2013 (ASHRAE 2013a), ISO Standard 7730-2005 (ISO 2005), and ISO Standard 9920-2009 (ISO 2009).

UTILIZATION

This research relates to the *ASHRAE Handbook—Fundamentals* (ASHRAE 2013b), specifically the section on indoor environmental quality, Chapter 9, Thermal Comfort; to ASHRAE Standard 55-2013 (ASHRAE 2013a) and to ISO Standard 7730-2005 (ISO 2005) and ISO Standard 9920-2009 (ISO 2009). The values for non-Western clothing insulation presented in this paper will assist in the use of these standards and allow engineers to determine comfort guidelines for buildings in countries where non-Western dress is common.

ACKNOWLEDGMENTS

The authors are indebted to various colleagues in different countries for helping in the selection of the clothing. Special thanks to those helping to procure the clothing (some of which was specially made to fit the manikins) goes to Dr. Vidhya Venugopal in India, Dr. Lucy Susanti in Indonesia, the Samanthas Afro Butik in Malmö, and Dr. Khaled E H Al-halefey Al-rashidi in Kuwait. Also, the support of the textile experts Mrs. Jan Shenton and Mrs. Anne Acosta from the Loughborough School of Arts for providing information on the composition of the clothing materials is gratefully acknowledged. ASHRAE's financial support for this work is gratefully acknowledged and ASHRAE TC 2.1, Project Management Committee is thanked for helpful comments and suggestions during the execution of the project.

NOMENCLATURE

f_{cl} = clothing area factor: ratio between the surface area of the clothed body, (including unclothed parts), and the surface of the nude body, dimensionless

I_a = insulation of air layers surrounding manikin and clothing, $m^2 \cdot K \cdot W^{-1}$ (clo)

I_{cl} = intrinsic clothing insulation value (without surrounding boundary air layers), $m^2 \cdot K \cdot W^{-1}$ (clo)

i_m = moisture permeability index (Woodcock permeability index), ratio between the total dry-clothing heat resistance (I_T) and the total evaporative clothing heat resistance ($R_{e,T}$) for a clothing ensemble, divided by the Lewis relation, (dimensionless)

I_T = total insulation value of clothing plus surrounding boundary air layers, $m^2 \cdot K \cdot W^{-1}$ (clo)

L = Lewis relation, ratio of the evaporative heat transfer coefficient to the convective heat transfer coefficient, 16.5 K/kPa

n.d. = nondimensional number

$R_{e,a}$ = evaporative resistance of the boundary air layer, resistance to vapor transport for the whole body at the boundary (skin or clothing), $m^2 \cdot Pa \cdot W^{-1}$ (1 $m^2 \cdot Pa \cdot W^{-1}$ = 0.0659 $lb_f \cdot h \cdot Btu^{-1}$)

$R_{e,T}$ = evaporative resistance of a clothing ensemble, resistance to vapor transport of a uniform layer of insulation covering the entire body that has the same effect on evaporative heat loss as the actual clothing under the tested conditions, $m^2 \cdot Pa \cdot W^{-1}$ (1 $m^2 \cdot Pa \cdot W^{-1}$ = 0.0659 $lb_f \cdot h \cdot Btu^{-1}$)

APPENDIX

See Table A-1.

Table A-1. Details on the Clothing Ensemble Composition for the Individual Ensembles, with Weights of the Components and Fabric/Fiber Composition

Ensemble	Item name	Weight, kg	Material	Ensemble	Item name	Weight, kg	Material
ASTM Calibration Ensemble	men's briefs	0.064	cotton	A1 (no scarf) A2 (with scarf) female, Pakistan	women's briefs	0.025	cotton
	t-shirt	0.150	cotton		bra	0.029	cotton
	protective nomex iii pants	0.449	nomex		*shalwar* (pants)	0.113	polycotton
	protective nomex iii shirt	0.430	nomex		*kameez* (shirt)	0.316	polycotton
	socks	0.069	cotton		scarf (A2 only)	0.137	polycotton
	athletic shoes	0.540	suede + nylon		female sandals	0.245	suede + plastic
B1(no scarf) B2 (with scarf) female, India	women's briefs	0.025	cotton	C male, Pakistan	men's briefs	0.064	cotton
	bra	0.029	cotton		*shalwar* (pants)	0.195	polycotton
	shalwar (pants)	0.160	polyester		*kameez* (shirt)	0.276	polycotton
	kameez (shirt)	0.280	polyester		socks	0.037	cotton
	scarf (A2 only)	0.120	polyester		athletic shoes	0.540	suede + nylon
	female sandals	0.245	suede + plastic				
D1 (no scarf) D2 (with scarf) female, Pakistan	women's briefs	0.025	cotton	E male, India	men's briefs	0.064	cotton
	bra	0.029	cotton		*shalwar* (pants)	0.296	polycotton
	shalwar (pants)	0.150	cotton		*kameez* (shirt)	0.506	polyester
	kameez (shirt)	0.194	cotton + polyester		socks	0.037	cotton
	scarf (D2 only)	0.128	polyester		athletic shoes	0.540	suede + nylon
	female sandals	0.245	suede + plastic				
F1 Long, fitted hijab, female, Pakistan	bra	0.029	cotton	F2 Short traditional hijab female, Pakistan	bra	0.029	cotton
	women's briefs	0.025	cotton		women's briefs	0.025	cotton
	stretch body	0.152	polycotton		stretch body	0.152	polycotton
	overshirt	0.130	polycotton		overshirt	0.130	polycotton
	jeans	0.390	cotton + lycra		jeans	0.390	cotton + lycra
	abaya (long dress)	0.466	polyester		*abaya* (long dress)	0.466	polyester
	long fitted hijab	0.248	synthetic nylon		short traditional hijab	0.063	woven viscose
	socks	0.037	cotton		socks	0.037	cotton
	athletic shoes	0.540	suede + nylon		athletic shoes	0.540	suede + nylon
F3 Long traditional hijab female, Pakistan	bra	0.029	cotton	F4 Long traditional hijab female, Pakistan (no stretch body)	bra	0.029	cotton
	women's briefs	0.025	cotton		women's briefs	0.025	cotton
	stretch body	0.152	polycotton		overshirt	0.130	polycotton
	overshirt	0.130	polycotton		jeans	0.390	cotton + lycra
	jeans	0.390	cotton + lycra		*abaya* (long dress)	0.466	polyester
	abaya (long dress)	0.466	polyester		long traditional *hijab*	0.081	cotton
	long traditional hijab	0.081	cotton		socks	0.037	cotton
	socks	0.037	cotton		athletic shoes	0.540	suede + nylon
	athletic shoes	0.540	suede + nylon				
F5 Short fitted hijab female, Pakistan	bra	0.029	cotton	F6 Short fitted *hijab* + *burka* female, Pakistan	bra	0.029	cotton
	women's briefs	0.025	cotton		women's briefs	0.025	cotton
	stretch body	0.152	polycotton		stretch body	0.152	polycotton
	overshirt	0.130	polycotton		overshirt	0.130	polycotton
	jeans	0.390	cotton + lycra		jeans	0.390	cotton + lycra
	abaya (long dress)	0.466	polyester		*abaya* (long dress)	0.466	polyester
	short fitted hijab	0.075	knitted nylon + lycra		short fitted hijab	0.075	knitted nylon + lycra
					burka	0.034	viscose
	socks	0.037	cotton		socks	0.037	cotton
	athletic shoes	0.540	suede + nylon		athletic shoes	0.540	suede + nylon

Table A-1. Details on the Clothing Ensemble Composition for the Individual Ensembles, with Weights of the Components and Fabric/Fiber Composition *(continued)*

Ensemble	Item name	Weight, kg	Material	Ensemble	Item name	Weight, kg	Material
G1 (no scarf) female, Indonesia	bra	0.029	cotton	G2 (with scarf) female, Indonesia	bra	0.029	cotton
	women’s briefs	0.025	cotton		women’s briefs	0.025	cotton
	long-sleeved shirt	0.204	polycotton		long-sleeved shirt	0.204	polycotton
	suit pants	0.354	polyester		*hijab*	0.060	cotton
	suit jacket	0.486	polyester		suit pants	0.354	polyester
	socks	0.037	cotton		suit jacket	0.486	polyester
	athletic shoes	0.540	suede + nylon		socks	0.037	cotton
					athletic shoes	0.540	suede + nylon
G3 (with scarf, no jacket) female, Indonesia	bra	0.029	cotton	H1 (no scarf) H2 (with scarf) female, schools, Indonesia	bra	0.029	cotton
	women’s briefs	0.025	cotton		women’s briefs	0.025	cotton
	long-sleeved shirt	0.204	polycotton		long-sleeved shirt	0.204	polycotton
	suit pants	0.354	polyester		skirt	0.357	polycotton
	hijab	0.060	cotton		headscarf (H2 only)	0.060	cotton
	socks	0.037	cotton		socks	0.037	cotton
	athletic shoes	0.540	suede + nylon		athletic shoes	0.540	suede + nylon
I male, service industry, Indonesia	men’s briefs	0.064	cotton	J1 male, Kuwait	men’s briefs	0.064	cotton
	work shirt	0.379	polycotton		*dishdasha* (*thowb*)	0.721	microfiber polyester
	work pants	0.508	polyester		long pants underwear,	0.230	cotton
	socks	0.037	cotton		long sleeve undershirt	0.262	cotton
	athletic shoes	0.540	suede + nylon		long *serwal* (pants)	0.195	polycotton
					tagiya (hat)	0.017	polycotton
					socks	0.037	cotton
					athletic shoes	0.540	suede + nylon
J2 male, Kuwait	men’s briefs	0.064	cotton	J3 male, Kuwait	men’s briefs	0.064	cotton
	dishdasha (*thowb*)	0.437	microfiber polyester		*dishdasha* (*thowb*)	0.437	microfiber polyester
	long pants underwear,	0.230	cotton		long pants underwear,	0.230	cotton
	long sleeve undershirt	0.262	cotton		long sleeve undershirt	0.262	cotton
	long *serwal* (pants)	0.195	polycotton		long *serwal* (pants)	0.195	polycotton
	tagiya (hat)	0.017	polycotton		*tagiya* (hat)	0.017	polycotton
	iqal (black cord)	0.142	plastic		*iqal* (black cord)	0.142	plastic
	ghutra (headdress)	0.156	cotton		*ghutra* (headscarf)	0.156	cotton
	socks	0.037	cotton		coat	0.458	viscose
	athletic shoes	0.540	suede + nylon		socks	0.037	cotton
					athletic shoes	0.540	suede + nylon
K1 male, Kuwait	men’s briefs	0.064	cotton	K2 (K1+ head dress) male, Kuwait	men’s briefs	0.064	cotton
	dishdasha (*thowb*)	0.437	polycotton		*dishdasha* (*thowb*)	0.437	polycotton
	short sleeved t-shirt	0.152	polycotton		short sleeved t-shirt	0.152	polycotton
	long *serwal* (pants)	0.195	polycotton		long *serwal* (pants)	0.195	polycotton
	tagiya (hat)	0.017	polycotton		*tagiya* (hat)	0.017	polycotton
	socks	0.037	cotton		*iqal* (cord)	0.142	plastic
	athletic shoes	0.540	suede + nylon		*ghutra* (headdress)	0.156	cotton
					socks	0.037	cotton
					athletic shoes	0.540	suede + nylon

Table A-1. Details on the Clothing Ensemble Composition for the Individual Ensembles, with Weights of the Components and Fabric/Fiber Composition *(continued)*

Ensemble	Item name	Weight, kg	Material	Ensemble	Item name	Weight, kg	Material
K3 (K2 + coat) male, Kuwait	men's briefs	0.064	cotton				
	dishdasha (*thowb*)	0.437	polycotton	L1 (without stretch body) female, Kuwait	bra	0.029	cotton
	short sleeved t-shirt	0.152	polycotton		women's briefs	0.025	cotton
	long *serwal* (pants)	0.195	polycotton		overshirt	0.130	polycotton
	tagiya (hat)	0.017	polycotton		jeans	0.391	cotton + lycra
	iqal (black cord)	0.142	plastic		*anta* (head cover)	0.030	polycotton
	ghutra (headscarf)	0.156	cotton		*hijab* (headscarf)	0.030	polyester
	coat	0.458	viscose		socks	0.037	cotton
	socks	0.037	cotton		athletic shoes	0.540	suede + nylon
	athletic shoes	0.540	suede + nylon				
				L3 (with stretch body and coat) female, Kuwait	bra	0.029	cotton
L2 (with stretch body) female, Kuwait	bra	0.029	cotton		women's briefs	0.025	cotton
	women's briefs	0.025	cotton		stretched body	0.152	polycotton
	stretched body	0.152	polycotton		overshirt	0.130	polycotton
	overshirt	0.130	polycotton		jeans	0.391	cotton + lycra
	jeans	0.391	cotton + lycra		*anta* (head cover)	0.030	polycotton
	anta (head cover)	0.030	polycotton		*hijab* (headscarf)	0.030	polyester
	hijab (headscarf)	0.030	polyester		coat	0.458	viscose
	socks	0.037	cotton		socks	0.037	cotton
	athletic shoes	0.540	suede + nylon		athletic shoes	0.540	suede + nylon
				MW1 winter (without head cover) MS2 (with head cover) female, Kuwait	bra	0.029	cotton
					women's briefs	0.025	cotton
MS1 summer, (without head cover) MS2 (with head cover) female, Kuwait	bra	0.029	cotton		long pants underwear,	0.230	cotton
	women's briefs	0.025	cotton		long sleeve undershirt	0.262	cotton
	full slip	0.201	cotton		full slip	0.201	cotton
	double layer *abaya* (dress)	0.801	polyester		double layer *abaya* (dress)	0.801	polyester
	anta (head cover—MS2 only)	0.030	cotton		*anta* (head cover – MW2 only)	0.030	cotton
	hijab (headscarf—MS2 only)	0.090	polyester		*hijab* (headscarf - MW2 only)	0.090	polyester
	female sandals	0.245	suede + plastic		socks	0.037	cotton
					athletic shoes	0.245	suede + plastic
N female, Ghana, Nigeria	bra	0.029	cotton	O female, Ghana, Nigeria	bra	0.029	cotton
	women's briefs	0.025	cotton		women's briefs	0.025	cotton
	cotton dress	0.341	cotton		long shirt	0.282	cotton
	head band	0.049	cotton		long pants	0.223	cotton
	female sandals	0.245	suede + plastic		female sandals	0.245	suede + plastic
P male, Ghana, Nigeria	men's briefs	0.064	cotton	Q male, Ghana, Nigeria	men's briefs	0.064	cotton
	short shirt with long sleeves	0.200	cotton		short shirt with short sleeves	0.203	cotton
	long pants	0.199	cotton		long pants	0.199	cotton
	male sandals	0.589	leather + plastic		male sandals	0.589	leather + plastic
R male, Ghana, Nigeria	men's briefs	0.064	cotton				
	short shirt with long sleeves	0.200	cotton	S female, Ghana, Nigeria	bra	0.029	cotton
	long pants	0.199	cotton		women's briefs	0.025	cotton
	boubou (wide-sleeved robe)	0.698	cotton		short shirt with long sleeves	0.200	cotton
	african hat	0.068	cotton		long pants	0.223	cotton
	male sandals	0.589	leather + plastic		female sandals	0.245	suede + plastic

Table A-1. Details on the Clothing Ensemble Composition for the Individual Ensembles, with Weights of the Components and Fabric/Fiber Composition *(continued)*

Ensemble	Item name	Weight, kg	Material	Ensemble	Item name	Weight, kg	Material
T male, Ghana, Nigeria	men's briefs short shirt with long sleeves shorts male sandals	0.064 0.200 0.127 0.589	cotton cotton cotton leather + plastic	U male, Ghana, Nigeria	men's briefs long shirt long pants african hat male sandals	0.064 0.282 0.199 0.068 0.589	cotton cotton cotton cotton leather + plastic
V1 (without underwear) male, Pakistan	men's briefs large pants matching long shirt socks athletic shoes	0.064 0.593 0.585 0.037 0.540	cotton polycotton polycotton cotton suede + cotton	V2 (with underwear) male, Pakistan	men's briefs long pants underwear long sleeved under-shirt large pants matching long shirt socks athletic shoes	0.064 0.230 0.262 0.593 0.585 0.037 0.540	cotton cotton cotton polycotton polycotton cotton suede + cotton
V3 (with under-wear + coat) male, Pakistan	men's briefs long pants underwear long sleeved undershirt large pants matching long shirt coat socks athletic shoes	0.064 0.230 0.262 0.593 0.585 0.458 0.037 0.540	cotton cotton cotton polycotton polycotton viscose cotton suede + cotton	W female, China	bra women's briefs camisole short sleeved *qipao* (chinese dress) female sandals	0.029 0.025 0.077 0.221 0.245	cotton cotton polycotton satin polyester suede + plastic
X1 (without shirt and head towel) female, India	bra women's briefs *churidhar* pants *churidhar* dress shawl female sandals	0.029 0.025 0.105 0.090 0.051 0.245	cotton cotton polycotton cotton polyester suede + plastic	X2 (with shirt and head towel) female, India	bra women's briefs *churidhar* pants *churidhar* dress shirt shawl towel (head) socks athletic shoes	0.029 0.025 0.105 0.090 0.208 0.051 0.206 0.037 0.540	cotton cotton polycotton cotton man-made acetate polyester cotton cotton suede + nylon
Y1 (without shirt and head towel) female, India	bra women's briefs underskirt blouse *saree* female sandals	0.029 0.025 0.143 0.041 0.275 0.245	cotton cotton cotton cotton synthetic polyester suede + plastic	Y2 (with shirt and head towel) female, India	bra women's briefs underskirt blouse *saree* shirt towel (head) socks athletic shoes	0.029 0.025 0.143 0.041 0.275 0.208 0.206 0.037 0.540	cotton cotton cotton cotton synthetic polyester man-made acetate cotton cotton suede + nylon
Z workwear male, India	men's briefs pants *bananian* (vest) shirt towel (head) socks athletic shoes	0.064 0.379 0.078 0.208 0.206 0.037 0.540	cotton polyester cotton man-made acetate cotton cotton suede + nylon				

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DISCUSSION

Hashem Akbari, Professor, Condordia University, Montreal, QC, Canada: Typically, the clothing data are presented as the physical properties of clothing and do not include film coefficient (convection coefficient). Is there a reason that you included film coefficient in your data for clothing?

George Havenith: Indeed, in our slide presentation I presented the data only as "total insulation," which is composed of the intrinsic clothing insulation and the surface air layer insulation (corrected for the increase in outer surface area due to clothing). The surface air layer insulation consists of the inverse of the sum of the convective and radiative heat transfer coefficients of the air layer, as you indicate.

In the actual publication, however, you will also find the separate data for intrinsic clothing insulation and for the outer surface air layer and for the correction factor for surface area "f_{cl}." This matches the conventional presentation.

For reasons of presentation time limits, I could not show this breakdown in components and chose to show the overall effects on the total insulation only in the presentation.

Ahmad Al-Sahhaf, PhD, Ministry of Electricity and Water, Nuzha, Kuwait: 1) Have you considered using infrared thermography in the study? 2) The presentation shows emphasis of the effect of convection heat transfer without the effect of radiation. The color of the clothing has a strong effect on thermal comfort. Is this aspect taken into account in the study?

George Havenith: 1) We tend to use infrared (IR) thermography in our research, but have not done so in this study. IR pictures would have provided us with the outer surface temperatures of the clothing, which has no direct role in the application of the standard. The average outer surface temperature can also be deducted in a different way, by knowing the intrinsic insulation and the outer air layer insulation—the ratio of the two links to the ratio of the temperature gradient between skin, the clothing, and environment.

2) The main application of ANSI/ASHRAE Standard 55-2013 is in indoor environments. As we have shown before for indoor and for solar radiation (Bröde et al, 2010. Heat gain from thermal radiation through protective clothing with different insulation, reflectivity and vapour permeability, *International Journal of Occupational Safety and Ergonomics* 16(2):231–44.), clothing color is irrelevant in the absence of direct solar radiation but does affect heat transfer in the visible solar spectrum. Thus, given the focus of this project on indoor conditions and the limits to the funding, the effect of solar radiation was not studied.

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