This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.

For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

Correction of clothing insulation for movement and wind effects, a meta-analysis

George Havenith¹ and Håkan O. Nilsson²

¹Loughborough University, Dept. Human Sciences, Loughborough, UK, LE11 3TU

(g.havenith@lboro.ac.uk)

²Division for Indoor Climate, Centre for Built Environment, Gävle University, SE-801 76 Gävle

Address for correspondance:

G.Havenith

Dept. human sciences

Loughborough University

Ashby Road

LE11 2SD

Loughborough

Tel 0044 1509 223031

Fax 0044 1509 223940

G.Havenith@lboro.ac.uk

Abstract

A meta-analysis of the effect of body and air movement on the insulation provided by workwear and cold-weather clothing ($1.22 \text{ clo } [0.189 \text{ m}^2 \cdot ^\circ\text{C} \cdot \text{W}^{-1}] < I_T < 4.14 \text{ clo } [0.642 \text{ m}^2 \cdot ^\circ\text{C} \cdot \text{W}^{-1}]$) using data from different sources was performed. For the effect of walking, datasets could be merged and a single prediction equation produced ($r^2=0.91$). For the effect of wind and interaction of movement and wind separate equations were required for regular workwear ($r^2=0.93$) and cold weather clothing ($r^2=0.97$). Differences were mainly due to the different amounts of nude surface area. An interaction between wind and walking effects was present (the size of the combined effects is less than sum of the separate effects), and for cold weather clothing an effect of clothing air permeability (p) was present (high $p \rightarrow$ bigger effect). The resulting prediction equations will be proposed for inclusion in European and ISO standards on protective clothing to assist the user in determining the real life clothing insulation value.

Keywords: clothing, protective clothing, clothing insulation, resultant insulation, body movement, air movement, wind, manikin

Introduction

Manikin measurements on clothing insulation received a vast amount of attention following the publication of the (EN-)ISO 9920 standard on 'Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of a clothing ensemble'. It provided listings of clothing ensembles with their respective insulation values as measured on manikins (I_T), for use in other standards assessing heat (ISO 7933) or cold stress (ISO TR 11079) or thermal comfort in buildings (ISO 7730) and was widely used for this purpose by ergonomists, occupational hygienists, building engineers etc. Over the years, more and more demand became apparent for insulation values of clothing in actual work situations (resultant insulation, $I_{T,r}$). The most important changes to clothing insulation as measured on a static manikin are caused by body movement of the user and by air movement in the environment. Most types of clothing ensembles have openings (e.g. collars, cuffs) that allow a certain air exchange with the environment. When work is performed, this air exchange may increase and change the

insulation of the clothing (Havenith et al., 1990^b). This effect is called the "pumping effect". In addition clothing may be compressed by wind, reducing its thickness, and wind may enter through the fabrics or openings and increase the air exchange of the microclimate air with the external environment. This would also change the resistance to heat and moisture transfer provided by the clothing.

To estimate the effect of body motion (pumping effect) and wind on the clothing insulation, a movable thermal manikin may be used in simulated wind conditions or heat balance experiments with human participants can be performed. Recently also virtual manikins have been used to make estimations of the effects from the environment and movement on the human microclimate (Buxton et al. 2002). As these methods are quite costly, a demand is present for simple estimation of these effects. A number of research projects have addressed this matter collecting a vast set of data on insulation values of various clothing types during movement and wind, and summarising the findings in prediction equations. Havenith et al. (1990^a) produced predictions for normal workwear for walking and light wind. Later Holmér et al. (1999), and Havenith et al. (2002) expanded the dataset, producing a set of correction equations that now is used in ISO 7933. Nilsson et al. (2000) studied cold weather clothing in walking and high wind speeds up to 18 m.s⁻¹. Kim and McCullough (2000) studied the effect of walking on cold weather clothing insulation.

The purpose of the present paper was to study the datasets produced in these studies and to find out whether these could be integrated in a simplified set of prediction equations. If not, the individual datasets' analysis was to be studied to see whether improvements could be made. The main criticism on the existing correction equations being that they can produce correction factors bigger than one, or produce values lower than one for the reference wind speed (G. Alfano, personal communication).

Methods

Data used for the respective studies were obtained from the literature or from authors where not published in detail: Havenith et al. (1990^{a,b}) based on data for 3 ensembles ($1.22 \text{ clo} < I_T < 1.72 \text{ clo}$; no gloves or hood) produced predictions for normal workwear in walking up to 1.2 m.s⁻¹ and wind up to 4 m.s⁻¹ (reference wind speed = 0.15 m.s⁻¹). They later (Holmér et al. 1999) expanded the dataset with 4 more workwear ensembles ($1.22 \text{ clo} < I_T < 1.84 \text{ clo}$; no gloves or hood). Nilsson et al. (2000) studied cold

weather clothing ($1.49 \text{ clo} < I_T < 3.46 \text{ clo}$) in walking speeds up to 0.8 m.s^{-1} and high wind speeds up to 18 m.s^{-1} (reference wind speed $= 0.4 \text{ m.s}^{-1}$). They also looked at the effect of air permeability of the clothing. Kim and McCullough (2000) studied the effect of walking on cold weather clothing insulation (reference wind speed $= 0.15 \text{ m.s}^{-1}$; $1.59 \text{ clo} < I_T < 4.14 \text{ clo}$; mixed with and without gloves and hood) and produced predictions of the insulation loss due to walking based on the number and thickness of garment layers on the calves and on the arms. They did not study wind.

All insulation values were calculated using the "parallel method" as described by Nilsson (1997). All data were brought together in a database and subsequently analysed with multiple (non) linear regression analyses using the statistical package SYSTAT. Prediction parameters used were wind speed, walking speed and air permeability. As parameters used by Kim & McCullough (e.g. material thickness) were not available for the other datasets and could not be estimated from the information available, these were not used as predictors in the overall analyses. For clothing where air permeability was not available this was where possible estimated using the guidance provided by Nilsson et al. (2000). Prediction quality was judged by significance ($p < 0.05$), explained variance values (r^2 ; adjusted) and Standard Errors of the Estimate (SEE).

Results

Wind effect

Re-analyses of the Havenith et al. (1990^{a,b}) and Holmér et al. (1999) data (standing still) showed that for these data no significant (nor graphically visible) effect of air permeability was present. Hence these data were lumped before comparison to Nilsson's data. The result of the analyses of the wind effect for all wind data is shown in Fig. 1.

Figure 1 about here

Walking effect

All datasets included walking, and from these data without added air speed were selected. Further, walking speeds between 0.8 and 1.2 m.s⁻¹ were selected for the analyses, as less than 20% of the data were for lower speeds. The majority of the data was for walking speeds between 0.8 and 1 m.s⁻¹.

In their 2000 publication, Kim and McCullough showed that the walking effect showed a strong correlation with the level of static insulation:

$$I_{T,r} = -0.393 + 0.893 \cdot I_{T,static} \quad (1)$$

with $r^2 = 0.95$. This analysis was repeated by adding the cold clothing data from Nilsson et al., ($r^2 = 0.91$)

$$I_{T,r} = -0.371 + 0.910 \cdot I_{T,static} \quad (2)$$

and in a second step the workwear data from Havenith et al. ($r^2 = 0.91$):

$$I_{T,r} = -0.255 + 0.868 \cdot I_{T,static} \quad (3)$$

These equations are presented in Fig. 2.

Interaction effects

When the walking effect was studied in relation to wind, it was evident that the larger the wind, the smaller the walking effect. In addition a small effect of the clothing permeability was evident: the lower the permeability, the larger the relative effect of walking (i.e. pumping) and vice versa.

Figure 2 about here

Overall analyses

The combined effect of wind and walking was analysed for the three datasets separately, because of the observed differences between the datasets. For the workwear data, the main difference to the originally produced equations is the abolishment of a constant in the exponential equation, and the subtraction of the reference wind speed from the actual wind speed, ensuring that for wind speeds equal

to the reference wind speed the correction factor equals 1. For the workwear data ($1.22 \text{ clo} < I_T < 1.84 \text{ clo}$;

Havenith et al., 1990^{a,b} and Holmér et al., 1999) the new correction equation reads:

$$I_{T,r} = \text{corr } I_T \times I_{T,\text{static}} \quad (4)$$

$$= e^{(-0.281 \times (v_{ar} - 0.15) + 0.044 \times (v_{ar} - 0.15)^2 - 0.492w + 0.176w^2)} \cdot I_{T,\text{static}}$$

with v_{ar} = wind speed relative to the person
 $(m \cdot s^{-1}$; minimum = $0.15 m \cdot s^{-1}$; maximum = $3.5 m \cdot s^{-1}$)
 and w = walking speed ($m \cdot s^{-1}$; maximum = $1.2 m \cdot s^{-1}$)

with $r^2 = 0.93$; SEE = 0.04.

For the cold weather clothing ($1.49 \text{ clo} < I_T < 3.46 \text{ clo}$), the original equation from the paper reads:

$$I_{T,r} = \left[0.54 * e^{(-0.15 * v_{ar} - 0.22 * w)} * p^{0.075} - 0.06 * \ln(p) + 0.5 \right] \cdot I_{T,\text{static}} \quad (5)$$

with p = clothing air permeability ($\text{lm}^{-2}\text{s}^{-1}$; typical permeability values that can be used are 1 for garments with impermeable membranes; 50 for densely woven workwear and 1000 for highly permeable garments (e.g. fleece without membrane)). This produced an r^2 value (observed vs. predicted) of 0.950 and a SEE of 0.059. re-analyses of the data, removing the offset, and incorporating a quadratic term for wind speed based on the residual analyses resulted in:

$$I_{T,r} = \left[e^{\{[-0.0512 * (v_{ar} - 0.4) + 0.794 * 10^{-3} * (v_{ar} - 0.4)^2 - 0.0639 * w] * p^{0.1434}\}} \right] \cdot I_{T,\text{static}} \quad (6)$$

with: $0 < \text{walk} < 1.2 \text{ m} \cdot \text{s}^{-1}$ and $0.4 < \text{wind} < 18 \text{ m} \cdot \text{s}^{-1}$ and $1 < p < 1000 \text{ lm}^{-2}\text{s}^{-1}$; $r^2 = 0.968$; SEE = 0.048. For the lower area of the wind range better results were obtained in a separate analysis:

$$I_{T,r} = e^{((-0.0881 * (v_{ar} - 0.4) + 0.0779 * (v_{ar} - 0.4)^2 - 0.0317 * (w)) * p^{0.2648})} \cdot I_{T,\text{static}} \quad (7)$$

with $r^2 = 0.931$, SEE = 0.023; $0 < \text{walk} < 1.2 \text{ m} \cdot \text{s}^{-1}$ and $0.4 < \text{wind} < 1 \text{ m} \cdot \text{s}^{-1}$ and $1 < p < 1000 \text{ lm}^{-2}\text{s}^{-1}$.

In order to allow estimation of the effect on even lighter clothing ($0 < I_{cl} < 0.6$ clo) an interpolation of equation (4) with the correction factor for nude subjects is suggested:

$$\frac{I_{T,r}}{I_{T,static}} = \frac{\{(0.6 - I_{cl})I_{T,r,nude} + I_{cl} \times I_{T,r,dressed}\}}{0.6} \quad (8)$$

With the correction for nude: ($I_{cl} = 0$ clo)

$$I_{T,r} = I_{a,r} = e^{(-0,533 \times (v_{ar} - 0,15) + 0,069 \times (v_{ar} - 0,15)^2 - 0,462w + 0,201w^2)} \cdot I_{a,static} \quad (9)$$

with v_{ar} = wind speed relative to the person

($m \cdot s^{-1}$; minimum = $0.15 m \cdot s^{-1}$; maximum = $3.5 m \cdot s^{-1}$)

and w = walking speed (ms^{-1} ; maximum = $1.2 m \cdot s^{-1}$)

Discussion

The databases used for the analyses were considered to be the most comprehensive available for this purpose. Other researchers have looked at the effects of wind and movement on clothing insulation too (Bouskill et al. 2002, Nielsen et al., 1965; Olesen and Madsen 1983) but the data and details of the clothing provided were not of sufficient quantity or detail to include these in the study.

An important issue in the comparison of data is that of the reference wind speed. This varies considerably between climatic chambers used for the measurement of clothing insulation and it can affect clothing insulation substantially. Havenith et al. (1990^a) found a reduction in insulation around 20% for the change from $0.15 m \cdot s^{-1}$ to $0.7 m \cdot s^{-1}$ for workwear. So, having a reference wind speed of 0.4 instead of $0.15 m \cdot s^{-1}$ will already have substantial impact on the data and lead to lower correction factors for the higher air speeds when the higher reference wind speed is used. For office workers and most industrial workers, air movement at the work place can be quite low and a low reference wind speed is best. Hence the choice for $<0.2 m \cdot s^{-1}$. For cold weather clothing that is used outside, such low wind speeds are highly unlikely and ENV342 has therefore chosen for a higher reference speed of $0.4 m \cdot s^{-1}$. Further, as many chambers used for the measurements cannot run stable with very low air speeds, this higher value is easier to achieve. However, in translating results from studies this is an important point to consider, as most manikin data presented in ISO9920 is obtained at low wind speeds (0.1 to $0.2 m \cdot s^{-1}$).

This problem is reflected in Fig. 2, as here the data by Nilsson et al. are based on a higher reference wind speed and due to the interaction of the walking effect with air speed (smaller effect at higher air speeds) it is clear why most of Nilsson's data for resultant insulation of cold weather clothing lies above those of Kim and McCullough who used a lower reference wind speed. The effect on the regression line is however rather small. Differences between the values calculated by equations (1),(2) and (3) are less than 0.1 clo, so equation (3) would be preferred as it is based on a larger data set.

For the overall wind effect, Fig. 1 shows the difference between Nilsson et al.'s and Havenith et al.'s data. Similar to earlier studies by Nilsson and Holmér (1997) no effect of permeability was observed in Havenith et al.'s data and they behave similar to highly permeable cold weather clothing. There are two reasons that can explain this: firstly as discussed above the reference wind speed is higher in Nilsson et al.'s data, resulting in a reduction of the effect size from this speed upwards. Secondly and more importantly, the cold weather ensembles all included gloves and most a hood, while in the Havenith et al. data hands and head were unclothed. Wind will affect the nude parts much more severely than the clothed parts, and this causes overall decreases in insulation to become much larger and differences in clothing material permeability to become more obscure in those data. Hence different correction equations are needed when the covered surface areas vary substantially. Hence equation (4) and (6) are to be used depending on the clothing configuration. These results also underline the requirement given in EN342 to use evenly distributed insulation where possible and valid.

Updated equations (3)(4)(6)(8) and (9) will be proposed for use in the revision of ISO standard 9920, which assists with the determination or estimation of clothing insulation. These new equations have the advantage over those previously published that they are based on more data, and that they have a form which now actually results in a correction factor of 1 at the reference wind speed. The latter is mainly important for use in 'comfort' applications (application of ISO 7730) as there very low wind speeds are feasible and the old equations produced correction factors bigger than one

References

- Bouskill LM, Havenith G, Kuklane K, Parsons KC and Withey WR (2002), Relationship Between Clothing Ventilation and Thermal Insulation, American Industrial Hygiene Association Journal, 63, 2002, pp 262-268
- Buxton A, Zhubrin S and Daanen H (2002) Implementation of clothing, microclimate and movement models for a virtual manikin, Proceedings of tenth Int. Conf. On Environmental Ergonomics, Sept 23-27, Fukuoka, Japan, pp 431-434
- ENV342 Protective clothing against cold European standardisation organisation (CEN TC162/WG4)Havenith G, Heus R and Lotens WA (1990^a) Resultant clothing insulation: a function of body movement, posture, wind, clothing fit and ensemble thickness. Ergonomics 33, pp 67-84.
- Havenith G, Heus R, and Lotens WA (1990^b) Clothing ventilation, vapour resistance and permeability index: changes due to posture, movement and wind. Ergonomics 33(8), 989-1005.
- Havenith G, Holmér I and Parsons KC (2002), Personal Factors in Thermal Comfort Assessment: Clothing Properties and Metabolic Heat Production, Energy and Buildings, 34, pp 581-591
- Holmér I, Nilsson H, Havenith G and Parsons KC (1999), Clothing Convective Heat Exchange - Proposal for improved Prediction in Standards and Models, Annals of Occupational Hygiene, 43(5) pp 329-337
- ISO 7730: Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. International Standardisation Organisation, Geneva
- ISO 7933: Hot environments – Analytical determination and interpretation of thermal stress using calculation of required sweat rate, International Standardisation Organisation, Geneva
- ISO/TR 11079: Evaluation of cold environments – Determination of required clothing insulation (IREQ), International Standardisation Organisation, Geneva
- ISO 9920 (1995) Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of a clothing ensemble; International Standardisation Organisation, Geneva

- Kim CS & McCullough EA (2000), Static and Dynamic Insulation Values for Cold Weather Protective Clothing in Performance of Protective Clothing: Issues and Priorities for the 21st Century. Vol. 7, ASTM STP 1386, C.N. Nelson & N.W. Henry (eds.), ASTM, Conshohocken, PA, pp 233-247.
- Nielsen R, Olesen BW and Fanger PO (1965). Effect of Physical activity and air velocity on the thermal insulation of clothing. *Ergonomics* vol 28 no. 12. 1617-1632
- Nilsson, HO, 1997, Analysis of two methods of calculating the total insulation. Proceedings of a European seminar on Thermal Manikin Testing (IIMM), Solna, Arbetslivsinstitutet, Department of Ergonomics, 17-22, ISSN 1401-2928.
- Nilsson HO, Anttonen H, and Holmér I. (2000) New algorithms for prediction of wind effects on cold protective clothing. "1st European Conference on Protective Clothing". Stockholm, Arbete och Hälsa 8, p17-20, ISBN 91-7045-559-7
- Nilsson, HO and Holmér I, 1997, Development and clothing measurements methods with the thermal manikin TORE. Proceedings of Fifth Scandinavian Symposium on Protective Clothing, Elsinore, Danish Work Environment Fund, 30-35.
- Olesen BW and Madsen TL (1983) Measurements of the thermal insulation of clothing by a movable manikin; Int. Congress of Medical and Biophysical Aspects of Protective Clothing; Lyon, July 1983

Fig. 1, Correction factor for conversion of static to dynamic insulation for all wind data; p =permeability in $\text{l.m}^{-2}.\text{s}^{-1}$

Fig. 2, relation between dynamic ($I_{T,r}$) and static (I_T) clothing insulation for 3 combinations of data. Solid line: Kim & McCullough, dashed line: Nilsson et al. data added, dotted line: Havenith et al. data added.