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Calculation of Clothing Insulation by Serial and Parallel Methods: Effects on Clothing Choice by IREQ and Thermal Responses in the Cold

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Cold protective clothing was studied in 2 European Union projects. The objectives were (a) to examine different insulation calculation methods as measured on a manikin (serial or parallel), for the prediction of cold stress (IREQ); (b) to consider the effects of cold protective clothing on metabolic rate; (c) to evaluate the movement and wind correction of clothing insulation values.

Tests were carried out on 8 subjects. The results showed the possibility of incorporating the effect of increases in metabolic rate values due to thick cold protective clothing into the IREQ model. Using the higher thermal insulation value from the serial method in the IREQ prediction, would lead to unacceptable cooling of the users. Thus, only the parallel insulation calculation method in EN 342:2004 should be used. The wind and motion correction equation (No. 2) gave realistic values for total resultant insulation; dynamic testing according to EN 342:2004 may be omitted.

cold protective clothing insulation IREQ serial parallel calculation method

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1. INTRODUCTION

1.1. Subzero Project

An earlier European Union (EU) project, Subzero (SZ), [1] investigated whether clothing insulations measured on various thermal manikins when used with the ISO standard for cold stress prediction [2] would lead to realistic predictions of the cold stress experienced by workers in certain climates. This was tested first by determining the thermal insulation of a number of clothing ensembles on manikins, calculating the thermoneutral status of a person wearing that clothing and working at a defined workload, and then by exposing human test subjects to this predicted cold climate while performing work wearing this clothing. Their responses, which should be thermoneutral if the model and the insulation measurement were correct, were compared to those predicted by Standard No. ISO/CD 11079:2001 [2] required clothing insulation (IREQ). Most the studied exposures were indeed at comfort level judged from mean skin and local temperatures.

1.1.1. Serial versus parallel insulation calculation method

However, several questions that arose in the course of the SZ project [1] were left unanswered upon project completion. Some were related to different options given in manikin testing standards [3, 4] for the way in which insulation is calculated, i.e., the serial and parallel methods. The serial method tends to overestimate the effect of the actual insulation when measured on a manikin with homogenous surface temperature distribution. However, the data produced in the past with this method were very popular, not only for giving higher insulation values that could be put on the clothing certification labels, but for also producing good predictions in models developed using the serial approach. In SZ, the clothing used had relatively evenly distributed insulation, which led to relatively close values for both serial and parallel calculations of insulation. However, the differences between the two methods are greatest if the insulation is unevenly distributed, which often occurs in real life or when thick cold protective clothing is used and clothing layers overlap. Hence, an open question is which of these methods will give the best predictions when insulation is distributed unevenly.

1.1.2. Effect of clothing weight and stiffness on metabolic rate

Another question was related to an apparent miscalculation of required insulation for activity at –25 °C in highly insulated (thick) clothing. Here the wearers were in reality substantially warmer than expected based on the IREQ prediction. Post hoc, a possible cause for this was identified in the increased metabolic rate of the subjects, resulting from the effect of clothing weight and stiffness on energy expenditure [5, 6, 7]. In thick clothing, people used more energy for the same activity than when wearing thinner clothing. This additional energy, released as heat, may have caused the subjects to be warmer than predicted, as this increase in energy consumption was not incorporated into the prediction model. This testing should therefore be repeated taking this predicted increase in metabolic rate into consideration. This, in turn, will change the test conditions for achieving thermal neutrality.

1.2. Thermprotect Project

These issues were further investigated in the current EU project, Thermprotect (TP) [8]. This looked into the issues concerning the different calculation methods for clothing insulation measured on a manikin (serial or parallel) [4], especially in cases of uneven insulation distribution over the body, where the differences between the methods are largest. In addition, issues concerning the correction of manikin clothing insulation values for movement and wind were considered. Finally, the effects of clothing on metabolic rate [7] that were not examined in SZ were now included in the analysis.

In physiological tests with human subjects wearing different clothing ensembles in the cold, the reliability of cold stress/strain predictions using Standard No. ISO/CD 11079:2001 (IREQ) [2] was assessed for the case in which the

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actual insulation of the ensembles was based on manikin measurements. The purpose of this was to validate the predictions with measured physiological values and to validate the manikins' data [3] against practice.

Thus, the following was expected (see Tables 1–2 for abbreviations):

- with uneven insulation the subjects' thermal responses should be around neutral if the IREQ calculation was carried out with the insulation values from the parallel method (AP);
- with uneven insulation the subjects' thermal responses should be on the cool/cold side if the IREQ calculation was carried out with the insulation values from the serial method (AS);
- with a lower walking speed that compensated for the effects on metabolic rate of clothing weight, friction and weight distribution, subjects should achieve thermoneutrality in accordance with the predictions for the thickest ensemble.

The tests on manikins required for human test planning were carried out earlier in this project and the results have been discussed elsewhere [9]. The data from the present study with some additional test conditions has also been used for validation of a checklist for assessment of cold related risk factors [10], thus linking the work to the Barents Interreg IIA [11] programme on risk assessment and management of cold related hazards in arctic workplaces.

In summary, the main objectives of the studies and this paper were

- to examine the consequences of different calculation methods for clothing insulation as measured on a manikin (serial or parallel), especially when insulation distribution was uneven, for the prediction of cold stress;
- to consider the effects of cold protective clothing on metabolic rate;
- to evaluate the correction of manikin clothing insulation values for movement and wind.

2. METHODS

Eight healthy nonsmoking male subjects (age 28 ± 5 years, weight 71.6 ± 11.1 kg and height 181 ± 6 cm) volunteered to participate in the experiment. None of them were working in the cold but all had previous experience of cold exposures to at least as low temperatures as –20 °C. Tests were carried out during the winter (January–February). Each subject performed each activity—walking on a treadmill (Exercise x-track elite, Exercise x.tech AS, Norway) at different speeds—at the same time of day with an interval of at least one day between the experimental sessions.

2.1. Ensemble Choice

The ensembles from the SZ project [12] (Table 1) were used in four conditions (Table 2). Ensemble B (BM) was used as a control condition in order to see if the TP subject group behaved in a way similar to the SZ subject group [13] and if the results were comparable. Ensemble A (AP and AS) was modified in order to introduce uneven insulation and create large differences between insulation values calculated by serial and parallel methods [4] of the same garment ensemble. The underwear pants were removed (only outer layer on legs) and an intermediate layer jacket was added (three layers on upper body). In order to compare these methods, both insulation values were used in the IREQ calculation [2] in order to choose the activity that corresponded to thermal neutrality. The activity level for ensemble C (CM) was reduced compared to the SZ condition by 20% by taking into account weight distribution (footwear weight) and effect of stiff and bulky clothes [7, 14, 15, 16].

The effective clothing insulation (I_{cle}) was measured on the thermal manikin [1, 9, 12]. Walking speeds were chosen [17] so that the activity level at the chosen ambient condition would correspond to thermal neutrality according to IREQ [2] as was also done in the SZ project [18].

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TABLE 1. Clothing Ensembles in the Tests

Garment (Code)		Thermal Insulation, R_{ct} (m^2K/W) and/or Description	BM Ensemble B	AP, AS Ensemble A	CM Ensemble C
Underwear	1	0.036	✓	✓ (shirt only)	
	2	0.087			✓
Intermediate		0.152 (jacket), 0.115 (pants)	✓	✓ (jacket only)	✓
Outer garment	1	0.183 (jacket), 0.123 (pants)	✓	✓	
	2	0.351			✓
Footwear	1	sneakers		✓	
	2	cold protective boots	✓		✓
Socks	1	0.087	✓	✓	✓
	2	0.166			✓
Handwear	1	gloves		✓	
	2	0.175 (mittens)	✓		✓
Headgear	1	0.168	✓	✓	
	2	0.331			✓

Notes. For more detailed garment description, see [1]. BM, AP, AS, CM—experimental conditions.

TABLE 2. Experimental Conditions

Code	Clothing	Clothing (Footwear) Weight (kg)	Insulation, I_{tr} ($m^2°C/W$)^1	Activity (Duration, min)	Metabolic Rate (W/m^2)		T_a (°C)
					Predicted^2	Measured	
BM	Ensemble B	6.2 (2.3)	0.375	3.5 km/hr (90)	135	162 ± 10	–10
AP	Uneven	3.9 (0.9)	0.281	4.9 km/hr (90)	182	194 ± 17	–10
AS	Uneven	3.9 (0.9)	0.398 (serial)	3.5 km/hr (90)	130	161 ± 12	–10
CM	Ensemble C	7.4 (2.3)	0.469	3.0 km/hr (90)	155	152 ± 17	–25

Notes. 1—insulation I_{tr} measured on walking manikin according to Standard No. EN 342:2004 [3] and calculated by the parallel method, unless defined differently, 2—predicted metabolic rate [17] used in IREQ calculation; T_a—ambient air temperature; BM, AP, AS, CM—experimental conditions.

2.2. Instrumentation and Procedure

Heart rate (Sport Tester, Polar Electro Oy, Finland), body core (rectal probe at a depth of 10 cm, YSI-401 Yellow Springs Instrument, USA, accuracy ±0.15 °C), skin (eight points [19], NTC-resistant temperature matched thermistors ACC-001, Rhopoint Components Ltd, UK, accuracy ±0.2 °C, time constant 10 s, fixed to skin with 3M Blenderm™ surgical tape, type 1525 covering the thermistors), and ambient air temperatures (PT100, 1/10 Class B sensor accuracy ±0.03 °C at 0 °C, logger PT-104; Pico Technology Ltd, accuracy ±0.01 °C) were recorded every 15 s. Each clothing piece was weighed separately in the beginning and at the end of each test (Sartorius 3804MP, Sartorius Gmbh, Germany, accuracy ±0.1 g). A subject was weighed nude and with all clothing in the beginning and at the end of each test (KC 240 GWB Mettler ID2 MultiRange, Germany, accuracy ±0.002 kg). Oxygen consumption was analysed (MetaMax I, Cortex GmbH, Germany) for about 5 min every half hour of the activity. The thermal sensation [20] was requested from the subject every 10 min (scale from –4 *very cold* to +4 *very hot*).

2.3. Analysis and Statistics

In some conditions mean skin temperature stayed under 32 °C and in some it stayed higher. In order to avoid mixing calculations with various coefficients for skin (T_{sk}, 0.2 alt. 0.35) and core (T_{rec}, 0.8 alt. 0.65) temperature, a floating equation for mean body temperature (T_b) calculation was used. If $T_{sk} > 33.5$ °C then 0.2 T_{sk} + 0.8 T_{rec} was used, and if $T_{sk} < 32.0$ °C then 0.35 T_{sk} + 0.65 T_{rec} was used. In between

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these the coefficients were floating by 0.1 depending on T_{sk} change by 0.1 °C.

The time profiles of the body temperatures recorded in the two experimental conditions (AS, AP) were statistically analysed applying repeated measurement ANOVA on the data averaged over 10-min intervals using linear mixed models with the repeated factors condition and time assuming an unstructured covariance structure for the condition factor and an autoregressive structure for the time factor [21].

3. RESULTS AND DISCUSSION

According to the results for the control condition (ensemble B) the subject groups of the present study and the SZ project were similar [1, 13]. The main comparison was made between subjects of the present study and the subject group that was tested by the same laboratory in SZ. Based on single-factor ANOVA of all the separate measured parameters, there were no significant differences in subjects' height, weight and age or in measured temperatures, subjective responses, etc. The only significant difference was observed in sweat evaporation (an average of 75 g for subjects in the present study versus 106 g for the previous). The measured metabolic rates were higher than the predicted (Table 2), similar to earlier results. Thus, we were able to extend the database and could rely on the data for comparison of conditions. Figure 1 shows mean body temperature (T_b) and Figure 2 thermal sensation over time for all described conditions.

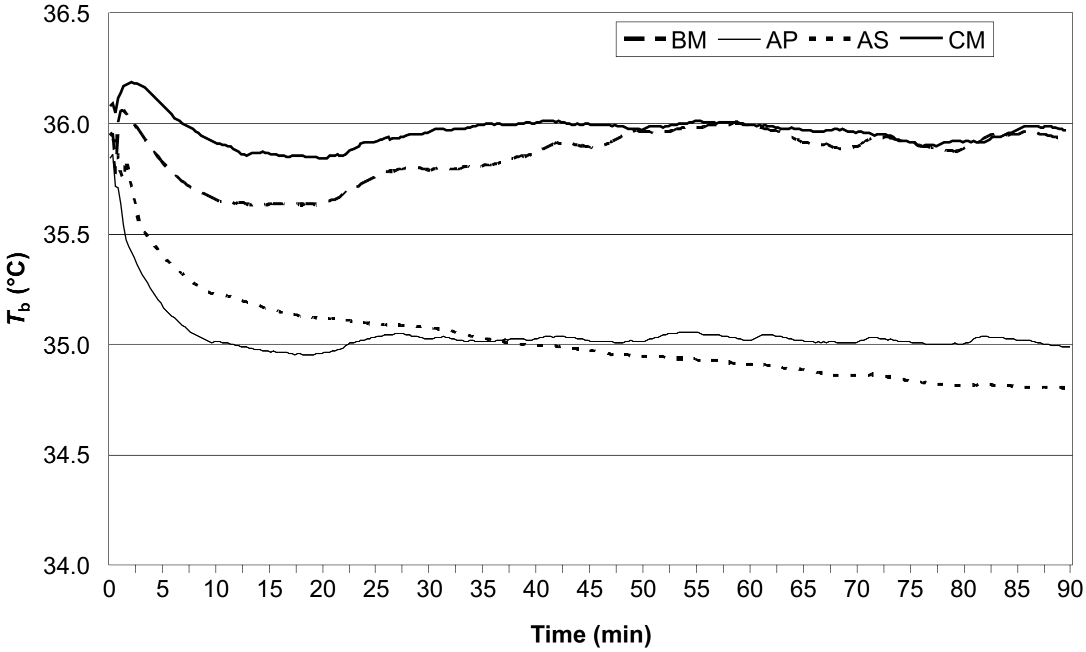

Figure 1. Development of averaged mean body temperature (T_b) for the different conditions (Table 1 and 2). *Notes.* BM, AP, AS, CM—experimental conditions.

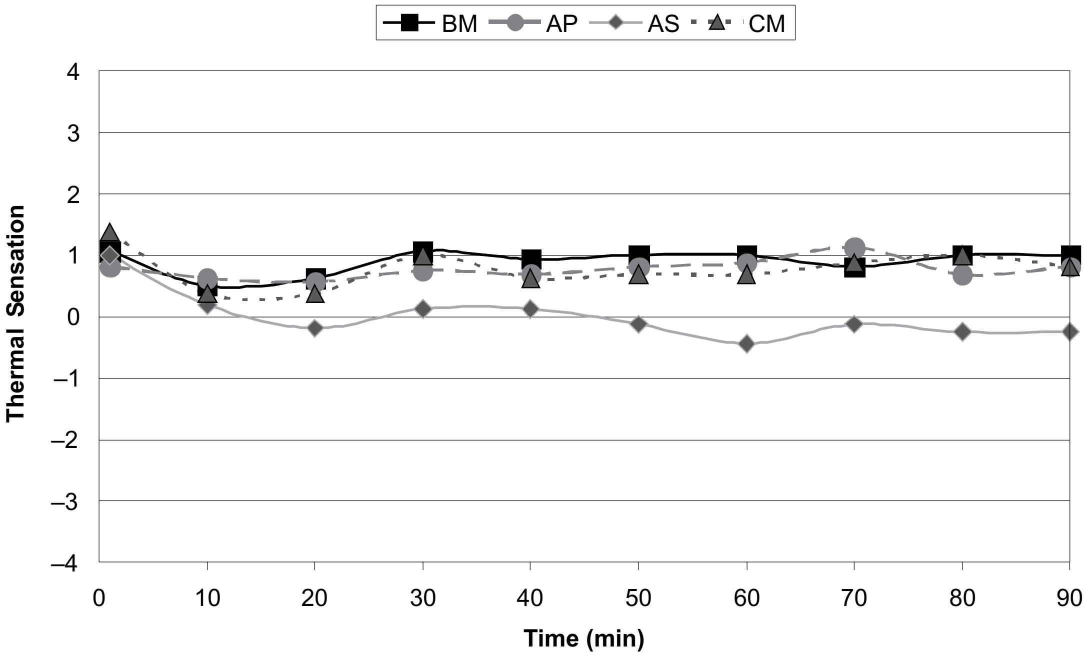

Figure 2. Thermal sensation over time. *Notes*. BM, AP, AS, CM—experimental conditions; –4—*very cold*, –3—*cold*, –2—*cool*, –1—*slightly cool*, 0—*neutral*, 1—*slightly warm*, 2—*warm*, 3—*hot*, 4—*very hot*.

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3.1. Mean Body Temperature

As seen in Figure 1, T_b of condition AP stabilized after an initial drop and stayed constant. This suggests that the subjects could continue working at IREQ defined conditions without further cooling. The subjects reported feeling, on average, between neutral and slightly warm. Table 2 shows that the chosen activity level for AP provided measured metabolic rates that were very close to the predicted one.

In condition AS, T_b continued to decrease at a constant rate after about 30 min of exposure. The difference between AP and AS at the end of 90 min was not great, however, statistics showed some significant differences. The results indicated that there was a significant trend with time (significant time effect, $p < .0001$), which differed significantly between the two conditions AS and AP (significant condition and time interaction, $p < .0001$). The nonsignificant condition effect said that the T_b data averaged over the whole period (90 min) did not differ significantly between AP and AS.

3.2. Sweating

The difference was also confirmed by the thermal sensation of the subjects: on average it stayed slightly below neutral in AS, while in AP it was slightly warm. With less sweat produced, condition AS would be more favourable in the cold: 102.7 ± 29.8 g versus 136.6 ± 79.2 g in AP (Figure 3). Although the absolute quantities were still quite low in both cases, the cooler condition of subjects seemed to attenuate sweat production in AS.

3.3. Metabolic Rate

Table 2 shows that the actual measured metabolic rate (161 W/m^2) was considerably higher for condition AS than the targeted/predicted one (130 W/m^2), and this difference was larger than for AP. The clothing for AS and AP was the same and the work rate was calculated by the same method for both. Although muscle tension (thermoregulatory muscle tone) [22] and shivering due to cold were neither observed nor reported, these reactions may explain why measured and predicted metabolic rates differed. Cooling to such a degree promotes performance

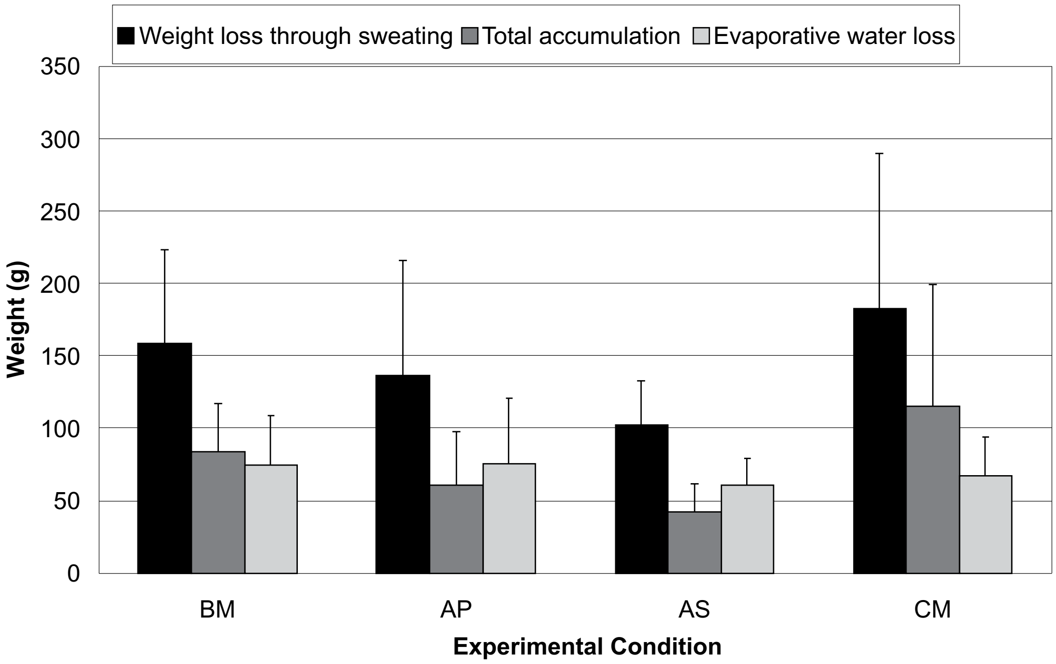

Figure 3. Sweating weight loss, absorption by clothing and evaporation. *Notes*. All data are corrected for respiratory water loss.

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deterioration [23] and should be avoided. If even lower activity had been selected to cope with thermoregulatory muscle tone in order to match the predicted metabolic rate (130 W/m^2), then the cooling rate of the subjects could actually have been much quicker or they could have started shivering. If shivering occurred then we might measure again higher metabolic rate than predicted, see reasonable body temperature and not very low thermal sensation. Even though we would get a reasonable physiological response, we would not be able to state that the subjects were comfortable. In practice, at this point one should decide how important discomfort is for performance compared to performance drop due to thicker clothes. However, this should not be decided based on an insulation calculation method, but by considering physiological responses. Thus, insulation values calculated by the serial method should not be used in the IREQ standard [2], especially if clothing insulation is unevenly distributed.

A reduction of the predicted metabolic rate by 20% in condition CM compared to SZ experiments [13] in order to account for increased energy consumption due to clothing weight, friction and weight distribution gave the expected results. The measured metabolic rate was very close to the expected one (Table 2). The total weight loss by sweating was reduced from 315.2 ± 116.3 g during the SZ test to 182.2 ± 107.7 g during these trials (Figure 3). Thus, the data from human tests may be easier compared to manikin trials carried out during the SZ project [1, 24].

3.4. Total Resultant Insulation Values

Figure 4 shows total resultant clothing insulation acquired from subject data and the dry manikin corrected for wind and walking speed. Somewhat lower insulation values for subjects could be related to moisture accumulation in the clothing (minor effect compared to ensemble weight and moisture quantity, see Table 2 and Figure 3) that is not considered in dry manikin tests, and to a more active motion pattern than in a rigid manikin.

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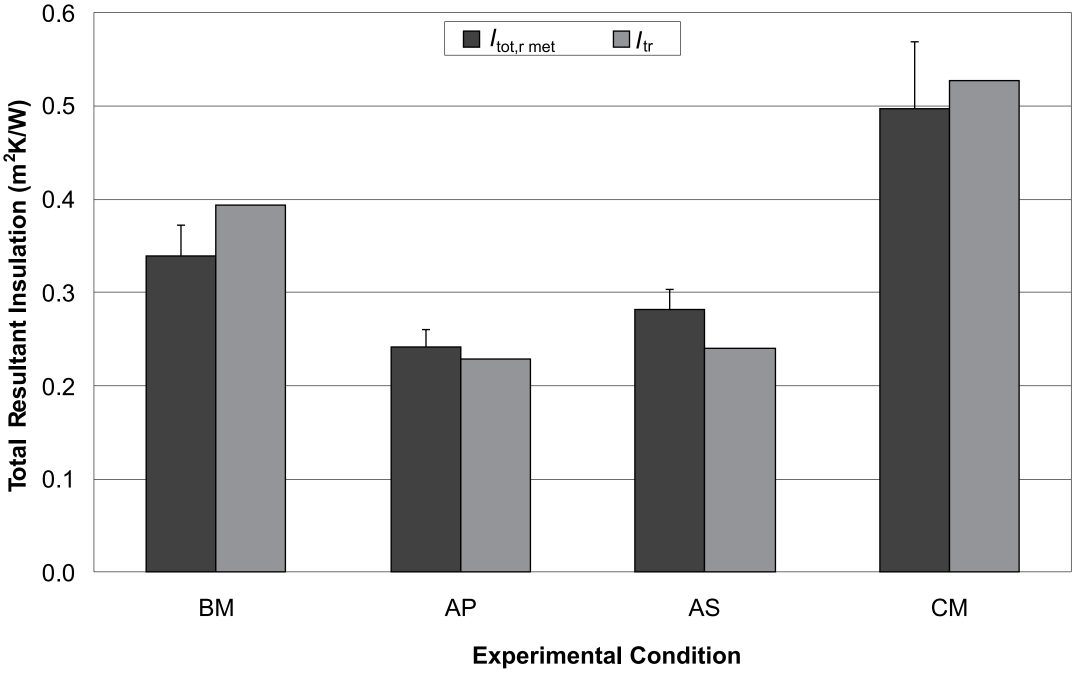

Figure 4. The total resultant clothing insulation measured on subjects ($I_{\text{tot,r met}}$) and calculated from static thermal manikin (I_{tr}) data [3, 25].

3.5. Discussion of SZ and TP Data

3.5.1. Total resultant insulation values

Figures 5 and 6 show a compilation of data from the two EU projects (SZ and TP) obtained at one laboratory ($I_{\text{tot,r met}}$) and mean values for all SZ partners ($I_{\text{tot,r met, SZ all}}$). These values are total resultant clothing insulation values from the subject data. Values are also given for the ensembles measured with a static manikin according to Standard No. EN 342:2004 [3] and corrected according to its Annex C, Equation 2 for the actual ambient conditions and walking speed ($I_{\text{tot,r calc}}$).

The measured and calculated values were reasonably close and for most cases within 10–15% variation. For high activity and wind (ensemble D [1] with 3 and 10 m/s wind from the front, walking 5 km/hr on 0° or 0.5° inclination) the differences between $I_{\text{tot,r met}}$ and $I_{\text{tot,r calc}}$ were much higher and might be related to considerable sweating [13], and further on subjects' data for ensemble D are not compared. Also, CH (ensemble C, 5 km/hr) differed more for the same reason (high sweating). In these conditions insulation measurements based on heat flow transducers ($I_{\text{tot,r HF}}$) showed values closer to the standard calculation. CM subject data (ensemble C, medium activity) were closer to the standard calculation. CM was repeated in the TP project with a 20% lower metabolic rate. Insulation values for this condition were even closer to manikin values (Figure 4).

3.5.2. Correction equations for wind and walking

Annex C [3] provides two equations for wind and walking correction. Equation 1 is for wind up to 2 m/s and Equation 2 is for higher wind speeds. Equation 1 is a simplified version of Equation 2 and does not account for the air permeability of the outer garment [25]. For ensembles A, B and C wind was less than 2 m/s. It can be seen in Figure 7 that Equation 1 estimated insulation reduction to be lower and thus gave higher insulation for all conditions than when using Equation 2. Ensemble D was not used in the comparison because Equation 1 (0.4–2 m/s) was not valid in the range of tested air velocity (3 and 10 m/s). In all conditions, Equation 2 gave less

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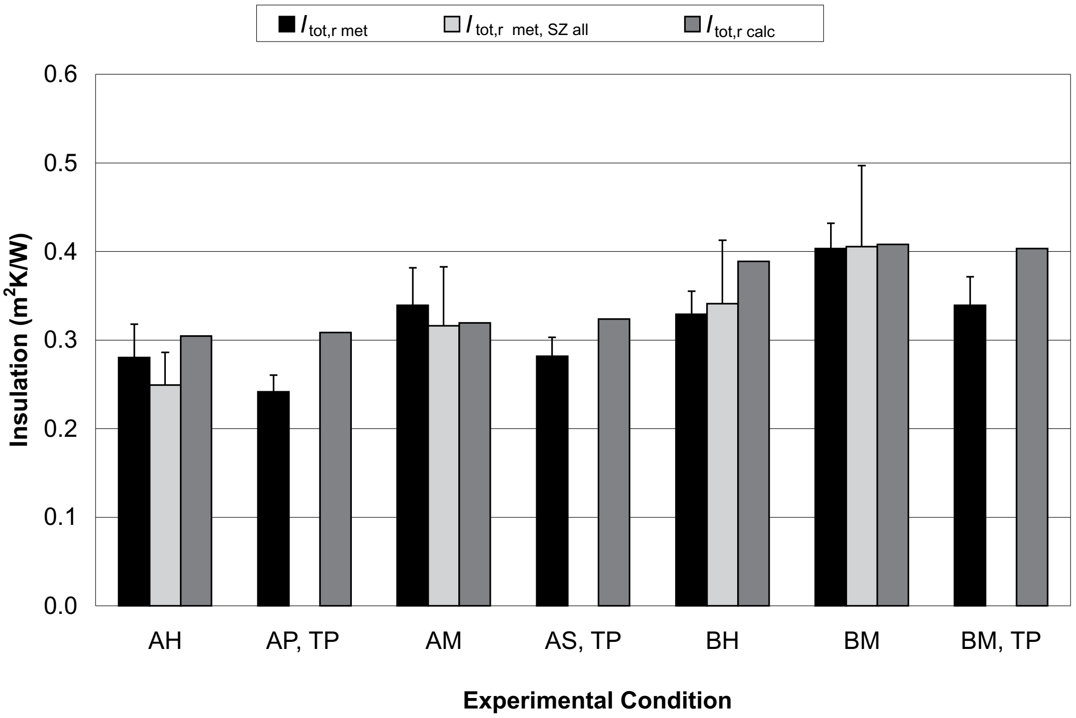

Figure 5. The total resultant clothing insulation values from the subject data from the National Institute for Working Life or the Lund (Thermprotect, TP) work group ($I_{tot,r\ met}$), Subzero (SZ) project partners ($I_{tot,r\ met,\ SZ\ all}$) and from the calculation according to Standard No. EN 342:2004 [3], Annex C, Equation 2 from static manikin data ($I_{tot,r\ calc}$) depending on actual ambient conditions and walking speed (H—high, M—medium) for ensembles A and B.

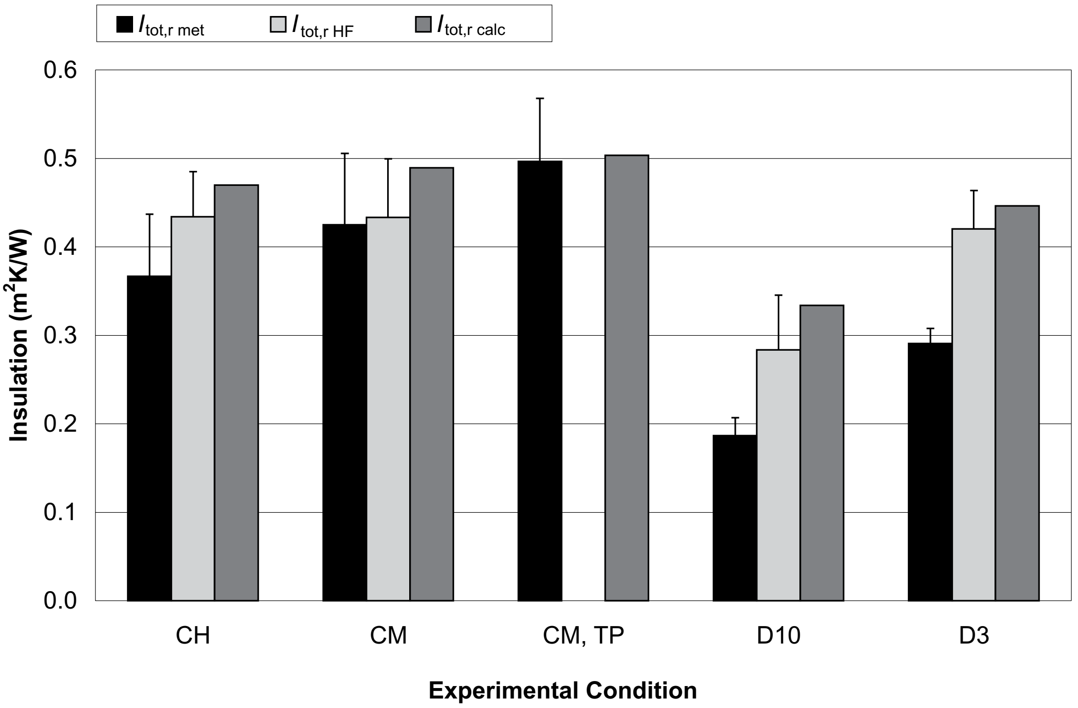

Figure 6. The total resultant clothing insulation values from the subject data from the Lund (Thermprotect) work group and Subzero project partners calculated from metabolic rate ($I_{tot,r\ met}$) based on heat flux measurements ($I_{tot,r\ HF}$) and from the calculation according to Standard No. EN 342:2004 [3], Annex C, Equation 2 ($I_{tot,r\ calc}$) from static manikin data (I_{tot}) depending on actual ambient conditions and walking speed (H—high, M—medium) for ensembles C and D (3, 10—wind velocity in m/s).

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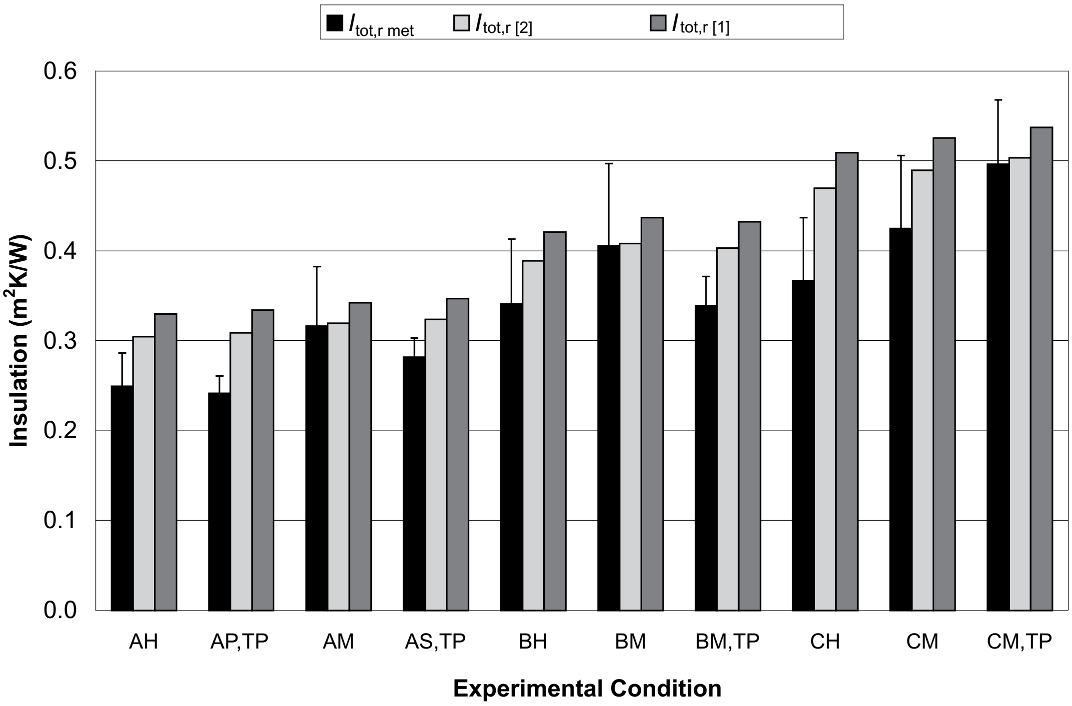

Figure 7. The total resultant clothing insulation values from the subject data from the Lund work group (Thermprotect) and Subzero project partners calculated from metabolic rate ($I_{tot,r\ met}$), and from the calculation according to Standard No. EN 342:2004 [3], Annex C, Equation 2 ($I_{tot,r\ [2]}$) and 1 ($I_{tot,r\ [1]}$) from static manikin data (walking speed: H—high, M—medium).

difference between measured (with subjects) and calculated values. Estimating insulation with Equation 1 may add 0.02 m^{2}K/W or more to the actual insulation of the clothing. Standard No. ISO 11079:2005 [2] uses Equation 2 in the IREQ calculation. These standard insulation values from thermal manikin are used for predicting protection levels and exposure times. It can be concluded that the corrections with Equation 1 are not sufficient to match the insulation values measured with subjects. Thus, Equation 2 is recommended to be used for all wind speeds in Standard No. EN 342:2004 [3].

3.5.3. Serial versus parallel insulation calculation method

All aforementioned standard calculations were based on the parallel calculation method from Standard No. EN ISO 15831:2004 [4]. Figure 8 shows the total resultant thermal insulation values of all used ensembles for all conditions in the SZ and TP projects measured on subjects ($I_{tot,r\ met}$) and calculated according to Annex C [3] from the static thermal manikin data based on parallel ($I_{tot,r\ [2],\ P}$) and serial ($I_{tot,r\ [2],\ S}$) insulation calculation methods [4]. The only serial calculation values that lay within the standard deviation of the subjects' results were the ones in conditions AM and BM. The rest were much higher than the subjects' values and the insulation calculated by the parallel method. Thus, the use of the serial calculation method was not justified.

In the SZ project, tests with the walking manikin were carried out as well. Figure 9 shows these values. According to Standard No. EN ISO 15831:2004 [4] manikin step length from toe to toe should be 63 ± 10 cm and step rate 45 ± 2 steps. That leaves the calculated manikin walking speed between 1.4 and 2.1 km/hr. In conditions in Figure 9, the subjects were walking with a velocity from 3.0 (CM in TP) to 3.8 km/hr (CM in SZ). Thus we might expect lower insulation values from the manikin tests if the walking speed were increased. Nevertheless, walking values using the parallel calculation method were always lower than those using the serial method.

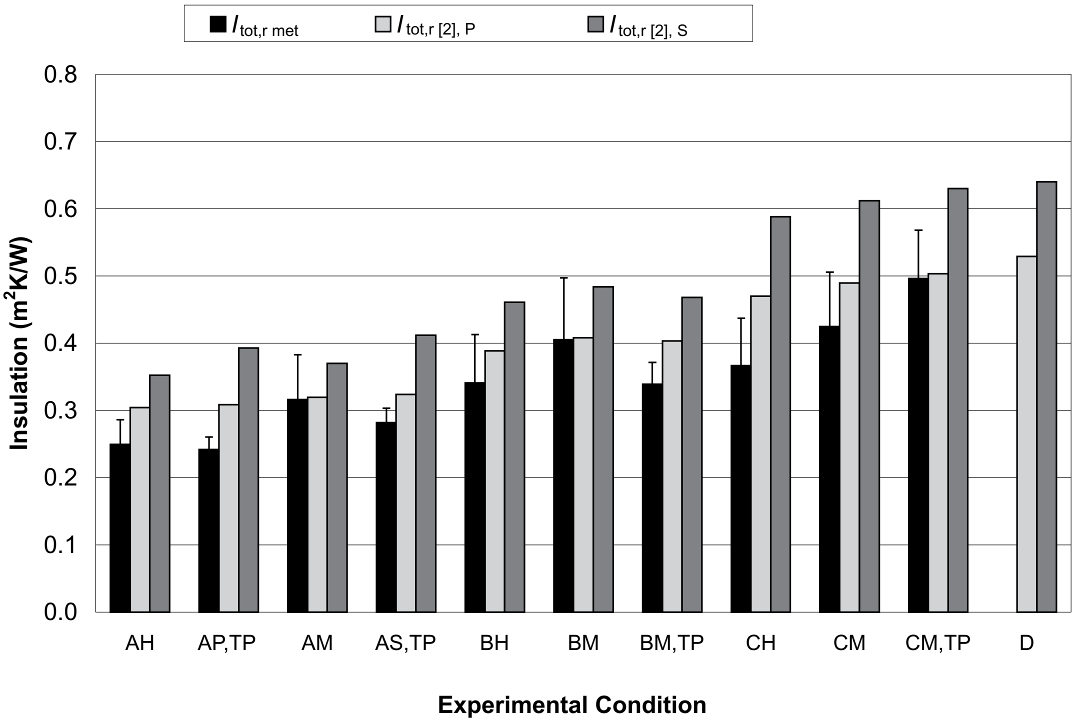

Figure 8. The total resultant thermal insulation values of all used ensembles for all conditions in Subzero and Thermprotect projects measured on subjects ($I_{tot,r\ met}$) and calculated according to Standard No. EN 342:2004 [3] Annex C, Equation 2 from static thermal manikin data based on parallel ($I_{tot,r\ [2],\ P}$) and serial ($I_{tot,r\ [2],\ S}$) insulation calculation methods of Standard No. EN ISO 15831:2004 [4] (walking speed: H—high, M—medium).

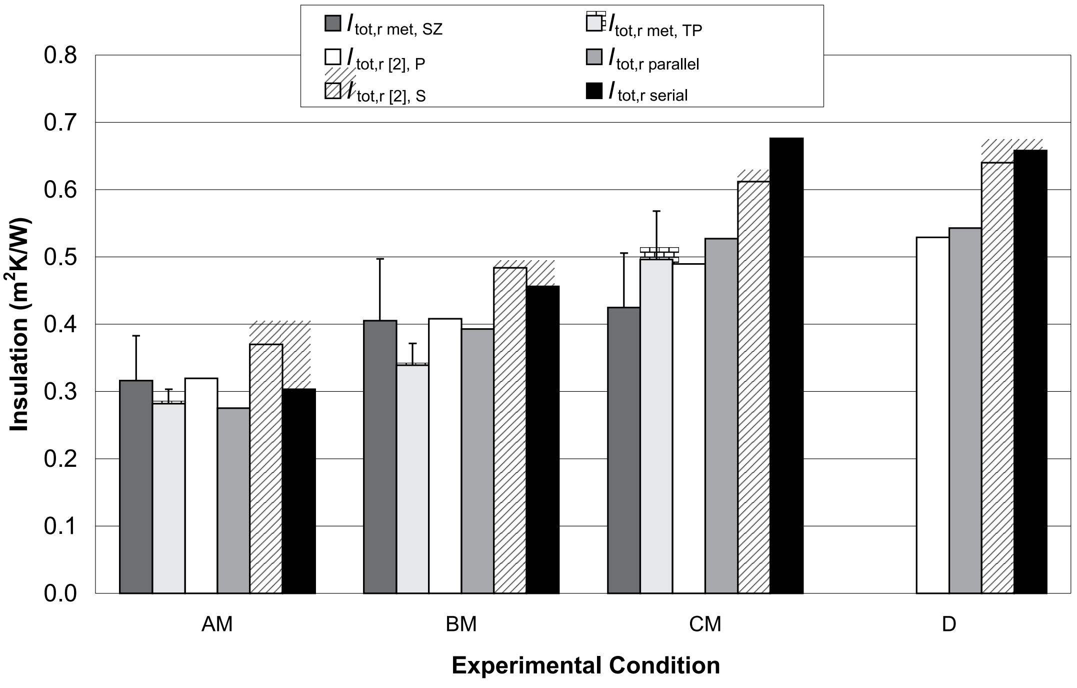

Figure 9. The total resultant thermal insulation values of all used ensembles for conditions with lowest activities in Subzero (SZ) and Thermprotect (TP) projects measured on subjects ($I_{tot,r\ met}$), calculated according to Standard No. EN 342:2004 [3] Annex C, Equation 2 from static thermal manikin data based on parallel ($I_{tot,r\ [2],\ P}$) and serial ($I_{tot,r\ [2],\ S}$) insulation calculation methods of Standard No. EN ISO 15831:2004 [4], and measured on a walking thermal manikin and calculated according to EN ISO 15831:2004 parallel ($I_{tot,r\ parallel}$) and serial ($I_{tot,r\ serial}$) calculation methods.

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The serial method calculation is most suitable for ensemble A. In ensemble A, the wind correction according to Equation 1 [3] also had values closest to the other results (Figure 7). However, to be within the scope of this standard, the resultant effective thermal insulation I_{cler} had to have a minimum value of 0.310 m^2K/W when measured in accordance with the standard. Accordingly, ensemble A was outside the scope of the standard as Annex C claims "manikin shall give an I_{tr} value for ensemble A of 0.299 m^2 K/W ± 3%" (p. 15) [3]. The I_{cler} value of this ensemble was around 0.22 m^2K/W. The serial method provided values that were too high, even for walking, for ensembles B, C and D and could not be used in conjunction with the evaluation of their protective value. These three ensembles were also more representative of cold protective clothing than ensemble A and fit within the scope of Standard No. EN 342:2004 [3]. Ensemble A was better for testing garments for cool environments [26].

4. CONCLUSIONS

- Values for metabolic rate used in ISO standards are typically taken from tables and equations in Standard No. ISO 8996:2004 [27] and lead to an overestimation of the cold stress when used in the cold stress standard [2]. This is due to the fact that these tables and equations do not take into account that protective clothing, and especially thick, heavy and bulky cold protective clothing leads to a significant increase in metabolic rate for identical activities compared to light clothing.
- Of the two calculation methods for insulation used for manikins (serial and parallel), the serial method provides a higher insulation value for a clothing ensemble compared to the parallel method both for static and walking conditions. This difference is larger for unequal distributions of insulation over the body. Using this higher value in IREQ [2] suggests lower temperature values for thermal neutrality than when the parallel values are used. The physiological tests have shown that the calculated thermal neutrality values for the serial insulation data are not true. Although, body cooling is slowed down, the maintaining of heat balance is achieved only at the cost of thermoregulatory muscle tone.
- As the two errors just described work in opposite directions, they may compensate for each other when combined. If we consider the effects that thick clothing have on metabolic heat production, then only the insulation values from the parallel calculation method should be used together with IREQ [2]. It is also recommended to only use the parallel insulation calculation method in Standard No. EN 342:2004 [3].
- Wind correction with Equation 1 [3] did not provide sufficient reduction to compare well with subject data. It is recommended to use only wind and motion correction with Equation 2 [3].
- Dynamic testing according to EN 342:2004 [3] can be omitted. The correction Equation 2 for cold protective clothing within the scope of this standard is more sensitive to the variation in walking and wind speed and gives a more realistic value for comparison with real conditions. The walking test [3] is just a special case and does not allow easy estimation of insulation change in various dynamic conditions.

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