

Parallel and Serial Methods of Calculating Thermal Insulation in European Manikin Standards

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Standard No. EN 15831:2004 provides 2 methods of calculating insulation: parallel and serial. The parallel method is similar to the global one defined in Standard No. ISO 9920:2007. Standards No. EN 342:2004, EN 14058:2004 and EN 13537:2002 refer to the methods defined in Standard No. EN ISO 15831:2004 for testing cold protective clothing or equipment. However, it is necessary to consider several issues, e.g., referring to measuring human subjects, when using the serial method. With one zone, there is no serial–parallel issue as the results are the same, while more zones increase the difference in insulation value between the methods. If insulation is evenly distributed, differences between the serial and parallel method are relatively small and proportional. However, with more insulation layers overlapping in heavy cold protective ensembles, the serial method produces higher insulation values than the parallel one and human studies. Therefore, the parallel method is recommended for standard testing.

thermal manikin European standard clothing insulation serial calculation method
parallel calculation method human subject studies

1. INTRODUCTION

Thermal manikins are widely used for evaluating clothing and thermal environment [1, 2]. Some methods of evaluating have become standards [3, 4, 5, 6]. Several others use the data acquired on thermal manikins, e.g., Standard No. ISO 11079:2007 [7]. Standards refer to or allow the use of specific methods of calculating. The choice of a method might depend on how the standard originated and which manikin was used to evaluate the method. Thus, depending on the definition of the method of calculating and the specific measuring procedure, the same method need not be valid for another standard. It may be confusing if different standards define a method differently while the term used is the same.

Standard No. ISO 9920:2007 defines three methods of calculating insulation: global, parallel and serial [8]. It presents the global method as a general one that works in any situation, and the parallel and serial as specific ones if certain prerequisites are fulfilled. Standard No. EN ISO 15831:2004 is the basic standard for testing manikins [9]. It presents only two methods: parallel and serial. It does not set specific conditions for using equations and defines the parallel method in a similar manner as the global one in Standard No. ISO 9920:2007 [8]. Thus, definitions of methods of calculating differ in those two standards. Confusion may be due to the historical use of different terms for the same equations [10, 11]. Other reasons for the differences can also be ignoring the area weighting of the surface temperature

when using the homogenous surface temperature regulation mode as required by Standard No. EN ISO 15831:2004 (section 5.1.2. Surface temperature) [9], or forgetting it when using comfort or constant heat flux regulation modes. Lee, Ko, Lee, et al. described a possible need for a new term [12].

Calculating insulation according to Standard No. EN 511:2006 differs from the aforementioned methods [5]. There is no reference to a model of serial or parallel calculation, as it is assumed that the whole hand is one zone. In this case, the serial and parallel models are similar. With more zones both methods differ more, depending on insulation and its distribution. Although total heat losses from the hand may be understood as the sum of power (in watts) for all measuring zones, it is still possible that in the case of a multizone hand model, different test houses select calculation methods according to their preference as the method of adding up zones is not defined in the standard. In the case of a multizone hand model, especially if surface temperature is deliberately inhomogeneous, it is recommended to use area weighted temperature (Equation 4) to obtain correct insulation values [8, 9, 13]. The same approach is also important when using, e.g., a one-zone manikin with many point sensors over the surface [14] to enhance accuracy of calculation. As calculating glove insulation is a special case, this article does not deal with it further but concentrates on the serial and parallel methods.

Although the discussion on parallel and serial methods had begun earlier, deeper analysis started most probably at the first European Seminar on Thermal Manikin Testing where Nilsson [10] presented his comparison and Redortier [11] discussed the significance of the outcome of these methods for the development of Standard No. EN 342:2004 [4] (at that time prENV 342). Later, the calculation methods were compared within various projects [1, 12, 15], and evaluated experimentally [12, 15, 16, 17, 18, 19, 20] and mathematically [13, 16, 20]. Since the parallel method in Standard No. EN 15831:2004 [9] and the global method in Standard No. ISO 9920:2007 [8] are identical, most studies favour

the parallel method except for a few special cases [13, 20].

One of these cases is related to human thermal responses, where Huang [13] refers to Bartels and Umbach [21]. The garments used for comparison in that study were relatively evenly insulated and not intended for extreme cold exposure (cf. garments A and B in the SUBZERO project [22]), so they gave relatively close serial and parallel values. The construction of manikins is also important, e.g., serial values from Hohenstein's copper manikin Charlie [21] are usually lower than from the Swedish plastic manikin Tore [23, 24].

To expand the discussion further into physiological aspects, this article uses data from two European projects [22, 25], and investigates which of those methods gave insulation values more similar to those obtained from human subjects. We limited the basis for discussion mainly to Standards No. EN 342:2004 [4] and EN 14058:2004 [26]. Those two standards and Standard No. EN 13537:2002 [27] refer to Standard No. EN 15831:2004 [9]. All those standards allow calculating insulation with either method or with their combination, e.g., average of parallel and serial values depending on the results of manikin calibration with reference ensembles. Standard No. EN 13537:2002 to some extent avoids potential problems with calculation methods by specific calibration procedures and a related physiological model for predicting user temperature (comfort, limit, extreme) [27]. As testing sleeping bags was recently discussed in detail by Kuklane and Dejke [28], this article does not refer to Standard No. EN 13537:2002 [27].

2. STANDARD NO. EN ISO 15831:2004

2.1. Serial Method

Standard No. EN ISO 15831:2004 [9] defines the serial method as surface area weighted thermal insulation:

$$I_t \text{ or } I_{tr} = \sum_i f_i \times \left[\frac{(T_{si} - T_a) \times a_i}{H_{ci}} \right], \quad (1)$$

$$f_i = \frac{a_i}{A}, \quad (2)$$

where I_t —total thermal insulation of the clothing ensemble with the stationary manikin ($\text{m}^2\text{C/W}$), I_{tr} —resultant total thermal insulation of the clothing ensemble with the manikin moving ($\text{m}^2\text{C/W}$), f_i —fraction of the total manikin surface area represented by the surface area of segment i , T_{si} —skin surface temperature of the body segment i of the manikin ($^{\circ}\text{C}$), T_a —air temperature within the climatic chamber ($^{\circ}\text{C}$), a_i —surface area of the body segment i of the manikin (m^2), H_{ci} —heating power supplied to the body segment i of the manikin (W), A —total body surface area of the manikin (m^2).

2.2. Parallel Method

In the parallel method, with homogeneous surface temperature, area weighting of temperature is not necessary. However, the following equation may appear in various applications and area weighting may be forgotten even when surface temperature is uneven. In Standard No. EN ISO 15831:2004 the parallel method is defined as surface area averaged thermal insulation [9]:

$$I_t \text{ or } I_{tr} = \frac{(T_s - T_a) \times A}{H_c}, \quad (3)$$

$$T_s = \sum_i f_i \times T_{si}, \quad (4)$$

$$H_c = \sum_i H_{ci}, \quad (5)$$

where T_s —mean skin surface temperature of the manikin ($^{\circ}\text{C}$), H_c —total heating power supplied to the manikin (W). As the equations are used in Standard No. EN 14058:2004 [26] and Standard No. EN 342:2004 [4], we evaluate them further in sections 3.1–3.4.

3. PROTECTIVE CLOTHING: STANDARDS NO. EN 14058:2004 AND EN 342:2004

3.1. Data Sets Used in Analysis

The main classification in Standard No. EN 14058:2004 is based on material tests [26]. Manikin testing is optional. Standard No. EN

14058:2004 and Standard No. EN 342:2004 [4] both use the same calibration reference ensembles and the same methodology of testing, although underwear combinations and reference clothes differ to some extent.

For our purposes, the evaluation involved three main data sets:

1. SUBZERO project [1, 15, 22, 24, 29, 30];
2. complementary SUBZERO testing within THERMPROTECT WP3 [15, 25, 31];
3. data from THERMPROTECT WP2 [25, 32, 33, 34].

Most of the data in set 1 come from seven institutes involved in the SUBZERO project [22]. Anttonen, Niskanen, Meinander, et al. reported major findings on dry testing on manikins [1]. The manikin report [24] made for the final project report [22] contains full details of those findings. Kuklane, Sandsund, Reinertsen, et al. compared specific subject data (conditions with uneven insulation) of complementary testing [15] to mean manikin data from two labs [31]. Tests on walking manikins were not available for comparison there. Set 3 involved light two-layer clothing outside the scope of Standards No. EN 14058:2004 [26] and EN 342:2004 [4]. We added it to extend available data sets with reliable values at low end for control purposes. We only used conditions where thermal neutrality of the subjects could be achieved with minimal sweating (PERM10D [33, 34]). Therefore, the walking velocity of the manikins reflected the actual walking velocity of the subjects [32]. As that particular garment was not a cold protective one, wind correction of static values was carried out according to Equation 32 in Standard No. ISO 9920:2007 [8].

3.2. Relationship Between Human Data and Calculation Methods

Figure 1a presents all paired data sets, i.e., human–manikin, showing all different walking velocities and environmental conditions. Figure 1b presents data with error bars of standard deviation only for conditions where the subject maintained stability in thermal neutrality and

the walking velocity was closest to the estimated manikin walking velocity (45 double steps/min, step length 0.63 m, estimated human walking velocity 0.95 m/s = 3.4 km/h) for any clothing ensemble.

We found the best correlation with all involved data in wind corrected static values of both parallel and serial calculation methods ($R^2 = .68$ and $.63$, respectively) (Figure 1a). The values of 342(2)P and 342(2)S were based on static tests and calculations according to Equation 2 in Annex C of Standard No. EN 342:2004 [4] using the same air and walking velocity for the parallel and serial calculation as the subjects had. We did not make the correction according to Equation 1 in Annex C of standard Equation 1 in Standard No. EN 342:2004 as it has been shown to considerably underestimate the reduction of insulation under wind and walking (Figure 7 in Kuklane, Gao, Holmér, et al. [15]).

Standard No. EN 342:2004 refers to testing dry insulation [4]. In manikin testing, measurements are usually taken only after manikin values reach stability at specified levels. However, stability at comfort level may be difficult to achieve in

human testing, and is caused by various reasons often unintended [35]. Thus, as a next step in this analysis we eliminated the human conditions with excess sweating. Those were the conditions where work against the wind, clothing weight, and high sweating rate led to much higher metabolic heat production than expected [15, 36]. We also eliminated uneven insulation and medium sweating. With minimal sweating conditions including light clothing, both regression lines of parallel methods practically followed the line of identity, while serial methods differed at high end much more (Figure 1b). Correlation was high in all cases ($R^2 = .91-.97$).

3.3. Comparison of Human Data and Calculation Methods, Wind and Walking Corrections

Figure 2 compares in detail the insulation of reference garments of human subjects and walking manikin results. It is clear that the parallel method gave results closer to values from human subjects than the serial one, especially when insulation was high and in the scope defined by Standard No. EN 342:2004 [4]. Figure 3 presents the data

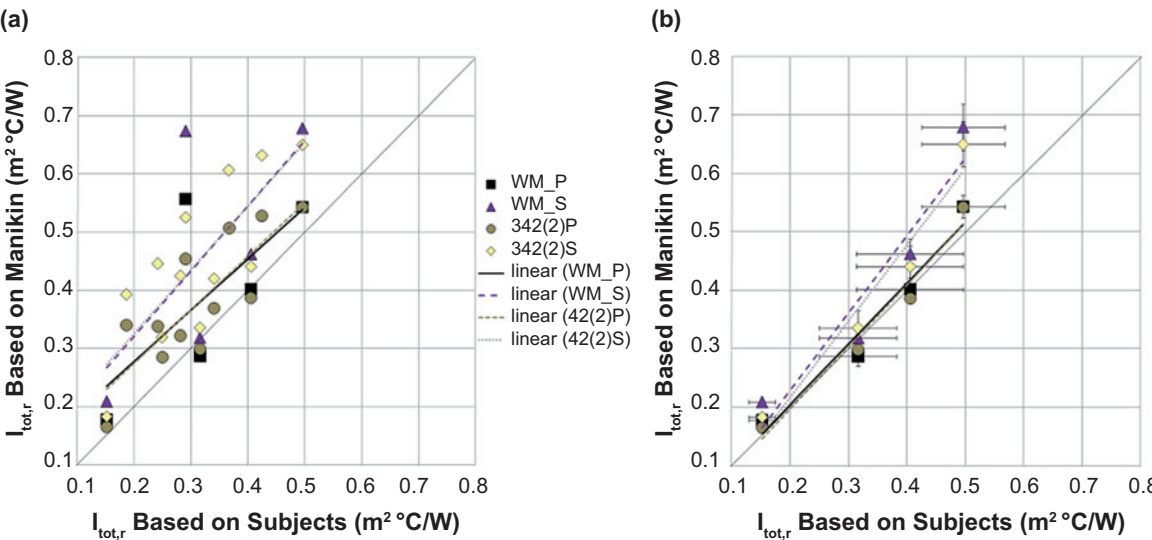


Figure 1. Regression analysis of (a) all involved data, (b) all data without conditions of heavy and medium sweating and uneven insulation. Notes. The values of total resultant clothing insulation ($I_{tot,r}$, $m^2 \cdot ^\circ C/W$) from the subjects were based on heat balance analysis. WM_P, WM_S—values acquired on walking manikin according to standard test for parallel and serial calculation, respectively; 342(2)P, 342(2)S—values based on static tests and calculations according to Equation 2 in Standard No. EN 342:2004 [4] using the same air and walking velocity as the subjects had, for parallel and serial calculation, respectively. Linear regression lines correspond to each specific method of acquiring the insulation.

of a walking manikin that had best fit (parallel) with human data compared to the results from static tests and corrected for wind and motion according to Equation 2 in Annex C of Standard No. EN 342:2004 [4] and Equation 35 in Standard No. ISO 9920:2007 [8]. Both corrections resulted in a good match. However, we did not study the effect of clothing design. All ensembles were modern trousers-jacket systems (except for the lightest ensemble, which was a coverall). In the case of traditional clothing such as long coats and female ensembles with long skirts, predictions

should be made carefully as the effect of ventilation due to motion and wind is most probably different.

Standards No. EN 342:2004 and EN 14058:2004 use the same measuring principles and calibration garments [4, 26]. In the case of even insulation, the difference between the serial and parallel methods is relatively small and proportional with slightly higher insulation resulting from the serial method. However, with more insulation layers overlapping in heavy cold protective ensembles the difference increases,

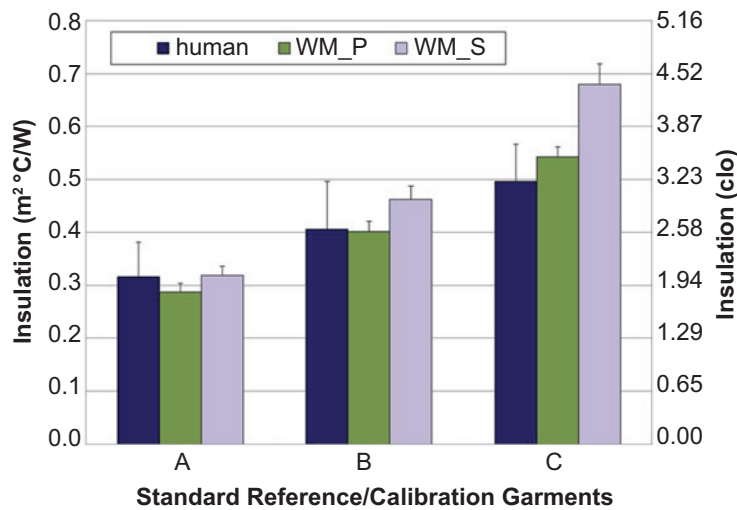


Figure 2. Comparison of insulation resulting from human subject tests and walking manikin tests. Notes. The comparison is for Subzero garments A, B, and C. WM_P—parallel calculation, WM_S—serial calculation. A and B are also the standard reference calibration ensembles in Standard No. EN 342:2004 [4].

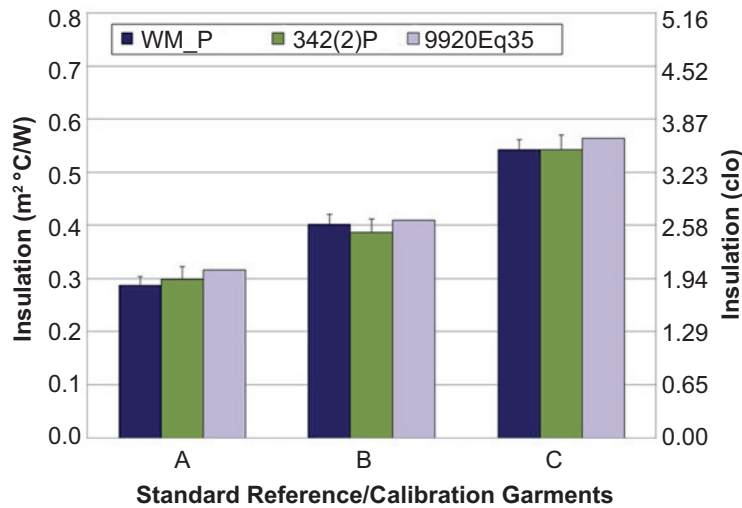


Figure 3. Comparison of insulation resulting from parallel values of walking manikin tests and static values. Notes. WM_P—value from walking manikin tests, 342(2)P—static values corrected for wind and motion according to Equation 2 in Standard No. EN 342:2004 [4], 9920Eq35—static values corrected for wind and walking according to Equation 35 in Standard No. ISO 9920:2007 [8].

and may not follow the linear relationship any more. The calibration ensembles are selected to represent proper cold protective garments. Thus, if a garment piece does not represent a proper element of a cold protective ensemble, e.g., it has a faulty design or manufacturing error, it is a thick single jacket or trousers with reference ensemble R (uneven insulation) [4], etc., the results may lead to wrong recommendations.

3.4. Additional Support for Parallel Method From Other Studies or Requirements

Research in Russia has a long tradition of measuring insulation on human subjects. Afanasieva, Bessonova, Burmistrova, et al. tested four ensembles with insulation similar and slightly higher than ensemble C of the SUBZERO project [1, 15, 22, 24, 29, 30] on human subjects and compared their results to manikin results [37]. In that comparison the parallel method gave results more similar to human testing than the serial one.

In their study on cold risks, Afanasieva, Bobrov, and Sokolov showed the requirements for cold protection in various climatic regions of Russia [38]. For a 2-h exposure to -25°C , they recommended using similar insulation as calculated with the parallel method for ensemble C of the SUBZERO project [1, 15, 22, 24, 29, 30]. The same recommendation can result from the calculation of required insulation [7]. Simultaneously, the insulation of the same ensemble resulting from the serial method would allow working with a metabolic rate of 130 W/m^2 for 2 h at -41°C [38].

Lee et al. compared and validated the serial and global method (or parallel, as in Standard No. EN ISO 15831:2004) [8] against human studies [12]. They measured the insulation of 26 clothing ensembles on manikins and human subjects. The sample covered a wide range of clothing ensembles up to ones with similar insulation like ensemble A mentioned in the SUBZERO project [22]. However, that means that there were no garment sets corresponding to cold protective clothing according to Standard No. EN 342:2004 [4]. From light summer to ordinary winter (cool weather) clothes, the study showed

agreement between the global method and human results, while the serial method proved unsuitable for estimating human responses. Global insulation values resulting from manikin tests were always lower than the results from human tests. Considering the additional insulation of a wooden chair for seated subjects, while the manikin was standing, it may be expected that under similar posture and insulation conditions the global values would have been even closer to human results, thus, supporting fully the results of this analysis on walking manikins and human subjects.

Based on those results, we can assume that in some cases the parallel method overestimates cold risks; however, it is always possible to open up the clothes. If the serial method underestimates risks, it is much more difficult to add something, especially if a person is outdoors for up to 8 h or even longer.

Holmér, Gao, and Wang studied insulation measurements taken on an electrically heated vest [39]. Adding 10 W in total to certain measuring zones increased the result of the serial method to impossible 83 clo ($12.9\text{ m}^2\text{C/W}$). It may be argued that manikin tests are not meant to measure clothing with auxiliary heating. However, what happens if the components of an ensemble use smart textile technology that affects the results in a similar way? A standard should prevent producing unrealistic results.

4. CONCLUSIONS

1. Differences between the values of dynamic insulation, and static insulation corrected for wind and walking are small, while static values are more flexible for predicting a variety of conditions.
2. In all observed conditions, parallel values gave a better fit than serial ones over the range of insulation levels.
3. Uneven distribution of insulation, especially layers overlapping in clothing for extreme cold protection, may cause higher insulation values in the serial method. That may put people at higher risks when serial insulation values are used for predicting and modelling.

4. The serial model should not be used despite good correlation with standard cold protective clothing with relatively even insulation distribution. However, any clothing outside the expected standard clothing definition may produce deviating values, which a standard should avoid.
5. The parallel method is rational and proven to fit well with subject data, and should be used in international standards.

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