Thermal Insulation of Clothing: Assessment of Cleanroom Clothing Ensembles

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ABSTRACT

In cleanrooms, the thermal optimization is not always possible, thus the suitable selection of clothing is important to achieve thermal comfort. In the case of specific cleanroom clothing, the values of thermal insulation are not specified in standards ISO 7730 and ISO 9920, and the use of casual ensembles instead would cause unreliable results. This study is focused on the thermal insulation assessment of four cleanroom clothing ensembles used for ISO 7 cleanrooms by means of a thermal manikin according to ISO 15831. The impact of the thermal insulation on the thermal satisfaction of users and the optimal comfort temperatures were also predicted. The results showed variations in the thermal insulation of the ensembles (ΔI_t = 0.3 clo) which are responsible for differences in the thermal sensation of the environment (PMV) and in the optimal comfort temperature (Δt_a = 3 °C). The outcomes of this research should improve the quality of the indoor environment of cleanrooms and ease the design and efficient cleanroom operation.

INTRODUCTION

Thermal environment in cleanrooms

Thermal comfort, together with other determining factors of the Indoor Environmental Quality, affect the level of satisfaction of occupants, their health but also their work productivity. In cleanrooms, the thermal comfort of occupants is often put aside in favour of the cleanliness. As the previous study (Roškotová, 2020) highlighted, the cleanroom environment is not designed preferentially to provide the suitable working environment, and thus the higher dissatisfaction with the environment is likely. The indoor environment of cleanrooms is fundamentally influenced by the required class of cleanliness according to ISO 14644-1 (2015) and the associated air distribution system. Moreover, temperature and relative humidity are tied to the requirements of ongoing processes and installed technologies and not to users' needs. This is also supported by EU GMP Annex 1 (2008) which states that temperature and relative humidity depend on the product and the type of ongoing operations and by these variables the cleanliness should not be affected. Frequently, these variables are tightly controlled by precise air conditioning, and as the study of Roškotová (2020) explained, the thermal conditions often do not correspond with the performed activity of users and clothing requirements.

In general, most cleanroom studies focus on the environment of operating theatres and assess the thermal comfort of surgeons, nurses and/or anaesthesiologists. However, as Mora et al. stated (2001), in these applications, unlike in offices, the thermal comfort is only a secondary consideration. Still, the best possible conditions must be ensured for the operating staff to enhance the success of the surgery. The study of Mazzacane et al. (2007) pointed out the difficulty in meeting the thermal expectations of all operating staff due to different activity levels and clothing. As a priority, the thermal conditions are maintained to achieve the suitable environment for the patient (Melhado et al., 2006) and result in shorter surgery recovery time (Hwang, 2006).

Among other applications, the thermal comfort is hardly considered or analysed. Due to the fact that the temperature optimisation in cleanrooms is often not possible, the cleanroom users are forced to take some adaptive actions to increase their thermal comfort and overall well-being. Although the simplest and probably the most effective action is the change in the clothing layers, in cleanrooms, the inappropriate choice of clothing or material may present a significant threat to the desired cleanliness (Roškotová, 2021). Some materials, such as cotton, are not appropriate for use in these applications due to the spontaneous release of particles, and thus become a potential threat to the desired cleanliness.

Cleanroom clothing

In general, the most common and the greatest source of contamination origins from cleanroom users, thus this type of clothing acts as a barrier filter to protect the cleanroom products and technologies from human contamination (Useller, 1969). The contaminants are not only brought into the room by the entrance of users, but are also generated by people inside the cleanroom due to their movement and behaviour, as well as body processes (Useller, 1969). To ensure the greatest efficiency, the correct design, material and size of the clothing should be considered.

The typical cleanroom clothing consists of a coat or two-piece suit or one-piece coverall and accessories such as gloves, face masks, shoe covers or overboots. Nevertheless, the actual combination of items depends on the class of cleanliness. There are few guidelines such as the IEST-RP-CC003.3 (IEST, 2011) or EU GMP Annex 1 (2008) that assess the necessity of cleanroom garments and make recommendations for different classes of cleanliness.

Clearly, the higher the class of cleanliness is demanded, the more complex clothing concept with increased technical requirements is essential (ISO 14644-5, 2004). Unfortunately, the need of high coverage clothing with special properties in critical applications may result in frequent discomfort of users due to personal restrictions and thermal dissatisfaction (ISO 14644-5, 2004) due to different thermal insulation (Roškotová, 2020). Unfortunately, this fact is very often not considered during the cleanroom operation. Additionally, the materials used for cleanroom clothing are often a great barrier to moisture, therefore, are very uncomfortable for long use. Results of Zwolinska's study (2012) revealed the similarity of cleanroom clothing to chemical protective clothing in terms of limited heat exchange and moisture transport between the human skin and environment.

According to the standard ISO 14644-5 (2004), not only the barrier properties against dispersed contamination but also the thermal comfort whenever is possible should be considered when choosing cleanroom garments and clothing materials. In reality, the prescribed sets of cleanroom clothing frequently do not reflect the thermal conditions and result in the thermal discomfort of the occupants. On the contrary, Uścinowicz et al. (2015) mentioned the importance of designing the HVAC system to provide the maximum available thermal comfort for each staff and type of clothing. On behalf of the individual applications and their requirements, this is not always possible.

Thermal insulation of cleanroom clothing

Besides the known environmental conditions and the level of activity, the occupants' clothing and its properties are essential for the thermal perception of the environment. The thermal properties of clothing significantly affect the heat balance of the organism, thus also the level of thermal satisfaction of occupants. Without the known and correctly determined values of the thermal insulation, the effect of clothing on the heat balance is skewed and the thermal comfort assessment is not reliable. Moreover, the optimal temperatures for the satisfaction of occupants cannot be determined.

In the case of cleanroom clothing, unfortunately, the values of the thermal insulation for these specific ensembles cannot be found in the widely used international standards ISO 7730 (2004) and ISO 9920 (2007). Only, the thermal insulation can be estimated based on the selected casual ensembles or as a combination of individual garments available in the standards, which clearly make the thermal comfort assessment unreliable. Skoog et al. (2005) in the study of thermal environment in hospitals acknowledged that the incorrect identification of clothing thermal insulation can be the reason for misleading results.

Despite many studies focused on the thermal comfort in operating theatres, the method of determining the thermal insulation of the particular clothing was frequently not stated, and the boundary conditions were often unknown or unclear. Thus, the reliability of these results can be questioned. Moreover, it was found out that the description of the clothing and the material of the clothing was often not published in these studies.

In fact, there are only two other options to determine the thermal insulation: by means of a thermal manikin or by testing the thermal properties of textile materials. The latter is a much easier method of the assessment of flat textiles designed for cleanroom clothing and can be measured with the use of e.g., Alambeta or Permetest devices (Matusiak, 2016). However, as Matusiak et al. (2016) presented, this method does not consider the air layer between the skin and the inner surface of clothing or the air layer between two layers of clothing.

The measurement by means of the thermal manikin based on the simulation of the heat exchange between the human body and the surrounding environment is not commonly applied for regular testing of clothing due to high investment costs and time-consuming experiments, and thus is used only for special clothing systems with protective properties (Matusiak, 2016). Despite the high accuracy, there are the following possible difficulties with this method that can lead to unreliable and vague results:

- Unsteady-state conditions of the manikin
- Non-uniform ambient conditions in the climatic chamber
- Wrong size of clothing
- Unsuitable control mode of the manikin
- Unsuitable calculation method of the thermal insulation

Determination of the thermal insulation properties of clothing by this precise method would improve the quality of the indoor environment of cleanrooms and help a better cleanroom design and operation. This study is focused on the thermal insulation assessment of various cleanroom clothing ensembles for the class of cleanliness ISO 7 with the use of the thermal manikin. The impact of the thermal insulation on the thermal satisfaction of users and the optimal comfort temperatures was also predicted. Cleanrooms operated as ISO 7 are the most frequently designed cleanrooms, however, the requirements on the used cleanroom clothing can significantly differ. Therefore, the outcomes of this study should cover the variations among different applications of ISO 7 cleanrooms.

METHODS

Clothing ensembles

For the purpose of this study, four frequently used cleanroom clothing ensembles for class ISO 7 were selected to be tested on the standing manikin placed inside the climatic chamber. These sets represent the most prescribed ensembles in this class of cleanliness. The ensembles A and B (details below) are also often used in the class ISO 8 and the ensemble C can be found in the class ISO 6, especially with the addition of the face mask. Selected ensembles differ in the type of the upper garment but also in the undergarments and the selected accessories such as the beard cover or gloves. The size of each garment was selected to fit the thermal manikin and to avoid the creation of misleadingly large air layers. A description of the tested clothing ensembles is provided below and the ensembles are displayed in Figure 1.

- Ensemble A - coat 3/4 of length (PES), street clothing (short-sleeved T-shirt (C), trousers (C)), short underpants (C) + socks (C), hair cover (NW), shoe cover (NW)
- Ensemble B - two-piece suit (PES), street clothing (short-sleeved T-shirt (C), trousers (C)), short underpants (C) + socks (C), hair cover (NW), shoe cover (NW)
- Ensemble C - coverall (PES), long undergarments (long-sleeved T-shirt (PP/C), trousers (PP/C)), short underpants (C) + socks (C), hair cover (NW), beard cover (NW), shoe cover (NW), gloves (N)
- Ensemble D - coverall (PES), short underpants (C) + socks (C), hair cover (NW), beard cover (NW), shoe cover (NW), gloves (N)

Abbreviations: (C) - cotton; (N) - nitrile; (NW) – nonwovens, disposable; (PES) - 98% polyester + 2% antistatic fiber, 100 g/m^2; (PP/C) - knitted fabric polypropylene/cotton with silver ion content.

Ensemble A Ensemble B Ensemble C & D

Figure 1. Assessed cleanroom clothing ensembles (ensembles C & D differ in the undergarments)

All garments were placed inside the climatic chamber for conditioning at least 12 hours prior to the experiment.

Thermal manikin and thermal insulation assessment

The assessment of the thermal insulation of cleanroom clothing was conducted with the use of the stationary Newton thermal manikin with 36 independently heated zones. Measurements were taken in accordance with the standard ISO 15831 (2004). The manikin was operated in the constant (uniform) surface temperature mode. In this control mode, the same required surface temperature of 34 ± 0.2 °C was applied to all zones. Based on the control mode, the heat flux was not controlled, however, the maximum change during each cycle was set to ± 2 %.

The steady-state conditions were maintained for 2 x 30 minutes in each measurement. To calculate the total thermal insulation of the clothing ensemble, the most suitable interval in terms of homogeneity was selected and the parallel method from ISO 15831 (2004) was applied (1).

$$I_t = \frac{\left(\left(\sum \frac{A_i}{A} \cdot T_{si}\right) - T_a\right) \cdot A}{0.155 \cdot \sum H_{ci}} \qquad (1)$$

where:
I_t is the total thermal insulation of clothing [clo], A_i is the surface area of segment i of the manikin [m^2], A is the surface area of thermal manikin [m^2], T_{si} is the local surface temperature of segment i [°C], T_a is the air temperature in the surrounding of the manikin [°C] and H_{ci} [W] is the local heat loss from segment i of the manikin.

Measurement of each clothing ensemble was repeated twice. The measurement was valid when the maximum difference between the results of the total thermal insulation from two cycles was not greater than 4 %. Then, the total thermal insulation was calculated as the average of both cycles.

To understand the real effect of clothing on the body heat balance, the basic (intrinsic) insulation was calculated from Equation (2) by subtracting the ratio of the surface air layer to the clothing area factor (f_{cl}) from the total insulation.

$$I_{cl} = I_t - \frac{I_a}{f_{cl}} \qquad (2)$$

where:
I_{cl} is the basic (intrinsic) thermal insulation of clothing [clo], I_t is the total thermal insulation of clothing [clo], I_a is the thermal insulation of the surface air layer [clo], f_{cl} is the clothing area factor [-].

The clothing area factor was calculated using the following Equation (3) from the standard ISO 9920.

$$f_{cl} = 1 + 0.28 \cdot I_{cl} \qquad (3)$$

where:
f_{cl} is the clothing area factor [-], I_{cl} is the basic (intrinsic) thermal insulation of clothing [clo].

In addition, the effective thermal insulation was calculated to understand the effect of the clothing ensemble without the surface air layer in a comparison to the nude state.

$$I_{cle} = I_t - I_a \quad (2)$$

where:
I_{cle} is the effective thermal insulation of clothing [clo], I_t is the total thermal insulation of clothing [clo], I_a is the thermal insulation of the surface air layer [clo].

The thermal insulation of the surface air layer was determined by the measurement with the nude manikin in the same environmental conditions. This measurement was made as the initial part of the experiment and the results were used for all clothing ensembles.

Climatic chamber and testing conditions

All experiments were carried out in the climatic chamber with controlled environment. Dimensions of the chamber are 4.4 m x 3.1 m x 2.9 m. The following conditions were maintained:

- Air temperature: 20.7 ± 0.2 °C
- Relative humidity: 50 ± 10 %
- Air velocity: 0.05 ± 0.01 m/s

The maintained air velocity was intentionally lower than the velocity stated in the standard ISO 15831 (< 0.4 m/s) due to the mixed-flow type of the air distribution system. With higher air velocity, the homogenous conditions would not have been achieved. Moreover, the stated air velocity is too high even in cleanrooms, where high air velocity is common.

The environmental conditions and their changes in the manikin's surroundings were monitored by two temperature sensors, a humidity sensor, a globe temperature and the air velocity probe. The sensors were placed at the height of 1.1 m and 1.7 m respectively. Additional sensors (temperature sensors, surface temperature sensors, a humidity sensor, globe temperature sensors and another air velocity probe) were installed to help with the achievement of the required environmental conditions prior to the experiment but also to monitor the conditions during the experiment.

RESULTS

The results of the thermal insulation assessment showed the variations in the total thermal insulation of different clothing ensembles. The measurement of each ensemble was repeated twice as the tolerances of the results were below the required maximum possible difference, thus the experiment can be assessed as accurate. The comparison of results from both cycles for each ensemble is displayed in Figure 2. The lowest difference was found for the Ensemble C.

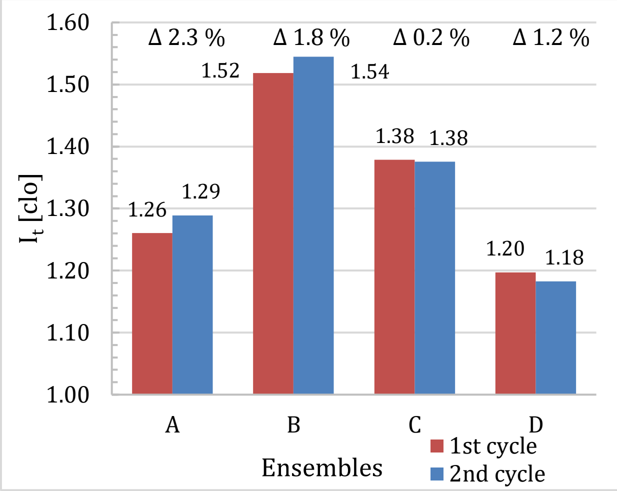

Figure 2. Differences in the results of I_t

Generally, when testing clothing ensembles, the differences in results from different cycles are caused by the variations in the environmental conditions (air velocity, air temperature etc.), by the slightly different posture of the manikin and by the occurrence of new or modified air layers. Due to the necessity to take off and put on the clothing ensemble again before all measuring cycles, the position of the clothing and individual garments can be modified and result in the increase or the reduction of the existing air layers or the occurrence of the new one. Nevertheless, this step helps to increase the overall accuracy of the clothing assessment by simulating the real use of the clothing when the position of layers each time may slightly vary.

According to Figure 3, the lowest value of the total thermal insulation was found out for the Ensemble D and the highest thermal insulation was assessed for the Ensemble B. Surely, the absence of the undergarments is responsible for the low thermal insulation. In comparison, the total thermal insulation of the Ensemble C representing the same set of clothing as the Ensemble D but with the undergarments was higher by 16 %.

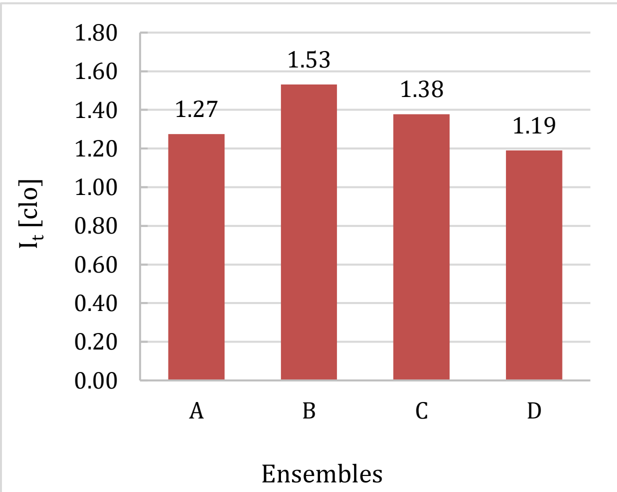

Figure 3. Results of the total thermal insulation of clothing I_t

Notably, the thermal insulation of the Ensemble B was higher than the insulation of the Ensemble C which was unexpected. Firstly, it might be caused by the different type of undergarments, and thus different thermal insulation. However, this statement can be examined by a new assessment only. Secondly, the two-piece suit might be also responsible for the high insulation due to the loose fit of clothing that does not require to tuck the suit in. Therefore, larger air layers between the clothing layers compared to the tight fit of the coverall in Ensemble C can be created. According to the standard ISO 15831 (2004), the thermal insulation of the air layers is much higher than the thermal insulation of the textile material (Matusiak, 2016).

Table 1 shows the results of the basic and effective clothing insulation of all ensembles. Based on the aforementioned Equation (3), the higher the total thermal insulation I_t, the higher the clothing area factor f_{cl}. Consequently, the basic thermal insulation varies accordingly. The difference caused by undergarments (Ensemble C and D) was increased up to 34 %.

Table 1. Results of the basic and effective clothing insulation

Ensemble	I_t [clo]	I_a [clo]	I_{cle} [clo]	f_{cl} [-]	I_{cl} [clo]
A	1.27	0.68	0.59	1.20	0.71
B	1.53	0.68	0.85	1.28	1.00
C	1.38	0.68	0.70	1.23	0.82
D	1.19	0.68	0.51	1.17	0.61

DISCUSSION

Considering the results, it is possible to conclude that even within the same class of cleanliness, clothing ensembles with various thermal properties can be found. The major reasons for the differences in the thermal insulation are different types of clothing garments resulting in different coverage of the body and different textile properties. As a consequence, a different level of thermal satisfaction of occupants can be expected.

In Figure 4, the impact of four different clothing ensembles on the thermal satisfaction of users was predicted for five different air temperatures and the same other environmental conditions (air temperature = mean radiant temperature, air velocity = 0.15 m/s, relative humidity = 45 %). To evaluate the thermal comfort of users, the Predicted Mean Vote index (PMV) was used. The neutral thermal sensation indicating the thermal comfort of the cleanroom users is found within the range of PMV = ± 0.5. Low thermal insulation, such as the insulation of the Ensemble D, results in a slight discomfort in the cold environment (18 °C). In contrast, at the temperature of 24 °C, the only clothing ensemble within the comfort range is the Ensemble D. Cleanroom users dressed in other ensembles would end up with the discomfort caused by too high temperatures. Overall, all selected clothing ensembles ensure the thermal comfort at temperatures of 20 and 22 °C.

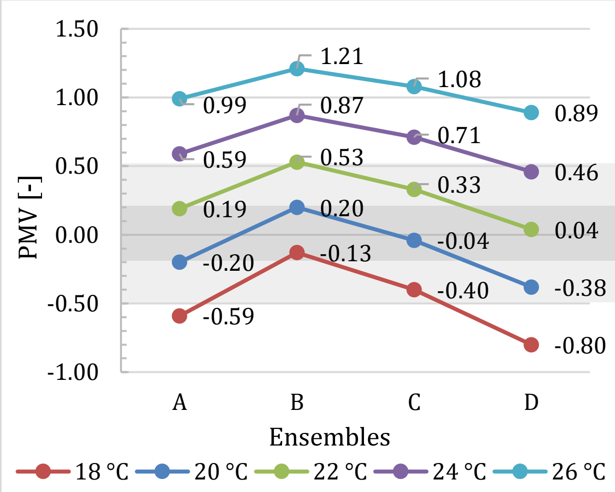

Figure 4. Changes in the PMV index for ensembles in environments with different temperature; PMV < 0.5 (light grey), PMV < 0.2 (grey)

With the known thermal insulation, the optimal (comfort) temperature for each clothing ensemble was determined and the results are displayed in Figure 5. For higher air movements and higher activity levels, as Havenith and Nilsson declared in their study (2004), the correction of clothing insulation (ISO 9920, 2007) should be applied to obtain reliable results.

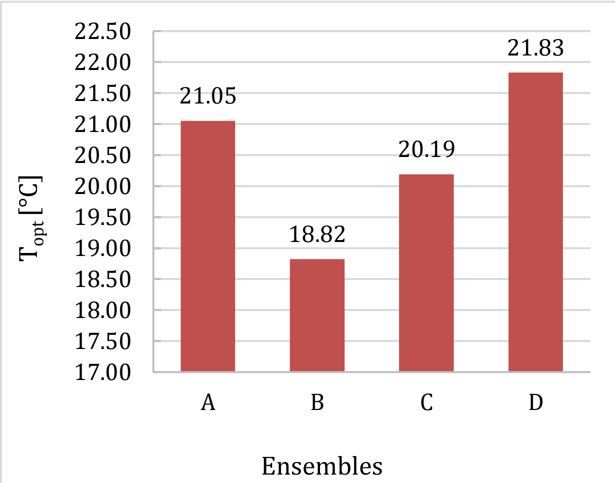

Figure 5. Optimal temperatures for each clothing ensemble

The analysis of the thermal comfort showed the overall thermal sensation of cleanroom occupants as well as the designed optimal temperatures to meet the neutral thermal sensation, however, these results do not consider the risk of local discomfort caused, e.g. by draught. Although the PMV is calculated as neutral, the perception of the environment on some parts of the body (e.g. a head or hands) may be different due to higher or lower local thermal insulation and may affect the overall perception of the environment. In some cases, it might be beneficial to create the comfort zones diagrams (Nilsson, 2004) and assess the perception of each zone of the body individually.

With the suitable choice of clothing ensembles, the thermal comfort improvement is possible even in cleanroom applications where the thermal optimisation is not always feasible. In reality, the selection of various clothing sets for a particular class of cleanliness is rarely available, and the cleanroom users cannot choose the alternative when poor thermal conditions occur. Naturally, it is possible to use a garment required for higher cleanliness in lower classes of cleanliness. For example, a coat can be replaced by a coverall with higher thermal insulation when the environment is evaluated as colder than the optimum. This replacement might also have a positive effect on the perception of draught and reduce the number of particles generated by cleanroom users. However, the financial costs have to be also considered. In fact, the most difficult is to satisfy high temperatures as there are not many lighter alternatives to the materials used.

Also, the type of clothing worn under the cleanroom clothing, the cleanroom undergarments, will improve not only the dispersion rate of particles but also the level of thermal satisfaction. These undergarments represent the easiest solution to achieve the thermal comfort.

CONCLUSIONS

With the development of modern technologies, the range of cleanroom applications goes beyond the healthcare sector or space industry, and the need for cleanrooms is still rising. Despite the wide automatization, people still play an important role in the cleanroom operation. Considering the fact that people present the major source of contaminants, their well-being should receive more attention as the inappropriate behaviour caused by dissatisfaction may significantly influence the cleanroom operation.

Given the thermal dissatisfaction, the sets of cleanroom clothing do not reflect the actual thermal conditions and needs of users. Moreover, clothing differs for each class of cleanliness, but the thermal conditions do not change appropriately. Thermal insulation of cleanroom clothing not included in the standards ISO 7730 or ISO 9920 makes the thermal comfort assessment difficult. With the current absence of the known thermal insulation of cleanroom ensembles, it is now necessary to evaluate the thermal comfort with the estimation of the thermal insulation, which, however, cause a considerable inaccuracy. The casual ensembles available in the standards cannot represent the specific cleanroom clothing. Thus, a more precise method of determining the thermal insulation with the use of a thermal manikin is needed.

Based on the fact that the cleanroom clothing differs with each class of cleanliness and the thermal insulation alike, one value of thermal insulation of cleanroom clothing is not sufficient to cover the properties of cleanroom clothing in general. Determination of the thermal insulation properties of clothing by means of a thermal manikin would improve the thermal comfort assessment and the quality of the indoor environment of cleanrooms, and also help with the cleanroom design and efficient operation. Despite the benefits and the high accuracy, the investments and operating costs are responsible for the limited applicability of this method.

This study showed the variations in the thermal insulation of cleanroom clothing ensembles that reflect the layers of garments and their cuts and materials. Within the same class of cleanliness, clothing ensembles with various thermal properties were found resulting in differences in the optimal comfort temperatures up to 3 °C between ensembles. Consequently, a different level of thermal satisfaction of users dressed in different clothing ensembles can be predicted within the same environment. However, as the temperature optimisation is not always possible in cleanrooms, the easiest option to improve the thermal comfort is to provide alternative sets of clothing with different thermal properties. Simultaneously, this measure would avoid the increased contamination by preventing the inappropriate users' choice of clothing. With the suitable choice of clothing ensembles, the thermal comfort improvement is possible even in applications with precise air conditioning.

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