STANOVENÍ VLASTNOSTÍ ODĚVŮ POMOCÍ TEPELNÝCH MANEKÝNŮ

CLOTHING PROPERTIES MEASUREMENT USING THERMAL MANIKINS

Róbert Toma[a]*, Kalev Kuklane[b], Jan Fišer[a], Miroslav Jícha[a]

[a] Brno University of Technology, Technická 2, 616 00 Brno, Czech Republic
[b] Lund University, Sölvegatan 26, 22100 Lund, Sweden
[*] *Corresponding author. e-mail: Robert.toma@vutbr.cz, tel.: +420 770 127 934*

Abstrakt

Při použití speciálních ochranných oděvů dojde často k omezení odvodu tepla z lidského těla, konvekcí, radiací ale hlavně omezením vypařování potu z pokožky, díky čemu může dojít k jeho přehřátí. Právě kvůli ochraně zdraví člověka při práci v speciálních oděvech jsou vyvíjeny predikční modely tepelné zátěže a fyziologie do kterých je nutno tyto skutečnosti zahrnout, a to v podobě parametrů oděvů pracovníka. Jedním z důležitých parametrů oděvů je výparný odpor, který charakterizuje schopnost oděvu propustit vodnou páru a tím nepřímo vyjadřuje také to, do jaké míry bude omezeno vypařování potu z pokožky. Výhodou měření této veličiny pomocí simulace pocení na tepelných manekýnech je zahrnutí tvaru lidského těla, a tedy i vzniklých vzduchových mezer v oděvné sestavě. V tomto příspěvku je shrnuta metodika simulace pocení na „suchém“ tepelném manekýnovi za použití před vlhčené pokožky manekýna, následně její aplikace v praxi a proměření jedné oděvné sestavy.

Klíčová slova: *výparný odpor, tepelný manekýn, ochranné oděvy,*

Abstract

Heat transfer from human body through convection, radiation and mainly through sweat evaporation from skin is often restricted when protective clothing is used, which may result in human´s body overheating in certain cases. Thus, it is important to include these restrictions into heat strain or physiological predictive models, such as PHS, as an input data in the form of clothing parameters. Purpose of the predictive models is to protect human´s health and to predict a maximum exposure time while using protective clothing. With regards to clothing thermal properties, the most important are thermal insulation and evaporative resistance, which characterize the ability of clothing ensembles to allow heat and vapor to go through the clothing layers and air gaps. This also indirectly defines the level of sweat evaporation restriction from the skin. The main advantage of measuring these values by means of thermal manikins is that it takes into consideration the shape of a human body, and thus also air layers and the design of the measured clothing. Following topics are discussed in this paper - the methodology of thermal insulation and evaporative resistance (using pre-wetted skin) measurement on dry thermal manikin and its application on two clothing ensembles for pesticide spraying and harvesting on sugarcane fields in Latin America.

Key words: *evaporative resistance, thermal manikin, thermal insulation, protective clothing*

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1. INTRODUCTION

As it is important to protect humans´ health, thermo-physiological predictive models are often used to calculate maximum exposure in given environment without their endangerment. Nowadays, more importance is given to this area of research as global warming and environmental changes are one of the most discussed issues around the world.

It is known that evaporation is the main thermoregulatory feature for a heat dissipation from the human body to the environment. Physically demanding jobs (e.g. firefighters, field workers) may be carried out in hot working environments. In such conditions a less permeable and often too insulated protective clothing is being used. This could result in reduction of sweat evaporation from human skin leading to an elevated skin temperature, core temperature or sweat rate [1]. This, together with insufficient water replacement and relaxation period, could in long term lead to work related disorders and multiple serious diseases, e.g. Chronic Kidney Disease (CKD). Those are the reasons why the heat stress prediction models (e.g. PHS) and thermo-physiological prediction models [2, 3] also contain clothing properties as one of the most important input data. Therefore, the clothing parameters should be measured with highest precision and accuracy possible to mitigate some errors in these predictions. Thermal manikins are the most realistic available option for measuring clothing parameters at the moment. Thus, a thermal manikin was used to obtain clothing properties of two ensembles used in sugarcane fields in Latin America in this study.

2. METHODS

2.1 Study design

The aim of this study was to identify reliable and applicable method for measuring evaporative resistance on thermal manikin and to determine clothing properties of two chosen ensembles with aim to use obtained data as an input to physiological prediction models, such as PHS. Tested clothing ensembles were obtained from a company, which provides protective clothing used by workers in real conditions on the sugarcane fields in Latin America, where warm and very humid weather is common. Sugarcane cutters (SC) and pesticide sprayer (CS) outfits were measured as those are the two most common types of work while cultivating sugarcane fields (Figure 1 a-d). The large size was chosen as those garments fit the manikin best out of available range.

The two most important clothing parameters for heat stress predictions, namely thermal insulation and evaporative resistance were measured using 17-zone thermal manikin TORE [4] at Lund University, Sweden (Figure 1).

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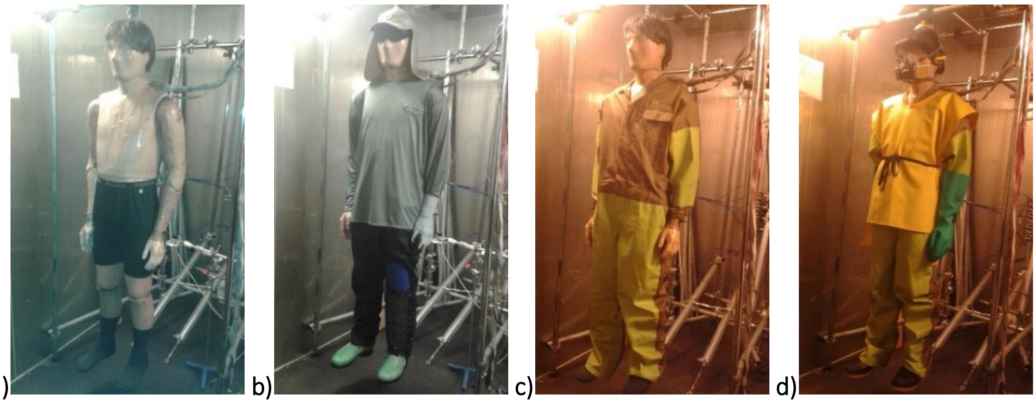
Figure 1: Tested clothing: a) underwear for both systems (provided by the laboratory); b) sugarcane harvester's outfit (glove only on one hand and leg protector on one leg); c) chemical sprayer's protective coverall on top of underwear; d) chemical sprayer's complete outfit with outer protective layers

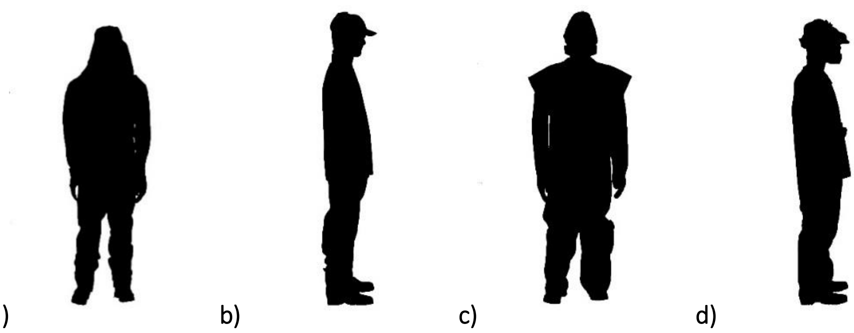


a) b) c) d)

2.2 Thermal insulation (I_t) measurement methodology

The thermal manikin was placed inside the climate chamber in the standing upright posture with hands down (Figure 1a) as this posture is typically reported and used in literature. Manikin´s surface temperature was set to 34°C. The ambient temperature was set and maintained at 20.0±0.1 °C (average of three temperatures measured at 0.1, 1.1 and 1.7m above the floor level) with 0.21±0.08 m/s air velocity to the manikin´s back (measured at 1.1m above the floor level) and air relative humidity inside the chamber was maintained between 30-60%. All parameters were set within the ranges stated in the standard ISO 9920 [5]. Both static thermal insulation I_t and dynamic thermal insulation $I_{t,r}$ with walking speed around 3.5 km/h (step rate set at 90 steps/min) were measured. Static thermal insulation was also measured for manikin´s skin used later for evaporative resistance measurements. Clothing area factor f_{cl} was also determined by photographic method using photos from two positions – 0° (front side of the standing manikin – Figure 2a,c) and 90° (right side of the standing manikin – Figure 2b,d). Thus, this allowed us to calculate intrinsic thermal insulation I_{cl} and resulting intrinsic thermal insulation $I_{cl,r}$ according to equation (7) in ISO 9920 standard.

Figure 2: Clothing area factor: a) SC - sugarcane cutter´s outfit 0°; b) SC - sugarcane cutter´s outfit 90°; c) CS - chemical sprayer's outfit 0°; d) CS - chemical sprayer's outfit 90°



a) b) c) d)

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2.3 Evaporative resistance (R_{et}) measurement methodology

As TORE manikin does not have any built-in sweating system for evaporative resistance testing, pre-wetted skin was used for sweating simulation [6]. The tight fit skin (d= 0.9 mm, 95 % CO, 5 % EL) covered whole manikin body except hands and feet. For sweating simulation on these body parts gloves (100 % CO) and socks (socks, 67 % CO, 30 % PES, 3 % EL) were used. Before every test, the skin was wetted and contained about 975g of water with no dripping occurring.

It was previously reported that measuring evaporative resistance in non-isothermal conditions ($T_{manikin} \neq T_{ambient} \neq T_{sk}$) may cause significant error as clothing dry insulation changes dramatically with absorbed moisture and so, isothermal conditions should be used [7, 8]. However, we were not able to setup isothermal conditions ($T_{manikin} = T_{ambient} = T_{sk}$) for our thermal manikin as we are only able to control manikin´s surface temperature and not the wetted skin temperature. Thus, so-called isothermal ($T_{manikin} = T_{ambient} \neq T_{sk}$) were used instead.

The thermal manikin was placed inside the chamber in the same upright posture and on the same place as in previous case of insulation measurements. However, whole manikin system was placed on weighting scale to monitor mass loss throughout the measurement (applies only for one of the three measured repetitions). Both thermal manikin´s surface temperature and ambient temperature were set on 34°C to ensure so-called isothermal conditions [9, 10]. Relative humidity was maintained below 50% to provide good water evaporation from manikin´s wetted skin. The air velocity was raised compared to thermal insulation tests to 0.54±0.16 m/s to ensure even distribution of relative humidity inside the chamber. Evaporative resistance was only measured in static conditions as the measurement setup with weighing scale did not allow walking stand to be used.

2.4 R_{et} calculation

There are two calculation methods for clothing evaporative resistance provided in ASTM standard from 2010 [11] – mass loss method and heat loss method. Mass loss method was removed from new version of this ASTM standard [12]. The reason behind it was probably the challenging aspect to use the mass loss method for calculating of localized values for separate body parts which were added in this new ASTM standard [12], and to diminish the discrepancies in measuring results between the laboratories caused by the use of different measuring and calculation methodology. According to Wang et al. [9] exclusion of mass loss method was not the right decision as this method is inherently correct from a physical point of view. Both mass loss method and heat loss method were used for calculation of whole body total evaporative resistance in our study.

2.5 Heat loss method

Evaporative resistance by heat loss method is calculated from area-weighted heat loss observed from thermal manikin software. According the ASTM standard [12], the evaporative resistance should be calculated from equation (1) from manikin´s surface temperature as it assumes that isothermal conditions are used ($T_{manikin} = T_{sk}$).

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$$R_{et,heat} = \frac{(p_{sk} - p_a)*A}{H_{e,heat}} \quad (1a)$$

$$R_{et,heat} = \frac{\left[exp\left(18.956 - \frac{4030.18}{T_{manikin}+235}\right)*RH_{sk} - exp\left(18.956 - \frac{4030.18}{T_a+235}\right)*RH_{a_{sk}}\right]*A}{H_{e,heat}} \quad (1b)$$

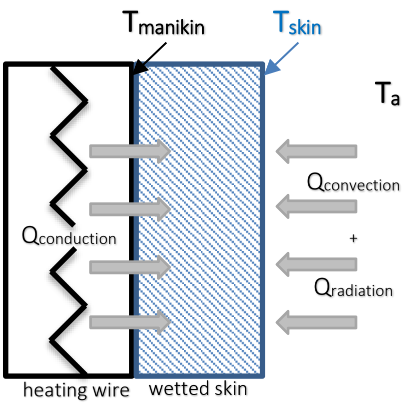
Where $R_{et,heat}$ is evaporative resistance calculated from heat loss method [m^2Pa/W], p_{sk} and p_a vapor pressure of saturated skin and air [Pa], $t_{manikin}$ and t_a is temperature of manikin´s surface and ambient temperature [°C], RH_{sk} (set at 96 % based on previous measurements) and RH_a is relative humidity near manikin´s surface and in the air respectively [%], A is manikin´s sweating surface area [m^2] and $H_{e,heat}$ is evaporative heat loss from manikin´s software [W]. $R_{et\_heat\_manikin}$ values were calculated from this equation.

To correct for lower skin temperature caused by water evaporation effect, equation (2) was used to mitigate the error in R_{et} calculation [13].

$$T_{sk} = T_{manikin} - 0.0132 * HL \quad (2)$$

Where T_{sk} is predicted textile skin temperature [°C], $T_{manikin}$ is manikin´s surface temperature [°C], controlled on 34°C and HL is heat flux obtained from manikin´s software [W/m2]. $R_{et\_heat\_skin}$ values were obtained by accommodating equation (2) for skin temperature into previous equation (1b).

Figure 3: The heat transfer mechanism among the manikin surface, the wetted skin and the environment in a so-called isothermal conditions (Ta = Tr = Tmanikin) without clothing, adapted from Wang et al., 2015 [10]



As there is a temperature gradient between wetted skin and environment, part of the heat needed for sweat evaporation from the skin is taken also from the environment through

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convection and radiation mechanisms as presented on Figure 3. In some cases (e.g. impermeable clothing, high insulation clothing) where evaporation is negligible and minimal power regulation to a manikin may cause overheating of its surface above set air temperature of 34°C, the effect can be reversed and the manikin has instead extra dry heat loss present. That is the reason why another correction for evaporative resistance calculation was proposed and is presented as equation (3).

$$Q_{evap} = H_{e,heat} + \frac{(T_a - T_{sk})}{I_t} \tag{3}$$

We get the final equation (4) for calculation of corrected evaporative resistance by implementing both equations (2) and (3) into equation (1).

$$\boldsymbol{R_{et,heat,corr}} = \frac{\left[exp\left(18.956 - \frac{4030.18}{t_{sk}+235}\right) * RH_{sk} - exp\left(18.956 - \frac{4030.18}{t_a+235}\right) * RH_{a_{sk}}\right] * \boldsymbol{A}}{H_{e,heat} + \frac{(T_a - T_{manikin}) + 0.0132 * HL}{I_t}} \tag{4}$$

Where Q_{evap} is part of the heat needed for evaporation taken from the environment [W], $H_{e,heat}$ is evaporative heat loss from manikin´s software [W], t_a and t_{sk} is ambient temperature and the predicted temperature of wetted the skin respectively [°C], I_t is the dry insulation measured on non-sweating manikin [m2.K/W]. $R_{et\_heat\_skin+envi}$ were determined according to equation (4).

Other proposed corrections (e.g. for moisture in clothing, for skin fabric) by Wang et al. [9, 10, 14] are more complicated to incorporate in practical measurements and were not considered in this study. With the use of clothing area factor f_{cl}, the whole body intrinsic evaporative resistance could be calculated for both clothing sets.

2.6 Mass loss method

This method is based on measurement of mass loss rate and by converting it to the evaporative heat loss by multiplying the latent heat of vaporization of water. The ASTM standard [11] is using manikin´s surface temperature for calculation of saturated vapor pressure p_{sk}. This needs to be corrected in a same way as in heat loss method using the predicted skin temperature based on equation (2). $R_{et,mass}$ - evaporative resistance calculated from mass loss method is calculated based on equation (5):

$$\boldsymbol{R_{et,mass}} = \frac{\left[exp\left(18.956 - \frac{4030}{t_{sk}+235}\right) * RH_{sk} - exp\left(18.956 - \frac{4030}{t_a+235}\right) * RH_{a_{sk}}\right] * \boldsymbol{A}}{\lambda * \frac{dm}{dt}} \tag{5}$$

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Where t_{sk} and t_a is predicted temperature of wetted skin and ambient temperature [°C], RH_{sk} (set at 96% based on previous measurements) and RH_a is relative humidity near manikin´s surface and air respectively [%], A is manikin´s sweating surface area [m^2], λ is vaporization heat of water at measured skin temperature [W.h/g] and dm/dt is an evaporation rate of moisture from the wetted skin [g/h].

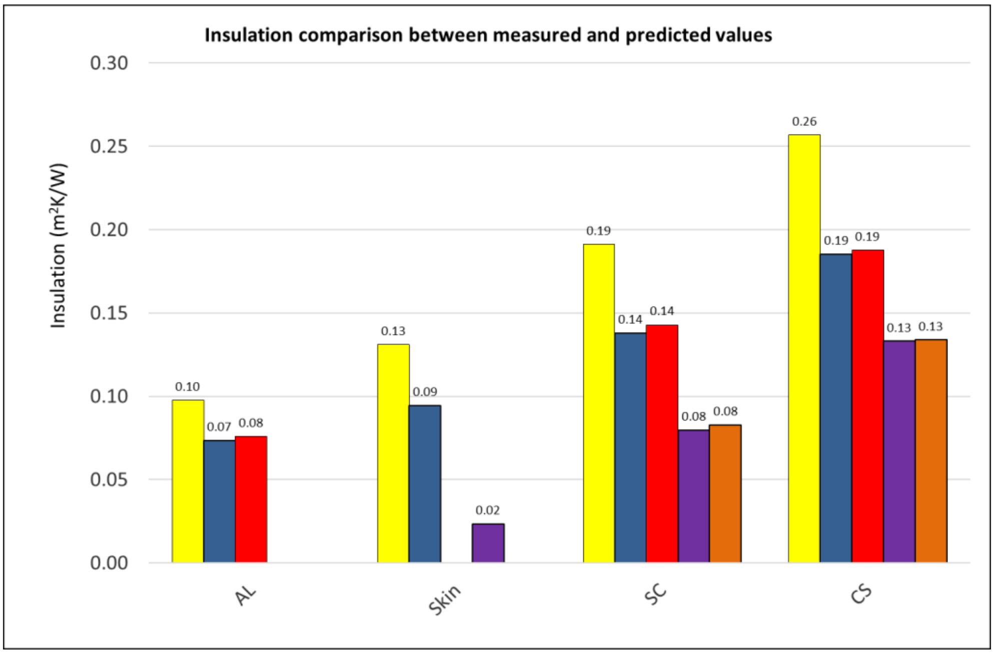
3. RESULTS

3.1 Thermal insulation

All presented thermal insulation values are average values of two independent measurements with difference lower than 4% between each other as required by ISO 9920 standard [5]. Total thermal insulation (I_t) of manikin´s skin used for evaporative resistance testing was measured only in static conditions and reached 0.131 m^2K/W.

Both static and dynamic values of thermal insulation are presented for SC and CS ensembles. Figure 4 shows two different values for resultant thermal insulation (including manikin movement and wind speed). $I_{tr\_predicted}$ values were calculated from total thermal insulation using equation (32) (equation (33) for a nude manikin) from chapter 8.2 of the ISO 9920 standard [5] while $I_{tr\_measured}$ are values of resulting thermal insulation obtained straight from dynamic measurements. The difference between predicted and measured values were -3.5, -3.6 and -1.4% for AL, SC and CS respectively. Similarly, both predicted and measured values of resultant intrinsic thermal insulation were calculated, with difference of -3.6 % for SC and -0.6 % for CS. These resultant intrinsic thermal insulation values were calculated using clothing area factor of 1.03 for Skin, 1.26 for SC and 1.41 for CS obtained with photographic method.

Figure 4: Overview of measured thermal insulation data for Air Layer (AL), manikin´s skin used for wet tests (skin), Sugarcane cutters outfit (SC) and sugarcane pesticide sprayers outfit (CS)



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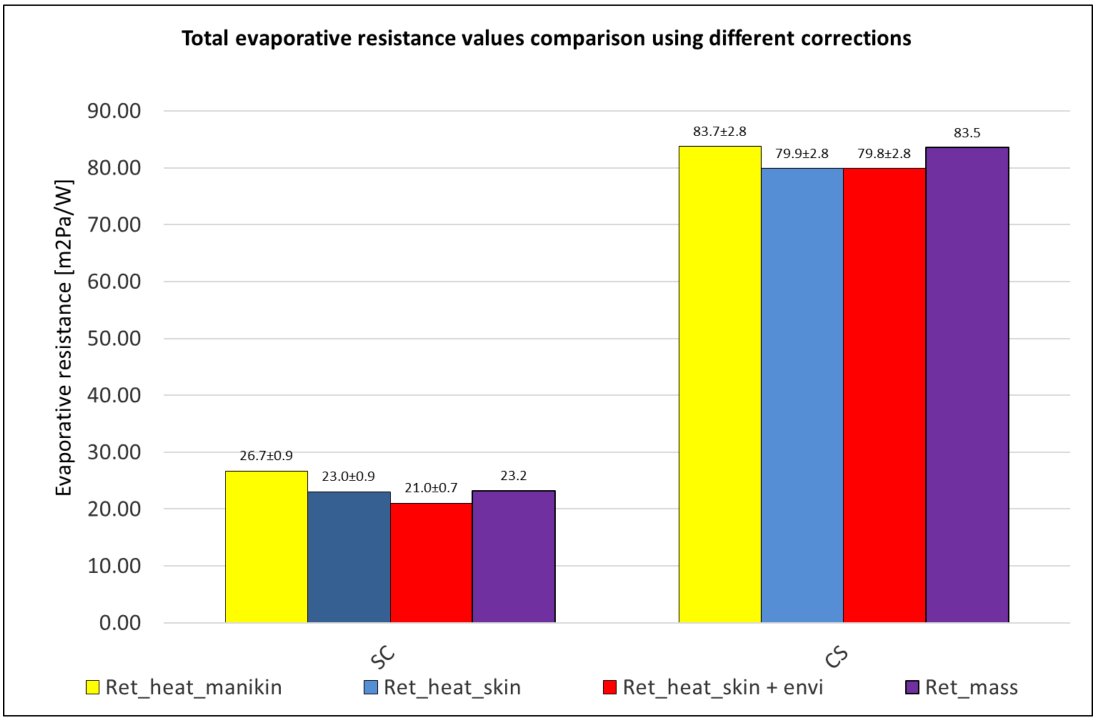
3.2 Evaporative resistance

Figure 5: Comparison of evaporative resistance values using different correction in heat loss method and mass loss method for both clothing sets



For evaporative resistance measurements, the presented values including standard deviation from heat loss method were calculated as an average of three independent measurements. However, mass loss method was measured only once for each clothing ensembles as a control measurement and thus no statistical analysis could have been applied.

Three different values of total evaporative resistance calculated from heat loss method using different corrections are showed in Figure 5 for both sets. Firstly, $R_{et\_heat\_manikin}$ values were calculated from the equation (1b). Secondly, $R_{et\_heat\_skin}$ values were obtained by accommodating correction for skin temperature (equation (2)) into previous equation (1b). Thirdly, $R_{et\_heat\_skin+envi}$ were determined according to equation (4) and finally, R_{et_mass} were calculated according to equation (5).

4. DISCUSSION

4.1 Difference between predicted and measured resultant thermal insulation values

As mentioned in result section, the difference of predicted values according to ISO9920 and measured insulation values was ranging from -1.4 to -3.5 % for resultant total thermal insulation. The difference was decreasing with rising total insulation of measured clothing. The accuracy of the prediction equation (32) is sufficient, however it is not clear which of the equations from ISO 99200 should have been used for our CS set. From the insulation point of

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view, we used equation (32), however our ensemble CS is specialized clothing with impermeable layers and therefore equation (36) should have been used. The difference between predicted and measured value while using equation (36) was significantly higher - 25.1 %. Therefore, we propose that more protective clothing ensembles should be measured in static and dynamic conditions to enhance the accuracy of this equation (36) or to propose a new special prediction equation for protective clothing. This could allow to measure total thermal insulation in static conditions only and then calculate the resultant values for purpose of heat stress modelling, which could save both time and money in this process. Also, aspect of clothing design should be considered.

4.2 Difference between R_{et} values obtained from multiple corrected equations

Mass loss method for calculation of evaporative resistance is correct from a physical point of view, thus corrections for heat loss methods were made to get as close as possible to calculated values from mass loss method.

On Figure 5, we can clearly see that for a CS clothing set there is no significant difference between R_{et} values calculated from multiple heat loss equations or measured by mass loss method. The CS set´s insulation was quite high and it also contained multiple impermeable layers, thus the heat transfer between skin and environment is negligible and mentioned corrections have almost no effect on calculated R_{et} values and value calculated from equation (1b) can be used for heat stress models. These results are in conformity with conclusions from Wang et al. [10] paper, which says that corrections should not be needed for impermeable clothing and for clothing with insulation higher than 2.5 clo. Although our measurement support this statement, it has been made based on measurement of one clothing ensemble [10] and so we propose more tests with high insulated and impermeable clothing should be done for verification. Also, it requires more research to study from which evaporative resistance range the corrections are needed and when they can be skipped.

As for set SC, it can be seen that the correction for skin temperature enhanced the accuracy nicely with 13.2 % difference between $R_{et\_heat\_manikin}$ (26.68 m^2Pa/W) and R_{et_mass} (23.17 m^2Pa/W) to only -0.6 % difference between $R_{et\_heat\_skin}$ (23.04 m^2Pa/W) and R_{et_mass} (23.17 m^2Pa/W). However, the R_{et} difference between mass loss method and correction for skin temperature and environmental gains is -10.1%, thus this correction did not improve the result further. This could be caused by the fact, that we measured mass loss method only once. If we compare the differences of 16.0, 3.9 and -6.0 % between $R_{et\_heat\_manikin}$ / Ret_{heat_skin} / $R_{et\_heat\_skin+envi}$ and R_{et_mass} respectively for only the third measurement (heat loss data and mass loss data taken in the same time), we could see that correction for skin temperature and environment is much closer to mass loss R_{et} value as previously, but the lowest difference is still for only skin temperature correction, thus this value could be used for modelling for these ensembles.

More detailed analyses of local values of the same clothing ensembles for each of the manikin´s zones were presented on the 12i3m - 12th International Meeting on Thermal Manikins and Modeling, Empa, St. Gallen, Switzerland [15].

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5. CONCLUSION

Two most important clothing properties, I_{cl} and R_{et}, for heat stress modelling were measured for two clothing ensembles used in sugarcane fields. Firstly, for thermal insulation measurements, we found that prediction equation (32) from ISO 9920 standard is not sufficiently accurate when used for protective clothing and its new version should be made for such a purpose in the future. Secondly, for evaporative measurements, both mass loss and heat loss method for calculation of evaporative resistance were used and some proposed corrections for heat loss method were accommodated. Our results are in conformity with Wang et al. findings [10], although we believe that verification should be done on bigger clothing database. Finally, we did not investigate other proposed corrections (e.g. for moisture in clothing, for skin fabric) by Wang et al. [9, 10, 14] in this study, but those should be also included and examined in any future studies for verification purposes.

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