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DETERMINATION OF CLOTHING EVAPORATIVE RESISTANCE FOR THERMO-PHYSIOLOGICAL MODELLING USING A THERMAL MANNEQUIN

ZJIŠŤOVÁNÍ VÝPARNÉHO ODPORU ODĚVŮ S VYUŽITÍM MANEKÝNA PRO VYUŽITÍ V SIMULAČNÍCH MODELECH TERMO-FYZIOLOGIE

DOCTORAL THESIS
DIZERTAČNÍ PRÁCE

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Content

1 INTRODUCTION

As it is important to protect humans´ health, thermo-physiological modeling is often used to calculate maximum exposure time for which could humans stay in given environment without their endangerment. Many workers are exposed to heat stress that can be exacerbated by the type of clothing they wear. The resulted heat strain can lead to short or long-term heat-related disorders. 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 (Kjellstrom et al. 2009; Błażejczyk et al. 2010; Angelova 2017).

It is known that evaporation is the main thermoregulatory feature for a heat dissipation from the human body to the environment. Hot working environment is typical for physically demanding jobs (e.g. soldiers, firefighters, builders, miners) for which more and more protective clothing and equipment is used to protect the workers from the primary risks (e.g. protection from flames for firefighters). Consequently, wearing of these less permeable protective clothing could often result in reduction of sweat evaporation from human skin leading to an elevated skin temperature, core temperature or sweat rate (Holmer 2006; Wang et al. 2011b). This phenomenon could be also seen on protective clothing usage in cold environments with high metabolic activity (e.g. mountain rescuers, fishers, athletes) as the conductivity is low through the insulated clothing and evaporation is limited by less permeable layers. Those are the reasons why the heat stress prediction models (e.g. PHS (ISO 7933 2004)) and thermo-physiological predictive models (Fiala et al. 1999; Havenith et al. 2012) also contain clothing properties as ones of the most important input data, namely the thermal insulation (I_t), clothing area factor (f_{cl}) and the evaporative resistance (R_{et}).

Therefore, the clothing parameters should be obtained with highest precision and accuracy possible (Wang et al. 2011b; Ueno and Sawada 2012) to mitigate some errors in these predictions. Thermal manikins are the most realistic available option for measuring clothing parameters at the moment. Although thermal insulation measurements on non-sweating manikins are well tested, precise and reliable, this cannot be said about measurement of evaporative resistance on sweating thermal manikins where significant discrepancies between results from different laboratories were found (Fan and Chen 2002; Richards and McCullough 2005; Wang et al. 2014; Wang 2017). Effects on evaporative resistance measurement protocols and calculations have been thoroughly investigated in recent years.

The aim of this thesis is to identify and apply a reliable method and procedure for measurement of evaporative resistance using manikin NEWTON in laboratory conditions at Brno University of Technology. Secondly, the repeatability of the measurements is investigated and accuracy of the methodology conducted at BUT is verified with data measured at Lund University on manikin TORE using the same measurement procedures, as the measurement of evaporative resistance is already well established there. Lastly, the study contains analysis of formulas and already proposed corrections for evaporative resistance calculation for heat loss method (Wang et al. 2015; Wang 2017), which will be accommodated and verified for multiple clothing ensembles covering the whole range of thermal insulation scale from *0.5* to *3.2 clo*. This study will widen the range of applications of manikin NEWTON at BUT opening the possibilities for new projects and will also enhanced the knowledge about clothing properties needed for thermo-physiological modeling.

2 EVAPORATIVE RESISTANCE

Total thermal resistance (I_t) is the value of thermal insulation from the body surface to the environment (including all clothing, enclosed air layers and boundary air layer) under reference conditions in static state (ISO 9920 2007). It´s measurements by the means of a thermal manikin are well documented and are showing high accuracy and repeatability (Wang et al. 2017). For example, in the corresponding ISO standard (ISO 15831 2004) the difference between two independent measurements should not exceed *4 %*. Similarly, in the ASTM standard (ASTM F1291-16 2016) results of three replications should not vary by more than *10 %* from the mean value. On the other hand, total evaporative resistance (R_{et}*),* which determines the amount of water vapor evaporation from a human body to an environment (including all clothing, enclosed air layers and boundary air layers) under reference condition in static state (ISO 9920 2007), is not well documented. Results from the previous interlaboratory studies on measurement of evaporative resistance (Richards et al. 2008; Mayor et al. 2012; Młynarczyk et al. 2018) shows that huge discrepancies of more than *50 %* were found between different institutions, mainly caused by sweating simulation systems, calculation methods of evaporative resistance (R_{et}), different test conditions etc. (Wang 2017). In most comprehensive round robin study found (Wang et al. 2014), the difference from mean values where, in most of the cases, around *4 %,* but in some extremes cases, the difference from mean values were more than *10 %* (up to *30 %* in one case).

2.1 Determination of evaporative resistance

In praxis, three methods to determine evaporative resistance of clothing are used: sweating guarded hot plates, sweating thermal manikins or measurements on human subjects. Studies show (Ross 2005) that evaporative resistance values from a sweating thermal manikin for heat stress simulations are more realistic than those from sweating guarded hot plates. The last method - human subject measurements are costly, time consuming and it may raise an ethical concern (Caravello et al. 2008).

2.2 Sweating simulation on thermal manikins

In the previous chapter, it was decided that sweating thermal manikins are the best option for evaporative resistance measurement regarding the precision, accuracy, and the ability to imitate human body in real conditions. There are many types and options of these manikins available around the world, for instance: (Koelblen et al. 2017).

- Manikins with water-filled body and skin from permeable waterproof material ("Walter" manikin (Chen et al. 2003), "Coppelius" (Varheenmaa 2014)).
- Manikins with water supply to tight-fitting fabric skin ("SAM" (Empa, Switzerland), "Newton" / "Adam" manikin (Thermetrics, Seattle, USA)).
- Manikins with pre-wetted tight-fitting fabric skin ("TORE" manikin Lund University, Sweden (Wang et al. 2010)).

2.2.1 Construction of pre-wetted sweating system

The concept was originally proposed by Goldman (R. F. Goldman 2006) and is still in use with some modifications. Human body shaped dry manikin with hard-shell body is dressed in tight fitted knitted textile skin (Wang et al. 2011a; Ueno and Sawada 2012; Koelblen et al. 2017). This textile is pre-wetted by tap water in washing machine for about *5 min* and then centrifuged for about *5 s* to ensure no water dripping. Manikin´s surface is control at *34 °C* to simulate the average temperature of human skin. Whole manikin system could be placed on a weighing scale with high accuracy which enables mass loss rate measurement. This system got also some imperfections as did the previous systems:

- impossible to control manikin´s skin temperature to calculate evaporative resistance precisely.
- pre-wetted skin tends to dry out after around *40-60 min* of testing.

2.3 Measurement and calculation of total evaporative resistance

In general, there are three different conditions possible to measure evaporative resistance.

- Non-isothermal conditions $(T_a \neq T_r \neq T_{sk})$
- Isothermal conditions $(T_a = T_r = T_{sk})$
- So-called isothermal conditions $(T_a = T_r = T_{manikin})$

T_{sk}	*manikin´s skin temperature*	*[°C]*
T_a	*ambient temperature of the environment*	*[°C]*
T_r	*radiant temperature in environment*	*[°C]*
$T_{manikin}$	*manikin´s surface temperature*	*[°C]*

It was found that measurement of the evaporative resistance in non-isothermal conditions causes significant error. As clothing materials absorb moisture, their dry thermal insulation changes accordingly (Chen et al. 2003; ISO 9920 2007; Xiaohong et al. 2010). However, it is also not possible to setup isothermal conditions for current sweating manikins as we are only able to control manikin surface temperature, not the temperature of the wetted manikin´s skin (it is not yet technically possible due to sensor limitations). Thus, so-called isothermal must be used instead. As it can be seen from Figure 1, in so-called isothermal conditions, the heat transfer process is very complex. Previous studies (Wang et al. 2011b, 2016) have demonstrated that the fabric 'skin' and wet clothing spots will draw heat from the ambient in a so-called isothermal environment due to the negative temperature gradient between the uncontrolled fabric 'skin' and the ambient. Thus, the heating that is supplied to the manikin is not equal to the actual energy that is used for water evaporation occurring in the wet fabric 'skin'-clothing system. As the fabric 'skin' should be tightly fitted to the manikin body, there is no or minimal air gap between the fabric 'skin' and the manikin surface. For the nude scenario in the so-called isothermal conditions, the heat will be transferred from the manikin surface to the fabric 'skin' mainly through conduction. The fabric 'skin' is directly exposed to the ambient air so the heat will be transferred from the ambient environment in to the fabric 'skin' by convection and radiation. If clothing is worn on top of the fabric 'skin', the heat transfer process will become more complicated. First, the moisture contained in the fabric 'skin' may be wicked away by the tested clothing and some moisture evaporation is from the tested clothing on the inner or outer surface of the clothing. In the so-called isothermal condition, the energy used for moisture evaporation occurring in the wet fabric 'skin' clothing system can only be drawn from either the heated manikin or the ambient environment. Thus, the heat may be transferred from the ambient air to some evaporation locations in the tested clothing and further to the saturated fabric 'skin'. This heat transfer process may involve convection, radiation and conduction (Wang et al. 2015).

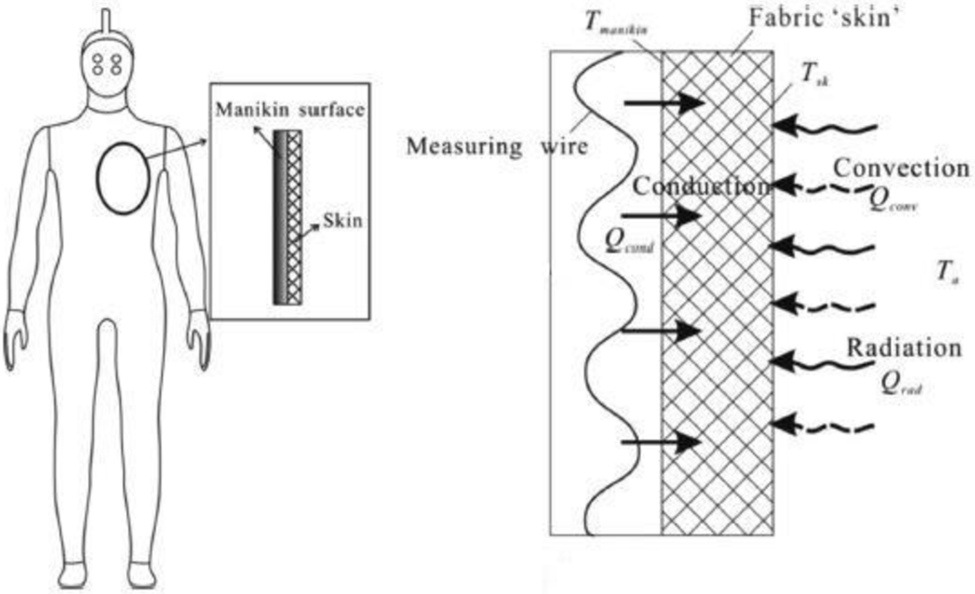

Figure 1: The heat transfer mechanism among the manikin surface, the wetted skin and the environment in a so-called isothermal conditions ($T_a = T_r = T_{manikin}$) without clothing, adapted from (Wang et al. 2015)

2.3.1 Calculation methods

There were two calculation methods for clothing evaporative resistance provided in ASTM standard from 2010 (ASTM F2370 - 10 2010) – mass loss method and heat loss method. Mass loss method was removed from new version of this standard (ASTM F2370-16 2016). The reason behind it is probably because it is challenging to use the mass loss method to calculate localized clothing evaporative resistance (Wang 2017) which were added in this new ASTM standard (ASTM F2370-16 2016). According to Wang (Wang 2017) exclusion of mass loss method was not the right decision as this method directly determining the intensity of mass transfer by evaporation and is closer to the physical nature of heat transfer by sweating.

2.3.2 Mass loss method

This method measures the mass loss rate and then converts it to the evaporative heat loss by multiplying the latent heat of vaporization of water.

$$R_{et,mass} = \frac{\Delta p_{iso} * A}{H_{e,mass}} = \frac{\Delta p_{iso} * A}{\lambda * \frac{dm}{dt}} \tag{1}$$

$R_{et,mass}$	*total clothing evaporative resistance calculated by mass loss method*	*[kPa.m^2/W]*
$H_{e,mass}$	*calculated evaporative heat loss from mass loss rate*	*[W]*
Δp_{iso}	*water vapor pressure gradient between wet skin and environment*	*[kPa]*
A	*sweating surface area*	*[m^2]*
λ	*vaporization heat of water at measured skin temperature*	*[W.h/g]*
dm/dt	*evaporation rate of moisture from the wet skin*	*[g/h]*

2.3.3 Heat loss method

Evaporative resistance is calculated from area-weighted heat loss observed from thermal manikin software.

$$R_{et,heat} = \frac{\Delta p_{iso} * A}{H_{e,heat}} \tag{2}$$

$R_{et,heat}$	*total clothing evaporative resistance calculated by heat loss method*	[$kPa.m^2/W$]
$H_{e,heat}$	*evaporative heat loss from manikin´s surface*	[W]
Δp_{iso}	*water vapor pressure gradient between wet skin and environment*	[kPa]
A	*sweating surface area*	[m^2]

2.3.4 Comparison of these methods

There are many studies comparing evaporative resistance calculated by these two methods. Firstly, nude manikin (manikin + wetted skin only) and five following clothing ensembles were measured on manikin TORE. Significant differences can be seen between the values of $R_{et,heat}$ calculated from heat loss method and the $R_{et,mass}$ (Wang et al. 2011a). Secondly, similar results were found by (Wang et al. 2009) in another study on manikin TORE where combinations of two wetted skin materials and two clothing ensembles were tested. It could be seen from these studies that R_{et} values calculated from heat loss method are always significantly larger (more than *10 %)* as those calculated from mass loss method. This is caused by todays imperfection in sweating manikin design – inability to control wetted skin temperature. This constrain researchers to usage of a so-called isothermal conditions where the heat for evaporation is also taken from the environment. Thus, some corrections had to be made for evaluation of R_{et} by heat loss method to mitigate resulting errors as the mass loss method yields physically correct values.

2.4 Different factors influencing Ret measurements and calculations

There were many factors investigated throughout the years to identify the source of errors and mitigate their effects on evaporative resistance measurement and calculation.

2.4.1 Effect of temperature difference

As we mentioned, significant error was made by calculating evaporative resistance using manikin surface temperature (due to technical difficulties and complexity of sensor attachment on wetted skin) and not the temperature of pre-wetted skin as it should be according to ASTM standard (ASTM F2370 - 10 2010). In 2010, Wang (Wang et al. 2010) conducted experiment with aim to see how much error usage of manikin surface temperature causes and how he could possibly predict wetted skin temperature for further calculations. In first part of his study, he managed to test the temperature difference between inner and outer side of the wetted skin and he found it can be neglected. From nude TORE manikin (nude manikin + wetted skin) tests he derived equation (3) for prediction of manikin´s skin temperature for environmental temperature range between *25 °C* and *34 °C*.

$$T_{sk} = 34.00 - 0.0132 * HL \tag{3}$$

T_{sk}	*predicted manikin´s skin temperature*	*[°C]*
HL	*heat loss from manikin´s total sweating area – heat flux*	*[W/m^2]*

Similar prediction was made by a thermal infrared camera (Havenith et al. 2008). However, this equation was only done for temperature of *34 °C* on Newton type manikin.

$$T_{sk} = 34.13 - 0.012 * HL \tag{4}$$

T_{sk}	*predicted manikin´s skin temperature*	*[°C]*
HL	*heat loss from manikin´s total sweating area – heat flux*	*[W/m^2]*

Six clothing ensembles were used for comparison of three temperatures – measured wetted skin temperature – t_{sk}, temperature predicted by equation (3) – t_{sk_p1} and temperature predicted by equation (4) – t_{sk_p2}. From statistical point of view using the root squared deviation method, predicted values from these two equations are not accurate enough on significance level of *0.95*. However, with consideration of temperature measurement precision of ± *0.3 °C*, agreement between observed data and predicted values can be always accepted within this precision level (Wang et al. 2010).

Next step in (Wang et al. 2010) was to determine total evaporative resistance of six previously mentioned clothing ensembles by using two predicted temperatures t_{sk_p1} (3) and t_{sk_p2} (4) and one measured temperature t_{sk} to see the difference between R_{et} values calculated from the manikin surface temperature, measured skin temperature and those calculated by predictive equations.

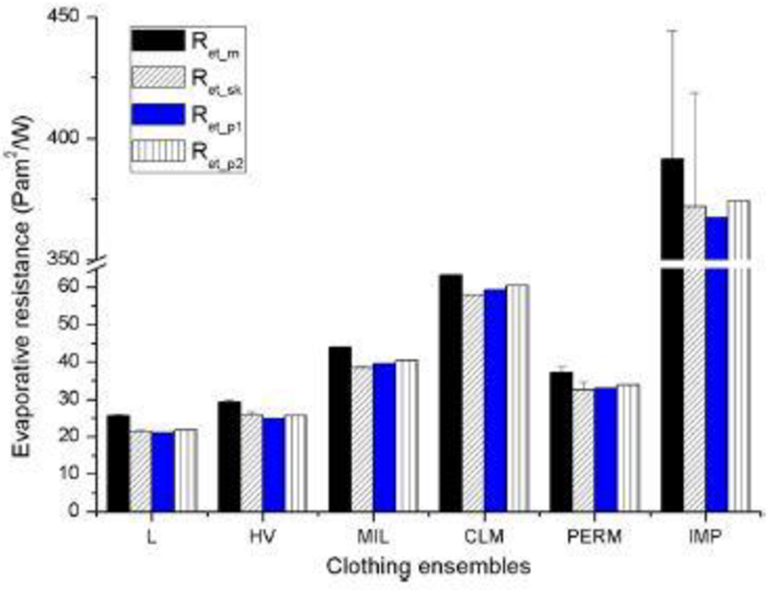

Figure 2: Comparison of R_{et} values calculated from prevailing mass loss method using manikin surface temperature – R_{et_m}, measured skin temperature – $R_{et\text{-}sk}$, predicted by equation (3) – $R_{et\text{-}p1}$, predicted by equation (4) – $R_{et\text{-}p2}$ taken from (Wang et al. 2010)

It can be clearly seen from the Figure 2 that values of R_{et} calculated from measured skin temperature, predicted temperature by equation (3) and (4) matching nicely. However, R_{et} values calculated by prevailing method – from the manikin surface temperature is significantly higher. Thus, these predictive equations enhance greatly the accuracy of clothing evaporative resistance measurements, especially for lower insulated and permeable clothing ensembles. In the erratum of the following study (Wang et al. 2011b), the difference between prevailing method (using manikin surface temperature) and method from ASTM standard (using wetted skin temperature) was thoroughly investigated. Firstly, it was found that prevailing method overestimates the clothing evaporative resistance by up from *3.8* to *23.7 %*.

2.4.2 Effect of moisture content on apparent ´wet´ thermal insulation

Thermal insulation governs the possible amount of body heat dissipated to the environment. Two types of thermal insulation are recognized – dry thermal insulation measured on dry manikin (ISO 15831 2004) and ´wet´ thermal insulation when measured clothing is fully or partially wet. The ´wet´ thermal insulation in presence of moisture and/or air movement is often referred to as apparent ´wet´ thermal insulation (Lotens et al. 1995; Wang et al. 2016).

$$I_{t,apparent} = I_t * (1 - 1 * 10^{-9} * w_t^3 + 1.6 * 10^{-6} * w_t^2 - 1.004 * 10^{-3} * w_t) \qquad (5)$$

$I_{t,apparent}$	*clothing apparent ´wet´ thermal insulation*	*[$m^2.K/W$]*
I_t	*clothing dry thermal insulation*	*[$m^2.K/W$]*
w_t	*the amount of moisture contained in the tested clothing $0 < w_t < 800g$*	*[g]*

Equation (5) describes the effect of moisture content on apparent ´wet´ thermal insulation and was deduced from Wang´s (Wang et al. 2016) dataset which correlates with data from Hall and Polte (Hall and Polte 1956).

2.4.3 Effect of clothing fit and size

Previous study also investigated the effect of fit/size on the thermal insulation. It was found that dry insulation of clothing increases with the increasing clothing size and then decreases with still increasing clothing size (Wang et al. 2016). The decrease of thermal insulation is caused by natural air convection between clothing and manikin body as the air gap becomes thick enough, normally thicker than *8 – 11 mm* (Wang et al. 2016). These findings are in accordance with result from (Chen et al. 2004). Although, the clothing size/fit has impact on dry thermal insulation, the effect on apparent ´wet´ thermal insulation and evaporative resistance is minimal. However, it is suggested that the right size of clothing fitting the manikin should be used if possible.

2.4.4 Fabric thickness and material effect on apparent ´wet´ thermal resistance

The missing requirements for manikin´s skin material in new ASTM standard (ASTM F2370-16 2016) led to the investigation of the effect of different fabric materials and its thickness on thermal insulation and evaporative resistance by means of sweating thermal manikins. In (Wang et al. 2017) conducted experiment where seven pieces of highly stretchable single-jersey knitted cotton and polyester fabric ´skins´ of different thicknesses were tested. New skin temperature predictive equations were made and the apparent ´wet´ thermal resistance was calculated using water content, thickness, and also the fabrics´ physical properties (e.g. mass per unit area, fabric conductivity, fiber density) for each of the seven samples. Results from this study showed that there is a linear relation between fabric thickness and its apparent ´wet´ thermal insulation for both cotton and polyester materials. To conclude, both fabric material and thickness have impact on apparent ´wet´ thermal resistance and hence on total evaporative resistance. It is suggested that skin with thickness from *0.40 mm* to around *0.55 mm* should be used for evaporative resistance measurements. Also, cotton material was better in maintaining skin wetness for longer time and it should be used rather than polyester to avoid skin´s drying during the test procedure especially on sweating manikins with no water supply.

In another study (Koelblen et al. 2017) the cotton material with around *0.50 mm* thickness was also labeled as the best option for making sweating simulation skin for thermal manikins.

2.5 Proposed approach for Ret measurements

Results from previous years were summarized to overview article about evaporative resistance measurement (Wang 2017). Although, no dry thermal insulation tests are needed for calculation of the $R_{er,real}$ because the observed heat loss from the manikin in so-called isothermal conditions represents the evaporative heat loss, some corrections must be used (Wang et al. 2011a; Wang 2017). It is suggested to follow this scheme when calculating real evaporative resistance measured in so-called isothermal conditions.

Apparent ´wet´ thermal fabric insulation calculation including skin fabric properties. Derivation of this equation can be found in overview article as appendix (Wang 2017).

$$AI_{wet} = \frac{(d_{fabric} * \rho_w)^2}{d_{fabric} * \rho_w{}^2 * k_{fiber} + (k_w - k_{fiber}) * w_c * m_{fabric} * (\rho_w + \rho_{fiber} * w_c)} \tag{6}$$

AI_{wet}	*apparent ´wet´ thermal insulation of the fabric*	*[m^2.K/W]*
d_{fabric}	*fabric thickness*	*[mm]*
ρ_{fiber}	*fiber density*	*[kg/m^3]*
ρ_w	*water density*	*[kg/m^3]*
k_{fiber}	*fiber thermal conductivity*	*[W/m.K]*
k_w	*water thermal conductivity*	*[W/m.K]*
m_{fabric}	*fabric´s mass per unit area*	*[g/m^2]*
w_c	*water content in fabric*	*[% g/g]*

Apparent ´wet´ thermal insulation is then used for skin temperature prediction to mitigate the error in evaporative resistance calculation caused by using manikin surface temperature (prevailing method) and not manikin´s skin temperature as stated in standard (ASTM F2370-16 2016).

$$T_{sk} = T_{manikin} - AI_{wet} * HL \tag{7}$$

T_{sk}	*predicted manikin´s skin temperature*	*[°C]*
$T_{manikin}$	*manikin´s surface temperature*	*[°C]*
AI_{wet}	*apparent ´wet´ thermal insulation of the fabric*	*[m^2.K/W]*
HL	*heat loss from manikin´s total sweating area – heat flux*	*[W/m^2]*

This predicted temperature is then used to correct heat loss for evaporation as part of it is taken from environment and the other part from thermal manikin. The final equation for corrected evaporative heat loss – Q_{evap} is as followed: (Wang et al. 2015; Lu et al. 2016).

$$Q_{evap} = H_{e,heat} + \frac{(T_a - T_{manikin}) + AI_{wet}*HL}{I_t*(1-1*10^{-9}*w_t^3+1.6*10^{-6}*w_t^2-1.004*10^{-3}*w_t)} \tag{8}$$

It can be easily deduced from equation (8) that the energy used for moisture evaporation during wet test in so-called isothermal conditions is always greater than the heating power supplied to the manikin. Finally, the Q_{evap} value can now be used for calculation the real evaporative resistance by heat loss method and should yield similar results to those from mass loss method.

Corrected heat loss method $$R_{et,heat,corr} = \frac{(p_{sk} - p_a)*A}{\mathrm{Q_{evap}}} \tag{9}$$

Mass loss method $$R_{et,mass} = \frac{\Delta p_{iso}*A}{H_{e,mass}} = \frac{(p_{sk} - p_a)*A}{\lambda*\frac{dm}{dt}} \tag{10}$$

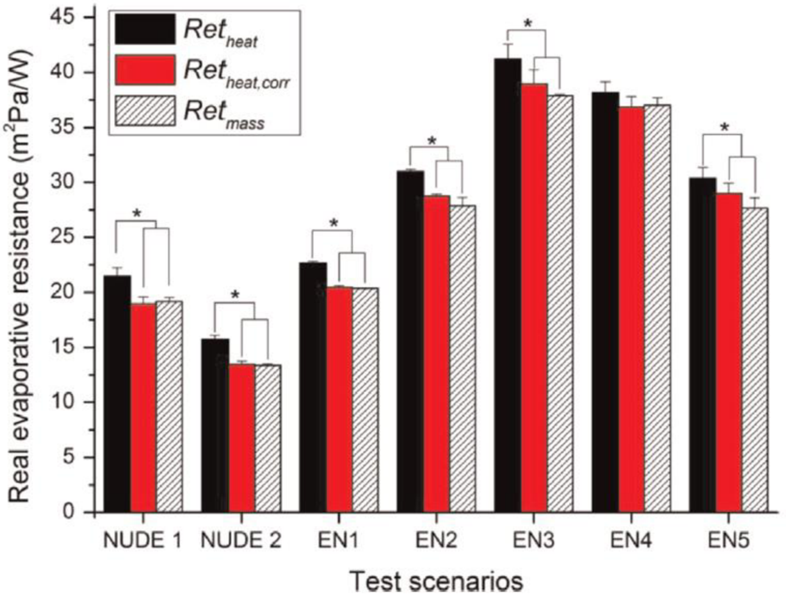

Figure 3: Comparison of real evaporative resistance values on 5 ensembles and two nude cases calculated from prevailing method (manikin surface temperature) – $R_{et,heat}$, from mass loss method – $R_{et,mass}$ and from corrected heat loss method – $R_{et,heat,corr}$, taken from (Wang et al. 2015).

It is clear from Figure 3 that correction for heat loss method improved the accuracy of real evaporative resistance by heat loss method and that there is no significant difference between $Ret_{heat,corr}$ and Ret_{mass}. In ensemble EN4, there is no significant difference between neither of the three methods as only small amount of heat (around *3.6 %*) was drawn from the ambient due to high insulation and impermeable layers of the clothing. To simplify the calculation, it is suggested that the heat loss method may be directly used for calculating clothing real evaporative resistance with no corrections for high insulation clothing (e.g., higher than *2.0 clo*). For low insulation and vapor permeable clothing, the heat loss method must be corrected before calculating clothing real evaporative resistance (Wang et al. 2015).

3 SUMMARY OF KNOWLEDGE GAP

Although the knowledge in the field of measuring thermal insulation (I_t) and clothing area factor by means of thermal manikin are extensive, the measurement of evaporative resistance (R_{et}) is not documented too well. It is known that the repeatability of the thermal insulation measurement is within the *4 %* difference when the correct methodology from standards (ISO 9920 2007) is used. This is not the case for evaporative resistance measurement. As multiple sweating simulations systems for manikin with different methodology and calculations methods are used around the world, it is very challenging to compare any results and the reproducibility its uncertain. As the round robin study (Wang et al. 2014) shows the difference from mean values of measurements from multiple laboratories around *10 %* (in extreme case *30 %* difference), the aim is to accommodate the evaporative resistance measurement using manikin NEWTON at BUT and reach the values within *10 %* from the results from manikin TORE at Lund University. This level of precision would validate the methodology of the measurement at BUT, as well as confirm the reproducibility of the measurement between different laboratories using same methodology.

Secondly, the mass loss is closer to the physical nature of heat transfer by sweating while accommodation of heat loss method is more challenging. The global aim is to find the right measuring methodology and calculation methods for evaporative resistance using heat loss method, which would allow to calculate also local evaporative resistance values for different body parts for use in physiological modeling. Multiple corrections were proposed in the literature for heat loss method, but they are not verified on bigger sample of clothing ensembles (usually done on 2 or 3 ensembles in the study). Thus, it is unknown to what extend should the proposed corrections be used for ensembles with different insulation or for protective clothing etc.

4 AIM AND OBJECTIVES

4.1 Aim of the thesis

Development and integration of the measurement procedure and calculation methods to determine clothing evaporative resistance using thermal manikin Newton and to validate the precision, repeatability and reproducibility of the measurement.

4.2 Objectives

To support all scientific questions, a set of specific objectives have been formulated:

I. Analyze the importance of obtaining precise clothing parameters for thermos-physiological modeling.
II. Analyze multiple methods to obtain clothing properties and confirm the importance of manikin measurements.
III. Identify the impact of local values for different body zones on thermo-physiological models.
IV. Study the influence of body posture and body movement on clothing properties.
V. Verify the evaporative resistance measurement methodology and calculations including all proposed corrections to obtain most precise values.
VI. Implement the evaporative measurements methodology in BUT including equipment and calculation methods.
VII. Verify the reproducibility of the evaporative resistance measurement between two laboratories.

4.3 Structure of the thesis

The aim and objectives have been addressed in four stand-alone peer-review journal papers and one soon to be published paper. The number of citations taken from ScienceDirect and Google scholar, excluding auto citation as of July 2023 is given in brackets:

POKORNÝ, J.; FIŠER, J.; FOJTLÍN, M.; KOPEČKOVÁ, B.; **TOMA, R**.; SLABOTINSKÝ, J.; JÍCHA, M. Verification of Fiala-based human thermophysiological model and its application to protective clothing under high metabolic rates. BUILDING AND ENVIRONMENT, 2017, vol. 126, no. 2017, p. 13-26. ISSN: 0360-1323. **(16)**

FOJTLÍN, M.; PSIKUTA, A.; FIŠER, J.; **TOMA, R**.; ANNAHEIM, S.; JÍCHA, M. Local clothing properties for thermo-physiological modelling: Comparison of methods and body positions. BUILDING AND ENVIRONMENT, 2019, vol. 2019, no. 155, p. 376-388. ISSN: 0360-1323. **(14)**

TOMA, R.; KUKLANE, K.; FOJTLÍN, M.; FIŠER, J.; JÍCHA, M. Using a thermal manikin to determine evaporative resistance and thermal insulation – A comparison of methods. Journal of Industrial Textiles, 2020, vol. 2020, no. 1, p. 1-23. ISSN: 1530-8057. **(5)**

KUKLANE, K.; **TOMA, R**.; A. I. LUCAS, R. Insulation and Evaporative Resistance of Clothing for Sugercane Harvesters and Chemical Sprayers, and Their Application in PHS Model-Based Exposure Predictions. International Journal of Environmental Research and Public Health (printed), 2020, vol. 17, no. 9, p. 1-12. ISSN: 1661-7827. **(8)**

TOMA, R.; KUKLANE, K.; FOJTLÍN, M.; FIŠER, J.; JÍCHA, M. Reproducibility of evaporative resistance measurements and calculations using different thermal manikins. (to be published)

4.4 The author's contribution to the papers

I. Conducted part of literature survey, part of data analysis and correcting of the manuscript

II. Conducted part of experimental work, part of literature survey and correcting of the manuscript

III. Conducted all of experimental work, literature survey, data analysis and writing of the manuscript

IV. Conducted majority of experimental work, part of the literature survey, part of data analysis and correcting of the manuscript

V. Conducted all of experimental work and numerical work, literature survey, data analysis and writing of the manuscript

5 SUMMARY OF THE CONDUCTED WORK

5.1 Paper I (Objectives I and III): Verification of Fiala-based human thermo-physiological model and its application to protective clothing under high metabolic rates

In this paper, a theory of how to predict thermal comfort and predict human heat stress in various conditions was studied. Although, fast and well established indices expressing heat stress, such as: PHS (Predicted Heat Strain) (ISO 7933 2004) , WBGT (Wet Bulb Globe Temperature) - ISO 7243 (Budd 2008), and thermal sensation and comfort PMV/PPD (Predicted Mean Vote/Predicted Percentage of Dissatisfied) - ISO 7730 (ČSN ISO 7730 1997) could be used, more detailed models should be used for prediction of heat stress in complex environments (Havenith and Fiala 2015). On one hand, complex models provide detailed results about human thermal state; on the other hand, they require rather detailed input data. From authors (Katić et al. 2016) perspective, the two most problematic parameters are metabolic rate and clothing properties.

Thermal and evaporative resistance of clothing can be determined, for example, according to ISO 9920 (ISO 9920 2007) and also directly measured using a guarded hot plate - ISO 11092 (ISO 11092 2014) or a thermal manikin - ISO 15831 (ISO 15831 2004). The thermal manikin has a human body shape which predetermines it as a suitable tool for the exact measurement of heat transfer coefficients at human body surface, as was described in (de Dear et al. 1997; Fojtlín et al. 2016). However, to obtain a detailed specification of clothing properties for each individual is rather problematic.

Fiala-based thermo-physiological model (FMTK model) was implemented and verified for protective clothing applications. The verification was carried out in three steps: validity of passive and active systems and correlation of the model with experimental data.

5.1.1 Summary of main findings

The passive system of the FMTK model was successfully verified and compared to Theseus-FE model, reaching an average error of local skin temperature of *0.07 °C* through all 49 sectors. A comparison of active system with Theseus-FE model was conducted and the agreement was very good in all transient test cases (in the ambient temperature range from *5 to 48 °C*). Although small differences were found in the simulation of higher metabolic rates, the FMTK model was successfully verified.

The second part of this paper presented the application of the FMTK model to the chemical protective clothing in warm/hot environmental conditions. The model successfully predicted exposure time for three different garments in various conditions. Results show the demand for deeper verification of the Fiala-based model for protective clothing applications. Several disadvantages were noticed with such a complex model, from which the proper definition of input data needed for the model is the most problematic one. Although we verified that the FMTK model itself is well constructed, a more attention should be paid to the complexity of the clothing model. The most of the inaccuracies stem from the estimation of local insulation parameters (both thermal and evaporative resistance) of clothing and from the effect of walking on the treadmill during the experiments. Thus, it is needed to find the best possible way of how to obtain precise clothing parameters used in the models.

5.2 Paper II (Objectives II, III and IV) Local clothing properties for thermo-physiological modelling: Comparison of methods and body positions

Paper II explores various methods for determining the clothing properties, with the aim of the study to explore possibilities to obtain local clothing parameters for better use in physiological modelling. The aim of the study was to explore various methods and compared them with the results of thermal manikin measurements, which is presently the most accurate method, but also requires expensive equipment, such as thermal manikins and a climatic chamber. The differences between standing and sitting body posture and effect of used method to obtain local clothing parameters on physiological modelling are also examine in the paper.

Table 1 summarizes the different scenarios examined. The selected methods include manikin measurements, analytical heat transfer modeling (Psikuta et al. 2018; Joshi et al. 2019) regression modeling (Veselá et al. 2018), empirical modeling (e.g. the UTCI model (Havenith et al. 2012)), and ISO based approaches (Nelson et al. 2005; ISO 9920 2007).

Case	f_{cl} (-)	I_{cl} ($m^2K.W^{-1}$)	$R_{e,cl}$ ($m^2Pa.W^{-1}$)	Position	Segments
1	3D scanning	Manikin heat loss	Manikin heat loss	sitting	13
2	Photography	Manikin heat loss	Manikin heat loss	standing	13
3	Physical model	Physical model	Physical model	sitting	8
4	Physical model	Physical model	Physical model	standing	10
5	Regression model	Regression model	Physical model	standing	11
6	ISO based model	ISO based model	ISO based model	standing	3
7	ISO Database	UTCI model	ISO Database	standing	7
8	ISO Database	ISO Database	ISO Database	standing	1

Table 1: Summary of the examined scenarios

In Case 1, the reference case, state-of-the-art methods were employed. To determine the f_{cl} (clothing area factor), a highly realistic three-dimensional (3D) scanning method was used. A specialized scanner was utilized to digitize the surface of both the nude and clothed body of a sitting manikin. For the determination of I_{cl} (thermal insulation) and $R_{e,cl}$ (evaporative resistance), a 34-zone Western Newton-type manikin (Thermetrics, Seattle, USA) was utilized. The manikin was seated on an adjustable perforated plastic chair inside a climatic chamber. Detailed descriptions of the chamber and the manikin could be found in (Fojtlín et al. 2016). The experimental conditions were set in accordance with ISO 15831:2004 (ISO 15831 2004). The $R_{e,cl}$ was determined using a pre-wetted tightly fitting, long sleeve overall, following the methods described in (Richards et al. 2008; Wang et al. 2011a). The measurement was conducted under isothermal conditions at *34 °C* (skin temperature equal to ambient temperature), with a relative humidity of *18 %* (partial water vapor pressure of *957 Pa*), and an air speed of *0.1 ± 0.05 m/s*. The calculation of evaporative resistance was performed using the heat loss method described in ASTM F2370 (ASTM F2370-16 2016).

5.2.1 Summary of main findings

The results of this study showed substantial variation among the methods for all examined clothing parameters, ranging from *13 – 43 %* in f_{cl}, *35 – 198 %* in I_{cl}, and *53 – 233 %* in $R_{e,cl}$ of the reference value (Case 1).

Changing the body position from standing to sitting results in a reorientation of various body parts and a redistribution of air gaps. Consequently, all three clothing thermal parameters are affected. Although the global thermal and evaporative resistances exhibited only minor changes (Yu et al. 2011), the local parameters displayed significantly higher error margins (up to *31 %* for f_{cl}, *80 %* for I_{cl} and *92 %* for $R_{e,cl}$).

The local thermo-physiological responses were clearly affected by the variation of the local clothing inputs. The error induced by clothing inputs, in this case, has no critical medical relevance such as un-compensated heat storage or dehydration. However, in thermal sensation and comfort studies, error in the local clothing input can cause substantial error in the thermal sensation modelling. Therefore, to get a high-quality prediction of physiological responses, it is crucial to always choose the most reliable method to determine the local clothing properties, respecting the body position.

It is worth noting, that there were huge discrepancies found on some body parts between independent tests measuring $R_{e,cl}$ while using thermal manikin in Case 1 and Case 2. Similar discrepancies were showed in previous studies (Richards et al. 2008; Młynarczyk et al. 2018), even for global values for the whole body. Even though clothing properties measurements using thermal manikin are the state-of-the art methods, repeatability of evaporative resistance measurement between independent tests, and also reproducibility between independent laboratories should be studied to guarantee the best possible input data for models.

5.3 Paper III (Objectives V, VI and VII): Determination of evaporative resistance and thermal insulation by means of thermal manikin – comparison of methods

The focus of Paper III was to determine three most important clothing properties for thermo-physiological modelling - clothing area factor, thermal insulation, and evaporative resistance, by means of a non-sweating thermal manikin using pre-wetted skin. The aim of this study was to identify, and possibly enhance, reliable and applicable methods to obtain protective clothing parameters using thermal manikin. As it could be seen from the results of Paper I and Paper II, the posture of the manikin and its movement is not to be neglected, so verification of multiple equations (EN 342 2004; ISO 9920 2007), used for predicting resultant total thermal insulation (I_{tr}) from total thermal insulation (I_t) was conducted. Secondly, multiple methods to measure and calculate evaporative resistance (ASTM F2370 - 10 2010) were examined, including various calculations and corrections (Wang et al. 2010, 2011b, 2015). According to the conclusions from Paper II, the repeatability of independent tests was also examined for evaporative resistance measurement. Finally, PHS simulations were conducted and a sensitivity analyses was done to observe the impact of the clothing properties, obtained by the different equations and corrections, on the workers' maximum exposure time.

5.3.1 Methods used to obtain clothing properties

All measurements and calculations were conducted on thermal manikin TORE (Kuklane et al. 2006) using two clothing ensembles used by agricultural workers in Latin America - sugarcane cutters (SC) and pesticide sprayers (PS).

The clothing area factor (f_{cl}) was determined by the photographic method. The widely used heat loss method was used to determine both the total thermal insulation (I_t) and the resultant total thermal insulation (I_{tr}) according to ISO 9920 (ISO 9920 2007). The walking stand for the manikin was used to simulate walking speed of approximately *3.5 km/h* (step rate set at *90 steps/min*). Multiple equations (Table 2) were used to predict the resultant total thermal insulation (I_{tr}) and the results were compared to the measured values.

	Equation label	Area of application	
Standard ISO 9920	(32)	light or normal clothing	$0.6 < I_{cl} < 1.4$ clo
	(33)	no clothing	$I_{cl} = 0$ clo
	(34)	low insulated clothing	$0 < I_{cl} < 0.6$ clo
	(35)	specialized or high insulated clothing	$I_{cl} > 1.4$ clo
	(36)	very low wind activity	
Standard EN 342	(EN342)	cold protective clothing	

Table 2: Overview of multiple investigated equations from standards for predicting resultant thermal insulation from total thermal insulation values.

Two calculations methods to determine evaporative resistance provided by (ASTM F2370 - 10 2010) were used – the mass loss method and the heat loss method (Havenith et al. 2008). Two corrections, namely for the skin temperature of the manikin (Wang et al. 2010, 2011b) and for the heat gains from the environment (Wang et al. 2015) were also used and evaluated.

5.3.2 Data analysis and sensitivity study

All thermal insulation values presented in this study are the averaged values of two independent measurements with a difference lower than *4 %* between them as required by the ISO 9920 standard (ISO 9920 2007). For the evaporative resistance measurements values were calculated as an average of three independent measurements. However, the mass loss method was measured only once for each clothing ensemble as a control measurement; therefore, no standard deviation could be presented.

PHS simulations were performed as part of sensitivity analyses to assess how variations in clothing properties, obtained through different equations and corrections, would impact the maximum exposure time for workers. The assessment of maximum exposure time was conducted based on two distinct criteria:

- D_Tre, representing the time it took for an average worker to reach a core temperature limit of *38 °C* (occupational exposure limit).
- Dwl_50, indicating the time it took for an average worker to reach the limit for water (sweat) loss.

With the exception of the measured clothing parameters resultant intrinsic thermal insulation (I_{clr}), and moisture permeability index (i_m), derived from measured thermal insulation and evaporative resistance), all parameters for the PHS simulations remained constant and aligned with the environmental conditions during lunchtime in the sugarcane fields of Latin America.

5.3.3 Summary of the main findings

The difference between measured values of the resultant intrinsic thermal insulation and those calculated according to equation (32) in ISO 9920 (ISO 9920 2007) ranged from *-0.6 to -3.6 %.* The accuracy of the equation (32) is sufficient and the difference decreased with the rising total thermal insulation for the ensemble. Bigger differences were found comparing the measured values with the prediction from equation (35) (*-27.9 %* for SC and *-27.3 %* for PS) and from equation used in EN 342 (EN 342 2004) (*-16.3 %* for SC and *-18.8 %* for PS). The issues is to choose the correct equation for clothing ensemble as it is not clear in some cases. From the perspective of thermal insulation, equation (32) from ISO 9920 (ISO 9920 2007) was the best fit for our clothing ensembles. On the other hand, equation (35) is meant to be applied to specialized clothing with impermeable layers, which was also true for used clothing sets. Equation from EN 342 (EN 342 2004) for cold protective clothing yields better results than equation (35) as it also takes into consideration impermeable layers, but used ensembles are not cold protective clothes. Although, it is possible to use these predictive equations to enhance the precision of thermo-physiological modelling in some cases, were it is clear which equation should be used, more versatile and robust equation should be developed on bigger database of clothing ensembles in the future.

For the evaporative resistance measurements, the mass loss and heat loss methods were firstly compared. For the SC ensemble, same results were obtained from both methods ($R_{et,h\_manikin} = R_{et,m} = 26.7\ m^2Pa/W$). For the PS set, the difference was slightly higher, amounting to *4,4 %* ($R_{et,h\_manikin} = 83.7\ m^2Pa/W$ and $R_{et,m} = 87.4\ m^2Pa/W$). Secondly, the discrepancies caused by the use of multiple corrections were investigated. In the mass loss method, the differences between values calculated from the manikin´s surface temperature and from the manikin´s skin temperature were *13.2 %* for the SC ensemble and *4.4 %* for the PS ensemble. Similarly, the heat loss method involved differences of *13.7 %* and *8.6 %* for SC and PS respectively. Moreover, when the correction for gains from the environment was used in the heat loss method, the differences compared to the raw values (calculated from the manikin´s surface temperature) were even higher *21.2 %* for SC and *8.7 %* for PS. We could see that the percentage differences between both the mass loss and the heat loss method are not significant when the same temperature (either the surface temperature or the skin temperature of the manikin) is used for their calculation. However, calculations based on the manikin´s surface temperature should not be used as this is not correct from a physical point of view. Water evaporates from the manikin's skin and not its surface, thus the vapor pressure of saturated skin needs to be used in the calculations.

The outcomes obtained through sensitivity analyses substantiate our observations regarding the utilization of the manikin's surface temperature. In the context of the SC ensemble, the criteria for core temperature were not met when the manikin's surface temperature was used in either the mass loss or heat loss approach. Conversely, when the projected skin temperature was adopted in both methods, the maximum exposure time was limited to approximately *55 minutes*. This discrepancy is substantial and holds the potential to introduce significant inaccuracies in PHS predictions, which could, in turn, have adverse implications for the well-being of sugarcane workers. When PS ensemble was used, the presence of multiple impermeable layers in the ensemble led to the minimal heat transfer between the skin and the environment, causing the mentioned corrections to exert minimal influence on calculated evaporative resistance values. This observation was further confirmed by the findings from the sensitivity analysis, where there were no disparities in exposure time based on water loss criteria and the core temperature limit was promptly reached (approximately within 30 minutes) across all scenarios.

Three independent measurements of evaporative resistance using heat loss method were conducted for the both sets. For SC ensemble, the standard deviation of three measurements was 0.90 and the values were within *4 %* (from *-3.74 %* to *2.15 %*) from their mean value. For the PS set, the standard deviation of three measurements was *2.76* and the values were also within *4 %* (from *-3.63 %* to *2,36 %*) from their mean value. These results shows very good repeatability of the measurements in the area of required precision of thermal insulation measurements stated in ISO 9920 (ISO 9920 2007).Results from this study show the need to correct for the pre-wetted skin temperature in the calculations of both methods in order for them to be physically correct.

5.4 Paper IV (Objectives I and IV): Insulation and evaporative resistance values of clothing for sugarcane harvesters and chemical sprayers in Latin America, and their application in PHS model-based exposure predictions

This study measured the clothing properties used in sugarcane fields in Latin America and utilized them in a standard tool for heat strain prediction - PHS. The aim of the study was to use the clothing parameters obtained during the manikin measurements used also for Paper III to obtain a heat strain prediction for advanced planning of a workday and for possible preparation of preventive measures against heat stress for sugarcane workers. Although more sophisticated prediction models could be used, the fairly simple PHS model was chosen for this study, as this model is easily available for everybody through web tool, has a low cost and has been validated in a wide range of hot conditions. The goal is to see of this model is capable of predicting heat strain for this kind of applications, for which the more sophisticated models might be too expensive to use. Exposure characteristics were calculated as the limit values of the core temperature and water loss based on an hour-by-hour approach under the extreme weather conditions of a hot day (with ambient temperature ranging from *18.6 °C* to *36.4 °C* and ground temperature ranging from *20.5 °C* to *52.1 °C*). This analysis encompassed various combinations of activity levels. Predictions were made for each hour separately and did not reflect the physiological status of the previous hour, thus there might be some overestimations or underestimations of the duration limited exposure (DLE).

For manikin testing, local values of total (I_t) and resultant (I_{tr}) thermal insulation were presented to analyze the impact of the movement on thermal insulation for different parts of the body. For evaporative resistance measurements, the local values were also presented to see the difference between body parts, which is important for use in more sophisticated thermos-physiological models.

5.4.1 Summary of main findings

Firstly, the impact of walking simulation was analyze. The whole body total thermal insulation (I_t) and resultant thermal insulation were compared for both sugarcane cutters (SC) and chemical sprayers (CP), reaching the difference of *25.3 %* and *26.8 %* respectively. These values are comparable with the prediction equation 32 from ISO 9920 (ISO 9920 2007). However, local thermal insulation in different manikin zones (body part) may vary from *0 %* (on Head) to *-48 %* (right hand) when SC ensemble was used and from *-2 %* (Head) o *-39 %* (Upper arms) when CP ensemble was used. The results clearly show the effect of body parts' swinging radius or being rigidly fixed in the walking manikin tests, where the biggest changes are for hands and feet, followed by arms and legs, then torso zones and finally the head, which is basically stationary during the test. For technical measurements and various model evaluations, we need to consider what differences between the zones do not match the reality. This may be built in the established correction equations in the future, e.g., for walking. There is also possibility of applying a higher air velocity during the measurements to offset for these differences, which might be very challenging as the differences are not similar for each zones.

Secondly, the local values and differences between different body parts were studied also for evaporative resistance data and as expected, huge differences were observed. When SC set was used, the values varied from $6.0\ m^2\ Pa/W$ (right hand) to $65.6\ m^2\ Pa/W$ (feet with protective boots). Similarly for CP set, the values varied from $20.4\ m^2\ Pa/W$ (head) to above $500\ m^2\ Pa/W$ (belly), where two tight impermeable layers were used on top of each other. This study utilized only the values for the complete ensembles in a standard occupational heat strain model PHS. However, it could be seen from the huge differences between body parts, why it is important to use sophisticated models with local values as input data for complex and more detailed purposes, for example in the area of protective clothing design development.

Lastly, measured clothing properties were used in the PHS model to predict heat train on hour-by-hour bases for workers on sugarcane fields in Nicaragua. The impact of heat exposure on workers wearing chemical protective clothing (CP) was significantly constrained by the rising core temperature. In oppose, for sugarcane cutters (SC), core temperatures surpassed *38 °C* only during the most vigorous activities and the hottest periods of the day. In such instances, it is recommended that continuous exposure should not exceed *50 minutes*, and it becomes essential to incorporate regular breaks for rest and hydration. The findings strongly reinforce the established suggestion to incorporate extended recovery/lunch breaks (*>2 hours*) in shaded, well-ventilated areas during the peak heat of the day, along with adequate fluid replacement. While the sensation of thirst might not hold as much significance compared to the increase in core temperature, dehydration can easily go unnoticed subconsciously (Parsons 2014). The results from the current study strongly recommend that more or less frequent drinking rest breaks should be enforced. By utilizing the PHS model to calculate water loss, recommendations for both the quantity and frequency of fluid intake can be approximated.

5.5 Paper V (Objectives V, VI and VII): Reproducibility of evaporative resistance measurements and calculations using different thermal manikins (to be published)

The aim of the final paper is to verify the reproducibility of the evaporative resistance measurements comparing the result from two different manikins measured in two different laboratories – Manikin TORE at Lund University and manikin NEWTON at BUT. The aim is to replicate the measurement scenario as much as possible and to compare the differences between the values obtained. Secondly, the goal is to accommodate all of the corrections for calculation of evaporative resistance from heat loss method proposed in the chapter 2.5 of this thesis and to analyze the impact of the corrections on the results. All corrections will be compared to the results of mass loss measurements using manikin´s skin temperature correction, as this values closer to the physical nature of heat transfer by sweating. As it is not possible to use mass loss method to obtain local evaporative resistance for different body parts, it is important to find the best possible calculation method for heat loss method, as it is crucial to obtain precise local values of clothing properties for thermo-physiological modelling. The study was conducted on 14 clothing ensembles covering the whole spectrum of thermal insulation from *0.5 clo to 3.2 clo* as described below.

5.5.1 Clothing ensembles

For the purpose of this study, *27* items from Taiga AB (Sweden) ambulance clothing system were tested individually on the thermal manikin Tore at Lund University according to ISO 15831 (ISO 15831 2004) following ISO 9920 (ISO 9920 2007) recommendations and basic insulation (I_{cl}) of each garment was calculated. More than *100* realistic clothing combinations were compiled and basic insulation was calculated according to the summation equation from ISO 9920 (ISO 9920 2007). Finally, *14* clothing ensembles were selected for this study.

Figure 4: 14 clothing ensembles from Taiga AB (Sweden) with basic thermal insulation from *0.5 to 3.2 clo* chosen for the study.

The clothing area factor (f_{cl}) of these ensembles were also measured using photographic method for both manikins TORE and NEWTON. It could be seen that the values for NEWTON manikin are slightly higher (in average by *4,6 %*), which is probably caused by slightly bigger dimensions of the NEWTON manikin and small differences in the shape of some body parts. Thermal insulation of chosen clothing ensembles were measured on manikin TORE at Lund University and were used in the calculation for evaporative resistance for both manikins, as there was no significant difference.

5.5.2 Measurement setup and equipment

Both manikins are dry manikins with no water supply and sweating simulation was done using pre-wetted tight-fitting skin from the same material (thickness *d= 0.9 mm*, *95 %* cotton, *5 %* elastane). Measurements using manikin TORE were conducted in the climatic chamber at Lund University, with dimensions height × width × length: *2 400×2 360×3 200 mm*. The manikin was placed in upright posture with the arms hanging freely with the air flowing to the manikin´s back. The whole setup was put on the scale (Mettler Toledo K240) to measure mass loss. For the manikin NEWTON measurements, the climate chamber in BUT (Fojtlín et al. 2016) was used, with dimensions height × width × length: *3 800×5 000×8 850 mm*. The setup was as close as possible to the measurements with manikin TORE - NEWTON was placed in the upright posture with the arms hanging freely with the air flowing to the manikin´s back and the whole stand was placed on the scale (Lesak 1T6060-LN/060kg) with the same precision as the Mettler scale used at Lund University. It was possible to setup the same conditions in both climate chambers with air temperature of *34 ±0.2 °C*, air humidity of *40 ±5 %* and air velocity of around *0.45 ±0.1 m/s* measured in three different heights one meter from the back of the manikin. Both manikins had the skin temperature of *34 ±0.2 °C* set and controlled.

5.5.3 Methods and Results

All 14 ensembles were measured twice on both manikins. The results were calculated as an average value from the two measurements on each manikin. Only the correction for manikin´s skin temperature was used while analyzing the reproducibility of the measurement.

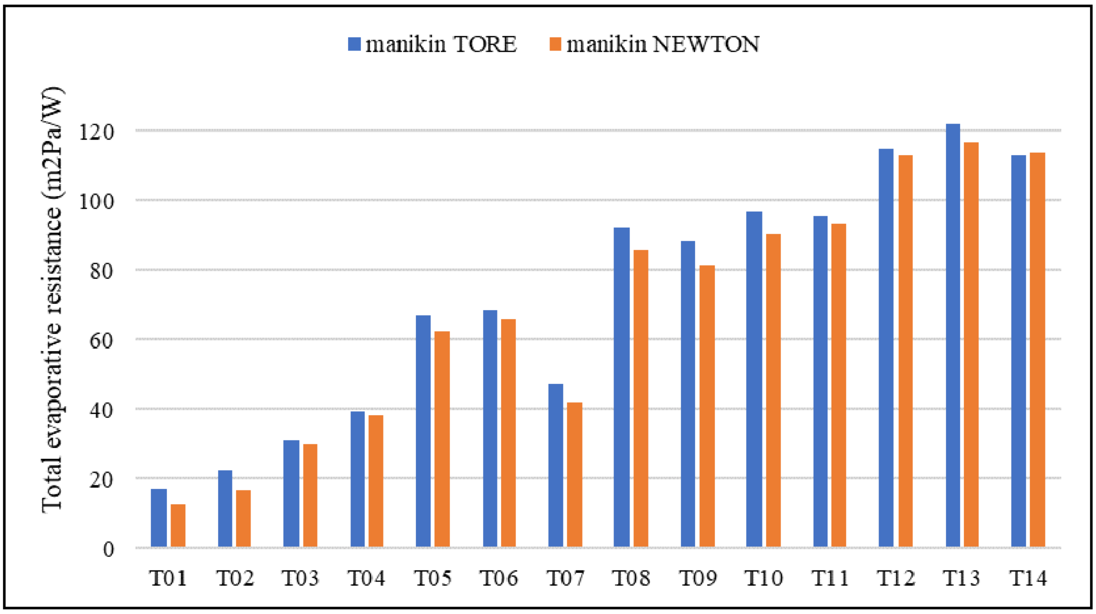

Figure 5: Comparison of total evaporative resistance values including correction for manikin´s skin temperature measured on both manikins calculated as an average of two measurements.

Paired two-tailed T-test was used to see if there is a difference between the total evaporative resistance (R_{et}) values obtain from different manikins. The p-value calculated from the T-test was *0.0000515* which means that there is enough evidence to suggest that there is a significant difference between these values. The same T-test was conducted for intrinsic evaporative resistance values (R_{ecl}) which takes into consideration slightly different shapes of the manikins´ bodies in form of clothing area factor (f_{cl}) for each ensemble. In this case, the p-value was *0.042*, which is very close to the significance level of *5 %* (*0.05*).

As mentioned earlier, mass loss method directly determining the intensity of mass transfer by evaporation, with the correction for manikin´s skin temperature (as we are only able to control manikin surface temperature) calculated as $\boldsymbol{R_{et,mass}} = \frac{\Delta p_{iso} * A}{H_{e,mass}} = \frac{(p_{sk} - p_a) * A}{\lambda * \frac{dm}{dt}}$ is closer to the physical nature of heat transfer by sweating, it was taken as the etalon calculation for evaluation of all corrections for heat loss method. Average values for each clothing set were calculated from all measurements (two measurements on TORE and two on NEWTON) for each correction. Paired two-tailed T-test was used to evaluate and compare the calculated total evaporative resistance (R_{et}) values from different corrections with the etalon value obtained from mass loss method using skin temperature ($R_{et\_Tskin\_mass\_loss}$). The same analysis was also done for intrinsic evaporative resistance (R_{ecl}) calculated using clothing area factors (f_{cl}). For the purposes of the correction evaluation, the *14* clothing ensembles were also divided into two groups and the corrections were tested in the same way using T-test for specific insulation groups – from *0.5 to 2.0 clo* and from *2.0 clo* to *3.2 clo*. The aim was to analyze the impact of the ensemble insulation on the calculated values through different corrections, as it was mentioned before that the corrections might be not needed for higher insulated clothing ensembles.

5.5.4 Summary of main findings

According to the results of statistical analysis, there is significant difference between the measurements on the manikin TORE and manikin NEWTON. These differences could be caused by size of the chamber with different air flow. The air velocity was control near the manikins in both chambers as stated above, but the air flow in the rest of the chamber is impossible to measure and thus, it may cause some differences. Another cause of the difference could be slightly different shape of the manikin´s bodies. It is important to compare the intrinsic evaporative resistance values, as those are calculated using clothing area factor (f_{cl}) and takes into consideration the shape of the manikin and fitting of the clothes. When comparing the intrinsic values, the results of statistical analysis was very close to the level of significance of *5 %*. As stated in chapter 2 of this thesis, the replications of thermal insulations measurements should not vary by more than *10 %* from the mean value according to the ASTM standard (ASTM F1291-16 2016) and we set similar level of desired repeatability in our hypothesis also for evaporative resistance measurements. This was achieved in all but two clothing ensembles with lowest insulation – for ensemble T01, the difference from mean value was *10.89 %* and for ensemble T02 it was *11.96 %*. This could be caused by drying of some parts of the manikin (especially parts not covered with clothing) during the test, as it is complicated to ensure wetness of the manikin´s skin when the evaporation is high while avoiding water dripping from the manikin. For the rest of the ensembles , the difference from the mean value was within *4 %,* which is similar to the thermal insulation tests according to the ISO 9920 (ISO 9920 2007).

As mentioned earlier, the correction for manikin´s skin temperature should be implemented in both measuring methods to be correct from the physical point of view. The mass loss method was used as etalon. According to our statistical analysis, it is needed to use the correction for manikin´s skin temperature for both methods. Corrections for the gains from the environment and moisture content in the clothing did not show good correlation with etalon values, unless there were used together with the correction for manikin´s skin fabric. Integration of this correction is very problematic, as it requires lot of input data about manikin´s skin, which are difficult to obtain and there is a risk of importing error to the calculation via this input data.
According to our measurements, there are no should be no differences in calculations for ensembles with different insulation. The statistical analysis showed the same results for ensembles below and also above *2 clo*. Thus, the results suggest that using of the correction for manikin´s skin temperature for heat loss method should be enough to obtain the evaporative resistance values with sufficient precision for thermo-physiological modeling.

6 CONCLUSIONS

This PhD thesis showed the development and integration of the measurement procedure and calculation methods to determine clothing evaporative resistance (R_{et}) using thermal manikin NEWTON at Brno University of Technology, including the precision validation and repeatability of the measurement.

The summary of the main conclusions from individual studies is as follows:

- Successful verification of the FMTK model, highlighting the importance to obtain precise clothing parameters as estimation is not sufficient.
- Estimation of clothing properties shows huge variations – the state-of-the-art methods to obtain clothing properties are using thermal manikin.
- It is necessary to use local values of clothing properties in thermo-physiological modeling to obtain precise predictions.
- Changing the body position results in a reorientation of various body parts and a redistribution of air gaps – it is important to obtain resultant clothing properties (I_{tr}).
- It is possible to calculate resultant thermal insulation (I_{tr}) from total thermal insulation (I_t) using equations in standards although one robust equation for all types of clothing would be beneficial.
- Methods to obtain thermal insulation (I_t) and clothing area factor (f_{cl}) are well documented and validated compared to methods to obtain and calculate evaporative resistance.
- Mass loss method is essentially correct, but it is currently not possible to obtain local values from this method due to technical limitations of the measurement equipment – heat loss method needs to be used to obtain local values..
- Correction for manikin´s skin temperature should be used in both mass loss and heat loss methods, as it is correct from physical point of view – we are only able to control manikin´s surface temperature, not pre-wetted skin temperature.
- Corrections for the gains from the environment and moisture content in the clothing should be used only in combination with the correction for manikin´s skin fabric.
- Correction for manikin´s skin fabric is complicated because multiple input data needed about manikin´s skin – risk of importing errors to calculation and not enhancing the results any further.
- Usage of heat loss method correction is not dependable on clothing´s insulation – corrections should be used for all ensembles even above *2 clo*.
- Using only the correction for manikin´s skin temperature is sufficient.
- Important to measure intrinsic evaporative resistance (R_{ecl}) – takes into account manikin´s shape and fitting to the clothing.
- Evaporative resistance (R_{et}) measurement and calculation successfully accommodate on manikin NEWTON at BUT.
- In all but two cases (*10.89 %* and *11.96 %),* the results are within *4 %* from the mean values, which is significantly better than *10 %* set in our hypothesis.

The evaporative resistance measurements were successfully accommodated, performed and validated on manikin NEWTON at BUT. The differences between measured values were in most cases within *4 %* which exceeded our expectations. In some case the differences were higher (up to *12 %*) and occurred on the least insulated clothing ensembles, with some body parts not covered with clothing.

6.1 Future research

There are multiple areas which could be studied further in the field of evaporative resistance measurements.

- Heat loss method and its corrections were proposed and studied because it is very challenging, with current technical limitations, to obtain local values from the mass loss method, which is essentially correct and is closer to the physical essence of heat transfer by sweating. In this thesis, only the repeatability of the total evaporative resistance values were studied, thus it would be beneficial to study the repeatability of the measurements also for local values, as it was showed that local values are necessary to obtain precise thermo-physiological predictions.

- As it was showed in the thesis, the body posture can influence the orientation of various body parts and a redistribution of air gaps. Multiple equations for prediction resultant thermal insulation values are proposed and were studied in this thesis. It is important to note that these predictions are also made only for total values and not for local values. One robust equation would be beneficial to cover local values prediction for all types of clothing. Most importantly, there are no equations for calculation of resultant evaporative resistance. This is another huge area of knowledge gap, were it is necessary to either measure resultant evaporative resistance values (using movement simulation of the manikin) or to propose equation for its prediction from the static values.

- As the manikin measurements are complicated and require expensive equipment, it would be beneficial to find an alternative way to obtain or predict clothing properties. This is especially difficult for special and protective clothing with specific garments and impermeable layers.

6.2 Limitations

The sweat evaporation from the human body a clothing properties blocking this evaporation is such a complex process, that it is impossible to capture all its features with current technical equipment and methodology. For example, the sweat simulation on thermal manikin is even on all body parts and manikin´s surface temperature is also controlled on the same value, which is not the case in real situations. Another examples could be movement of the person wearing the clothes, moisture content stuck in the clothes from the previous activity, changing level of activity (sweating and cooling), changing air gaps or environmental conditions, such as changing temperature, air humidity or raining wetting the clothes from outside. Each of these effects plays a considerable role in the evaporation of the sweat and thus, in the thermoregulation of the person.

Further limitations are linked with the laboratory approach itself as several aspects presented in the real-life applications had to be omitted. For example, constant air flow, humidity and temperature in the climate chamber of the manikin or pre-set level of sweating.

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Introduction

I am motived, well-organized and flexible person seeking return to the more practical side of RnD projects, since I was involved in more economic and administrative side of RnD in recent years.

Work experience

01/2020 – SÚČASNOSŤ BRATISLAVA, SLOVAKIA
Innovation consultant
Ayming Slovensko s.r.o.
Identification of RnD projects for the purposoure of tax deduction

02/2018 – 12/2019 CZECH REPUBLIC
Doctoral student / researcher
Brno University of Technology, Energy Institute
Research and implementation of new measuring methodologies using sweat simulation method on thermal manikin

05/2018 – 10/2018 LUND, SWEDEN
Guest researcher
Lund University
Research of protective clothing properties based on thermal manikin measurements

06/2014 – 06/2017
MLADÁ BOLESLAV, CZECH REPUBLIC
Intern
Škoda Auto a.s.
innovative HVAC system project

02/2016 – 05/2016 BRNO, CZECH REPUBLIC
Intern
AZ Klima a.s.

Education

06/2016 – PRESENT CZECH REPUBLIC
PhD in Design and Process Engineering - Environmental Engineering
Brno University of Technology, Energy Institute

09/2014 – 06/2016 CZECH REPUBLIC
Master´s degree in Environmental Engineering
Brno University of Technology, Energy Institute

06/2010 – 09/2010 AUSTRALIA
English course
Perth International College of English
IELTS english course

Certificates

03/2017
CAE
Cambridge Assesment
https://bit.ly/2TiNeRT
Score 197

Languages

100 % Slovak

100 % English

20 % German

10 % Swedish

Publications

12/2020
Common clothing area factor estimation equations are inaccurate for highly insulating (Icl>2 clo) and non-western loose-fitting clothing ensembles
Industrial Health

11/2020
Validation of ISO 9920 clothing item insulation summation method based on an ambulance personnel clothing system
Industrial Health

04/2020
Insulation and Evaporative Resistance of Clothing for Sugarcane Harvesters and Chemical Sprayers, and Their Application in PHS Model-Based Exposure Predictions
International Journal of Environmental Research and Public Health

01/2020
Using a thermal manikin to determine evaporative resistance and thermal insulation – A comparison of methods
Journal of Industrial Textiles

11/2019
A comparison of methods for measuring thermal insulation of military clothing
Journal of Industrial Textiles

11/2019
Thermal model of an unconditioned, heated and ventilated seat to predict human thermo-physiological response and local thermal sensation
Building and Environment

04/2019
Local clothing properties for thermo-physiological modelling: Comparison of methods and body positions
Building and Environment

12/2018
Determination of car seat contact area for personalised thermal sensation modelling
PLoS ONE

08/2017
Verification of Fiala-based human thermophysiological model and its application to protective clothing under high metabolic rates
Building and Environment

Publications

01/2017
Impact of measurable physical phenomena on contact thermal comfort
The European Physical Journal Conferences

Skills

Driving license	**B2**
MS Office	
AutoCAD	
Autodesk Inventor	

Strengths

\# Well-organized # Optimistic # Punctual
\# Trustworthy # Patient # Pedantic

Hobbies

Ski touring
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Travel planning
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ABSTRACT

Global warming and environmental changes are currently one of the main topics discussed around the world. As we could start to see the signs of climate changes, more attention needs to be placed on the protection of humans health, as the changing climate could have impact also in places, were it was not the case in the past. Many professions, especially the ones using some kind of protective clothing, could be in danger from heat stress. It is known that sweat evaporation is the main thermoregulatory feature for a heat dissipation from the human body to the environment and these protective clothing, with combination with higher metabolic rates during the work, could be potentially dangerous. These are the reason why heat stress prediction models and thermo-physiological models are being enhanced and used widely. One of the most problematic input data for these models are clothing properties - thermal insulation, clothing area factor and evaporative resistance, whose inaccuracy could have huge impact on the resultant physiological prediction. Although thermal insulation measurements on thermal manikins are well tested, precise and reliable, this cannot be said about measurement of evaporative resistance using manikins, including manikin NEWTON at Brno University of Technology.

Thus, the aim of this study was the development of the measurement procedure and calculation methods to determine clothing evaporative resistance using thermal manikin NEWTON at BUT. Measurement setup and methodology was successfully validated using dataset measured on manikin TORE at Lund University, with the results laying within 4 % of the mean values in all but two cases. The results shows that with strict measurement methodology, it is possible to achieve good reproducibility of the measurement, which was not the case in previous studies. Furthermore, the results shows that repeatability of the measurement is also within 4 % on both manikins, as same repeatability precision is set in the standards for thermal insulation measurements. Lastly, the mass loss method is essentially correct and closer to the physical nature of heat transfer by sweating, but with the current technical limitations, it is very challenging to obtain local evaporative resistance values from this method. Thus, heat loss method must be used to obtain these local values. Multiple corrections for the calculation of evaporative resistance values from the heat loss method were tested and verified. This could be of interest to engineers and researchers in the field of thermo-physiological modeling, as local values of clothing properties are essential to obtain precise physiological predictions. Finally, the possibility to obtain evaporative resistance values at BUT could potentially bring new opportunities for projects and cooperations.

ABSTRAKT

Globálne otepľovanie a klimatické zmeny sú aktuálne jednou z najdiskutovanejších tém na svete. Keďže začíname vidieť jasné známky klimatických zmien, je nutné sa čoraz viac zaoberať ochranou ľudského zdravia pred tepelnou záťažou aj na miestach sveta, kde táto téma nebola v minulosti aktuálna. Pracovníci vo viacerých profesiách, hlavne v tých ktoré využívajú špeciálne ochranné odevy, môžu byť potencionálne ohrozený vplyvom tepla. Je známe že vyparovanie potu z tela je hlavným termoregulačným prvkom ľudského tela a práve použitie takýchto ochranných odevov, obmedzujúcich toto vyparovanie, v kombinácií s vysokou aktivitou môže byť zdraviu nebezpečné. Z týchto dôvodov sa do popredia dostávajú termofyziologické modeli alebo predikčné modeli tepelnej záťaže, ktoré sú neustále vylepšované a aplikované v rôznych situáciách. Jednými z najproblematickejších vstupných dát takýchto modelov patria vlastnosti odevu – tepelná izolácia, faktor oblasti prekrytia oblečením a odpor odevu proti vyparovaniu, ktorých nepresné hodnoty môžu spôsobiť veľké nepresnosti vo finálny predikciách týchto modelov. Napriek tomu že meranie tepelnej izolácie odevu pomocou tepelných manekýnov je už zavedené, spoľahlivé a presné, to isté nie je možné povedať o meraní odporu odevu proti vyparovaniu, ktoré je stále vo svojich začiatkoch.

Cieľom tejto práce bolo vyvinúť a implementovať experimentálne zariadenie, procedúru merania a spôsob kalkulácie pre získanie odporu odevu proti vyparovaniu pomocou manekýna NEWTON-a na VUT v Brne. Výsledky merania boli validované na základe dát nameraných pomocou manekýna TORE na Univerzite v Lunde. Reprodukovateľnosť merania bola na úrovni do 4 % rozdielu od strednej hodnoty takmer vo všetkých prípadoch. Výsledky ukazujú že je možné dosiahnuť dobrej reprodukovateľnosti merania pri striktnom dodržaní metodológie merania. Výsledky taktiež ukázali dobru opakovateľnosť merania, kedy bol dosiahnutý výsledok opäť na úrovni 4 % na oboch manekýnoch, čo je zároveň aj požadovaná hranica určená v normách pre meranie tepelnej izolácie odevu. Ďalším bodom práce bola verifikácia samotnej kalkulácie výparného odporu. Aj keď mass loss metóda určuje priamo intenzitu prenosu hmoty vyparovaním a najbližšie opisuje samotný jav vyparovania potu z ľudského tela, nie je vhodná pre určenie lokálnych hodnôt odporu proti vyparovaniu odevov z dôvodu technických limitácií senzorov a tepelných manekýnov. Z tohto dôvodu je použitá heat loss metóda, ktorej výpočet však musí byť korigovaný. Súčasťou práce bolo testovanie a verifikácia viacerých korekcií tejto metódy, čo môže byť prínosom výskumných pracovníkov z oblasti termofyziológie, keďže tieto lokálne hodnoty vlastností odevov sú pre dosiahnutie presných predikcii priam nevyhnutné. Úspešná implementácia a validácia možnosti merania odporu odevu proti vyparovaniu na VUT v Brne pomocou tepelného manekýna prináša taktiež nové možnosti pre ďalšie projekty a kooperácie v rámci výskumnej ci komerčnej činnosti Univerzity.