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Verification of Fiala-based human thermophysiological model and its application to protective clothing under high metabolic rates

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ABSTRACT

In the past years, a theory of how to predict human heat stress and thermal comfort using advanced thermo-physiological models has been broadly extended. These models are more complex than the well-established overall indices of the heat stress (ISO 7933) and thermal comfort (ISO 7730) and they allow to simulate the effects of metabolism, thermoregulation, and clothing on human thermal state in greater detail. However, the most discussed issue is a validity of such complex models. The validation process of multi-segment thermophysiological models has to be focused not only on the overall parameters, but also on the local ones. The aim of this study is to verify our implementation of Fiala-based model with similar models and measurements. To conclude with, the results were in a good agreement with the original Fiala model with respect to the simulation of the passive system, the active system, and the DTS index (Dynamical Thermal Sensation) for a wide range of ambient temperatures (from 5 °C to 48 °C). Further, the study covers testing of protective clothing, such as Tychem-F and military NBC (nuclear, biological, chemical) suit FOP M2000 including the Klimatex underwear. The mean absolute deviations (MAD) of rectal temperature, mean skin temperature, and local skin temperatures, valid for protective clothing in a range from 25 °C to 40 °C and metabolic rates up to 4.3 met, were 0.20 °C, 0.78 °C and 1.25 °C respectively.

1. Introduction

The interaction with ambient thermal environments is everyday experience of human beings. Mostly, it is not wittingly perceived and people respond to the stimulus subconsciously, especially when the conditions are comfortable. In uncomfortable environments (hot or cold), people tend to acclimatize themselves by altering their clothing, posture, activity or HVAC setting (Heating, Ventilation & Air-conditioning). If this is not applicable, the exposure to an inappropriate thermal load is perceived as a thermal stress, which can lead, in extreme situations, to hypothermia or hyperthermia. To reduce these risks, mainly under challenging environmental conditions, a well-designed and correctly used protective clothing is needed. A special category of protective clothing is a chemical protective clothing that prevents contamination of human skin and respiratory system with hazardous materials. Fabrics used to produce protective suits are typically less permeable compared to standard materials, or even impermeable. This directly influences sweat evaporation, moisture transport, and reduces effective cooling power of moisture evaporation, which may cause a severe heat stress under warm/hot conditions or at higher metabolic rates. In extreme situations, an uncompensable heat stress manifested by uncontrolled body temperature rise is life threatening. To prevent hazards of heat stroke, the design of chemical protective clothing plays an essential role with respect to its protective abilities and permeability properties. Moreover, there is also a need to test the already commercially available ensembles and reveal their performance under typical conditions of operation. In the case of environmental conditions with a fixed metabolic rate according to Fletcher et al. [1], the exposure is considered safe until the deep body temperature exceeds 38.5 °C.

For the fast screening of the effect of environmental conditions on a human, it is possible to use well established indices expressing the heat stress, such as: PHS (Predicted Heat Strain) - ISO 7933 [2], WBGT (Wet Bulb Globe Temperature) - ISO 7243 [3], and thermal

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sensation and comfort PMV/PPD (Predicted Mean Vote/Predicted Percentage of Dissatisfied) - ISO 7730 [4]. PHS and PMV indices are based on the overall heat balance of the human body and require a small amount of input data to quickly yield reasonably accurate results.

On the other hand, in some cases, these results have a rather coarse character and need to be taken carefully. Mainly in the case of the protective clothing and higher metabolic rates, the more complex thermophysiological models are recommended to be used instead: "*It should be noted that WBGT is rough screening index, and for screening such as simplification may be acceptable. For detailed analysis of protective clothing effects, more complex models would be needed though*" [5]. In the cited paper by Havenith & Fiala, a variety of problems regarding heat stress indices and thermophysiological modelling are discussed along with their limitations and recent development.

Thermophysiological models simulate human physiological responses in a complex way describing the heat transfer phenomena inside the body, and also the heat exchange with the ambient environment. Generally, these types of models are able to take into account: (1) the body constitution (weight, height, fat percentage, etc.), thermoregulation and cardiovascular system; (2) environmental conditions (air temperature, air speed, relative humidity, and mean radiant temperature); (3) personal factors (activity level, clothing insulation – thermal resistance and water vapour permeability).

One of the first and major motivations to develop human thermophysiological models was the evaluation of heat stress under various environmental conditions. Attempts to compose numerical models started in the 60's of 20th century as a part of medical research for military purposes. Such models were aimed to simulate the physical characteristics of the human thermal regulatory system in transient conditions including a simulation of blood vessel system (for detailed description see Wissler's 225-nodes model [6]). A later 25-node model by Stolwijk [7] was used for NASA to monitor the performance of Apollo astronauts. The main improvement of the model was an incorporation of thermoregulatory mathematical model. The development of the multi-segment models continued with the Fiala [8] and Tanabe [9] models designed also for thermal comfort applications. Their motivation was to extend the capability of the approach to deal with the asymmetric transient environmental conditions, which is not possible with the whole-body thermal comfort models based on the heat balance principle, e.g. Fanger [10] and Gagge [11]. Until now this issue has not been solved completely and there is a need for reliable thermal sensation/comfort predictions that are capable to capture non-uniform transient conditions, with a potential to become a basis for ISO standard [12].

Today, except for the original codes by Wissler et al. [6,13] and Fiala [8,14], there are other Fiala-based models either for scientific purposes (e.g. ThermoSEM [15,16]) or codes implemented in commercial software (e.g. Theseus-FE [17], Radtherm [18]). Certain models allow for personalization of the input parameters, namely body weight, percentage of body fat, etc. Although the theory behind the Fiala model is well described and documented, the model is mostly a part of commercial software and the source code is proprietary.

The reliability of the Fiala physiological model was the motivation to derive the Universal Thermal Climate Index (UTCI) [19], which was proved to be a more complex indicator of human thermal stress than the previous individual heat stress indices [20]. Also, a combination of Fiala-based model as the virtual manikin with the real thermal manikin was investigated by Hepokoski et al. [18]. In recent years, a virtual manikin has been incorporated and coupled with the advance simulation tools dealing with the complex simulation of heat transfer using the CFD (Computational Fluid Dynamics). This opens a new space for virtual thermal comfort engineering to directly investigate the local effects of the environment on the human using thermophysiological models for a detailed design and case studies [21–23].

The research in the field of thermoregulation models lasts for more than 60 years and the development of advanced models was also influenced by the rise of computational power. The introduction of the UTCI index was one of the first achievements that contribute to a higher acceptability of thermophysiological models by the community in environmental ergonomics. Yet, there are still many challenges with regards to special applications of the model, e.g. the area of protective clothing, thermal comfort predictions, and exploitation of physical or virtual thermal manikins.

Apart from plentiful opportunities, every simulation has its disadvantages which stem mainly from its complexity. On one hand, complex models provide detailed results about human thermal state; on the other hand, they require rather detailed input data. Katić [24] states that *"Even though sophisticated models were developed … the accuracy of the inputs has to be assured in order to incorporate models in the design process of buildings and daily applications of thermal comfort*". In practical applications, this means that a precise determination of environmental and personal parameters is essential to obtain satisfactory results. Moreover, the equipment required to do so might be available only in laboratory conditions. From the authors' experience, the problematical part is a precise specification of the metabolic rate. Even more uncertainty lies in identification of local insulation and permeability properties of clothing. Both mentioned parameters are defined as follows.

Metabolic rate can be specified by ISO 8996 [25]. *"The direct measurement of oxygen consumption provides the most accurate estimate of metabolic heat production. However, it is difficult to measure oxygen uptake in the field … These limitations make other, simpler, metabolic rate evaluation methods more practical for field measurements. Other methods to assess heat production are direct and indirect calorimetry methods and simpler indirect methods based on heart-rate measurements"* [26].

Thermal and evaporative resistance of clothing can be determined according to ISO 9920 [27] and also directly measured using a guarded hot plate - ISO 11092 [28] or a thermal manikin - ISO 15831 [29]. 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 Refs. [30,31]. However, a detailed specification of clothing properties for each individual is rather problematic. The main problem is a dressing procedure specific for each person, which implies hardly predicable air gaps and openings. Also, permeability of membranes and thermal resistance of garments depend on the treatment with this specific piece of clothing over time (washing, etc.). Another fact to consider is that the data in ISO 9920 are mostly measured on a stationary manikin while in the field the actual thermal resistance is typically lower than in laboratory conditions. Namely, the human body motion inflicts the boundary layer at the clothing surface, and even the air flow through the clothing layers and in the air gaps is more intensive.

1.1. Motivation

A wide acceptability of the Fiala model is mainly because of its extensive validation by different laboratories. Martinéz et al. [32] verified the latest version of the original Fiala model (FPCm5.3) against experimental data. The root-mean-square deviations (rmsd) of core, mean skin and local skin temperatures were 0.26 °C, 0.92 °C and 1.32 °C respectively.

These results correspond with findings of Psikuta: "*In particular,*