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REVIEW OF THE DOCTORAL DISSERTATION

Candidate's Name: **Otgonsuren Sukhbat, M.Sc.**

Title of the doctoral dissertation: **Shaping the physiological comfort performance of multilayer clothing assemblies for firefighters**

Supervisor: **Prof. dr hab. Eng. Małgorzata Matusiak**

Reviewer: **Dr hab. Eng. Katarzyna Majchrzycka, Prof. CIOP-PIB**

Basis for the preparation of the review:

Contract work No. W4D/D/Dz/2023/15 of the Lodz University of Technology, Faculty of Material Technologies and Textile Design, dated July 24, 2023.

1. Scientific Value of the Dissertation

1.1 Relevance of the Research Topic and Originality

The doctoral dissertation concerns issues related to the design of heat and moisture transfer through textile sets intended for the construction of clothing for firefighters. This topic is widely published in scientific literature. Such great interest in shaping thermal comfort in protective clothing used by rescue services results from the characteristics of work conditions. Due to the lack of possibility to identify hazards that may occur during rescue operations, the primary purpose of using protective clothing is to provide maximum protection in the expected environmental conditions. For this reason, the materials used in the protective clothing for firefighters must be highly resistant to flame and the penetration of chemical substances, and at the same time they should have appropriate mechanical strength. Another important element is also the need to ensure isolation of the respiratory system from inhaling contaminated and hot air, which significantly worsens the thermal discomfort of firefighters. For this reason, methods to improve the ability to remove heat emitted by a firefighter's body and reduce skin temperature while maintaining a high level of protection are still being searched for.

Research works are carried out in many directions due to the significant difficulty in achieving a compromise between the safety of the clothing user and his comfort. Initially, researchers were focused on the selection of textile sets using materials that are able to transport heat and moisture from the skin to the outer layer. In the following years, technically advanced materials started to be used, such as superabsorbents and phase change elements in particular. In recent years, work has been focused on cooling systems applied to the bottom layer of protective clothing. Research was also carried out on the development of IT tools for designing heat flow through textile sets.

Despite great interest in the above issues, no significant improvement in the comfort of work in protective clothing used by firefighters during rescue operations has been achieved so far. It can therefore be concluded that the research undertaken as part of the doctoral thesis is still valid.

The work is part of the research direction related to the development of textiles used to improve human safety in the work and life environment. The scientific nature of the doctoral dissertation consists in testing a number of variants of material sets intended for clothing and underwear for firefighters and, on this basis, developing theoretical foundations for shaping the comfort of the clothing use. The work was particularly focused on the analysis of moisture transport through textile sets. The knowledge gained while modeling the geometry of material sets has the implementation potential.

1.2 Scientific Value of the Chapters

The doctoral dissertation includes eight chapters documenting the course of research and the obtained results, including their analysis.

In the first chapter, the PhD student explained the purpose of the work and formulated a research hypothesis. Cognitive aspects were emphasized that are an added value to previously presented in the literature research results. Explanation of the moisture transport phenomenon in multi-layer textile sets intended for protective clothing, including the underwear was considered to be the key issue.

The second chapter contains the literature review related to the topic. The review covered many formal threads related to the analysis of hazards occurring in the work environment of firefighters, as well as legal requirements related to the examination of protective clothing in the system related to making these products available on the common EU market. This knowledge is essential when designing new products intended for protection during rescue operations. It is important to remember that thermal comfort, although very important for humans, must be considered after the protective properties of the clothing are provided at the required level. An extensive fragment of the literature review concerned the analysis of research related to broadly understood thermal comfort, with particular emphasis on the phenomenon of water vapor transport. Much space has been devoted to the analysis of issues related to the construction of protective clothing for firefighters, focusing on their multi-layer structure and the underwear used, but relatively few references concern shaping the parameters of multi-layer material sets intended for protective clothing for firefighters in terms of thermal comfort using research methods such as a skin model, a sweating torso or a thermal mannikin.

The third chapter presents theoretical considerations related to the transport of heat and liquid moisture through multi-layer sets of textile materials. The phenomena were analyzed taking into account the transfer of heat and mass through textile layers and air present between the clothing components. Generalized equations were formulated to describe the thermal resistance of multi-layer clothing during use and the transport of liquid moisture through multi-layer textile materials.

The fourth chapter presents the materials and methods used when conducting the planned tests. The experimental part included tests of materials typically used in firefighters' clothing and underwear constructions, with a focus on possibility to improve the comfort of using protective clothing during rescue operations. The chapter describes in detail the research methods used in terms of equipment and measurement procedures. A discussion regarding measurement limitations and adopted research variants is also included.

Chapter five focuses on presenting the test results of thermal insulation properties of materials used in the design of protective clothing for firefighters. It contains the results of research conducted by the PhD student along with a discussion based on the state of knowledge in this area. At the end of the chapter, conclusions are presented, which constitute the PhD student's contribution to expanding knowledge about the possibilities of shaping thermal comfort through the appropriate selection of the number and geometry of layers of textile sets intended for protective clothing for firefighters.

In chapter six, the PhD student presents the results of research on the penetration of water vapor through textile sets intended for clothing for firefighters. Similarly to the previous chapter, an extensive discussion of the results obtained is presented, and conclusions are formulated at the end of the chapter.

Chapter seven presents an analysis of the phenomenon of moisture transport through materials intended for clothing and underwear for firefighters. The cognitive value of the content from this chapter should be emphasized in the context of acquiring new knowledge regarding the design of protective clothing products. In conclusions, the PhD student highlighted the significant impact of the geometry of knitted fabrics used to produce underwear on the efficiency of transport of liquid accumulated on a firefighter's skin during rescue operations in the protective clothing. This gives a basis for the conclusion that when designing new products, the selection of the appropriate geometry of the layer in direct contact with the skin of the clothing user will be of key importance for the efficiency of liquid drainage.

In chapter eight, an attempt was made to describe the textile set using the General Quality Index. This idea of the PhD student should be considered worth emphasizing. The use of this type of approach is very important in the process of designing new complex products. This saves the designer's time and work, as well as the costs incurred to implement product innovations. The chapter contains conclusions. It was emphasized that selection of the parameters for the calculation of the General Quality Index and determination of the significance of their impact on achieving the assumed functionality are particularly important.

The doctoral dissertation also contains an unnumbered chapter presenting final conclusions directed on obtaining new knowledge.

2. Scientific rigor of the Dissertation

2.1 The ability to justify the research problem

The research problem was formulated on the basis of a literature review, in particular the work conditions of firefighters and published research results related to the possibility of shaping the microclimate under protective clothing. It has been shown that despite numerous works carried out by scientists around the world, the problem of improving the comfort of work in protective clothing used during rescue operations is still worth taking up.

It was noted that the issues discussed in the doctoral dissertation are only related to comfort, and do not include issues related to the protective properties of the material sets selected for analysis. However, it is difficult to treat these two issues separately, because the level of protection provided by protective clothing should be appropriately selected to the expected conditions of use in the work

environment and the higher the level of protection, the worse the properties of material sets related to thermal comfort. However, in the dissertation, the PhD student indicates awareness of the essence of this issue, which allows to assume that the knowledge generated as a result of the work is mainly focused on the stage of preliminary design of textile sets intended for the production of protective clothing for firefighters.

The PhD student placed particular emphasis on the lack of research related to the transport of moisture through layers of protective clothing and underwear. Another interesting idea is the possibility of using the General Quality Index in the process of designing new products. The justification for undertaking research work has been properly documented and does not raise any objections.

2.2 Clarity of the formulated research hypotheses

The main goal of the doctoral thesis was to develop theoretical foundations for shaping the construction of textile sets intended for clothing and underwear for firefighters, with particular emphasis on moisture transport.

One research hypothesis was presented. It assumes that the appropriate selection of materials in a multi-layer clothing set intended for the construction of protective clothing, including underwear, will improve the firefighter's thermal comfort while performing professional activities.

The hypothesis presents rather a generally formulated issue. It is difficult to find confirmation of the innovative nature of the research work in relation to previous research known from the literature. In particular, there is no reference to the possibility of influencing the course of moisture transport through the layers of the textile set as a phenomenon little examined by previous researchers, in accordance with the PhD student's request.

In the thesis also the attempt was made to use the General Quality Index for the initial assessment of multi-layer clothing sets and underwear knitted fabrics intended for firefighters' clothing. This issue was not reflected in the research hypothesis, although this method of approaching the comparative analysis of sets should be considered innovative and valuable from the point of view of manufacturers of this type of products.

2.3 Selection of research methods and statistical tools for data analysis

The research was carried out on woven and knitted fabrics typically used for the production of protective clothing for firefighters and commonly used underwear. Material samples were taken from the ready-made products. In the case of clothing, these were products certified with the CE conformity mark. 28 variants of multi-layer sets were created from materials taken from protective clothing and underwear.

In order to test the properties influencing on the firefighter's thermal comfort the following methods were selected:

- Moisture Management Tester,
- Alambeta,
- Permetest.

They allow for quick measurement of selected parameters and are suitable for the initial assessment of textile sets at the design stage of new products in terms of their thermal insulation properties and ability to transport water vapor and moisture. The measuring instruments had specialized software enabling the determination of all important parameters, although the Permetest failure prevented all planned tests from being performed.

In the context of the selection of the research methodology, there is, however, a lack of information on what was the basis for the selection of this equipment, taking into account the

availability of other methods used to assess the comfort properties of protective clothing (i.e. skin model, sweating torso, thermal manikin).

In most cases, statistical analysis was performed using non-parametric post-hoc tests: the Kruskal-Wallis ANOVA test and the Median test. The selection of tests was preceded by an analysis of the possibility of obtaining reliable results of statistical analysis, taking into account the distribution of the obtained test results and the number of variables. The statistical analysis was performed correctly, although it would have been more beneficial to perform at least 4 repetitions for the statistical analysis instead of 3 repetitions performed by the PhD student in the case of tests conducted with a use of Alambeta and Permetest.

The PhD student conducted the research program in a sufficient manner to formulate final conclusions appropriate to confirm the cognitive challenges posed.

2.4 Critical analysis of results and the ability to interpret them against the background of subject literature

The PhD student's ability to synthesize and analyze research results should be appreciated. The documentation of the research works carried out includes a summary in each area, which clearly proves the achievement of intermediate goals aimed at confirming the hypothesis.

The variants of multi-layer textile sets used in the research, consisting of materials used for the production of protective clothing and underwear for firefighters, enabled to obtain sufficient data to conduct an analysis aimed at identifying key relationships of the influence of individual layers on the heat and moisture transport. This will enable designers of this type of products to select appropriate materials in terms of their geometry and arrangement in the ready-made product. It has been proven that optimal and appropriate selection of materials in the textile set can improve the comfort of work in firefighter clothing.

It is worth to emphasize the systematicity of the analysis of research results and formulation of indirect conclusions, which contributes to obtaining gradual confirmation of the set research goals.

3. Editorial correctness of the dissertation

The doctoral dissertation contains all information that, in a logical and understandable way for the reader, illustrates the PhD student's cognitive path from formulating the research problem until it is resolved. The basic substantive content is described in eight chapters, the layout of which is clear and correct. The initial chapters constitute an introduction to the research issues, including the premises for formulating a research hypothesis and a review of the literature on the topic. The further chapters constitute the main core of the doctoral dissertation. They present the course of theoretical and experimental research work. The chapters have a similar arrangement of presented content and contain research results and their discussion. Chapter eight discusses the concept of the General Quality Index, which constitutes an attempt to support design activities related to new products for firefighters. The doctoral dissertation ends with an unnumbered chapter containing a summary of the obtained results with a focus on demonstrating the achievement of the research hypothesis.

In addition to the basic content, the doctoral dissertation contains an exhaustive list of selected abbreviations and terms. Nevertheless, the PhD student did not avoid some inaccuracies, e.g. with regard to thermal resistance, the unit ' mK/Wm^2 ' was given incorrectly in many places, while on page 11 the correct ' Km^2W^{-1} ' was given, and the same applies to the units of water vapor resistance

('mK²/W or m²Pa/W' is given in the list of symbols, and later in the work the incorrect 'mK²/W' appears mainly) and thermal conductivity (on page 73 'W/m/K' is given, while 'mW/m.K' is given on page 75). Moreover, the same symbols are given for different parameters (e.g. thermal resistance 'R' and 'r'). The abbreviation 'EU' (European Regulation instead of European Union) was also incorrectly explained.

Appropriately described 51 tables and 94 figures are presented in the thesis. Most of them are authored by the PhD student, while for the rest the literature sources are given. They illustrate the results of the research carried out. Documentation related to measurement stands and research procedures is also described. Figures and tables are referenced in the text of the dissertation in a chronological and appropriate manner. They enrich the presented content and facilitate proper understanding of the results of the work carried out.

The references are presented in a unified form. The PhD student analyzed 169 literature items. Literature references in the text of the dissertation are justified and indicate the PhD student's knowledge of the theoretical foundations related to the areas of research. However, normative references in the list of literature require corrections, as the dating of standards EN 469, item 46 and EN ISO 11611 item 47 is incorrect.

The doctoral dissertation was written linguistically correctly, but it should be noted that in many places different terms were used for the same parameter of the weight per square meter, e.g. weight of per square, mass per square meter, surface mass, area mass. This requires correction.

4. Critical Comments

- Section 4.2.3 presents Permetest as a device that determines, among others, water vapor resistance expressed in 'm²Pa/W', indicating that the measurement is, in principle, similar to testing on a skin model in accordance with the provisions of the ISO 11092 standard. However, the description lacks detailed methodological assumptions, in particular the exact conditions for conducting the tests, e.g. air velocity and explanation of quite a wide range of relative humidity from 45% to 60%.
- PhD student mentioned that water vapor resistance tests were conducted in isothermal conditions in constant temperature conditions (section 4.2.3). Such methodological approach is proper in order to avoid dry heat transfer and provide only wet heat transfer due to evaporation during the tests. However, all results obtained from tests performed with a use of Permetest presented in the dissertation are expressed in 'mK.m².W⁻¹' so including temperature difference between the sides of the sample (expressed by Kelvin in the provided unit) what suggests non-isothermal conditions. This requires clarification.
- In Section 8 on page 166 it is written that position "1" corresponds to the lowest position, while position "28" corresponds to the highest position in the ranking, and the higher the General Quality Index, the higher the quality (p. 179). This means that in Table 8.1 the variant for which the lowest thermal resistance value was obtained was considered the worst. This approach is questionable, so please explain this classification decision.
- In the case of protective clothing for firefighters, it is required that water vapor resistance according to EN 469 standard cannot exceed 45 m²Pa/W (level Z1). Attention was drawn to the fact that although the material sets, according to the PhD student's declaration, were taken from the certified protective clothing, only the SS3 set obtained a value of the water vapor resistance below the required level of 45 m²Pa/W. Have the results of water vapor resistance been verified with data available from the manufacturer of individual variants of material sets? How can these discrepancies be explained?

5. Final assessment

The main achievement of the PhD student was to expand the knowledge regarding the design of textile sets intended for protective clothing for firefighters and underwear in order to improve thermal comfort. Research on the phenomenon of liquid transport through textile sets and an attempt to qualitatively assess them using the General Quality Index should be considered as particularly important. The proposed concept of assessing the quality of multi-layer sets intended for clothing and underwear for firefighters based on the selection of parameters that have a significant impact on the transport of heat and moisture is worth its dissemination. There is a chance that the introduction of the General Quality Index into design practice will contribute to shortening the time needed for pre-implementation work of new products intended to protect firefighters. It is also possible to further develop this concept for other types of protective clothing.

The doctoral dissertation submitted for a review constitutes the independent and original work of the PhD student, in particular regarding:

- selection of combinations of layers of textile sets containing both protective woven fabrics and knitted fabrics, the main purpose of which is to improve the comfort of use of protective clothing used during rescue operations,
- establishing a program of research and theoretical considerations related to the analysis of parameters influencing the development of thermal comfort of textile sets used for the construction of protective clothing and underwear, with particular emphasis on the little-recognized phenomenon of liquid transport with a use of MMT device,
- the concept of using the General Quality Index to assess the quality of textile sets intended for protective products in terms of ensuring that the final product achieves the most satisfactory thermal comfort.

The PhD student demonstrated knowledge of the study and analysis of phenomena occurring in materials intended for the construction of products for firefighters in terms of heat and moisture transport. In the construction of textile sets, PhD student used a new concept of combining woven and knitted fabrics, which allowed for a total assessment of the thermal comfort of the clothing and underwear set. In my opinion, the goal and hypothesis of the doctoral dissertation have been achieved. It has been shown that through the appropriate selection of materials included in the protective clothing and underwear worn by a firefighter, it is possible to influence parameters related to thermal comfort. This may contribute to improved work comfort during rescue operations, which is one of the important elements of the system for ensuring safe work conditions.

The PhD student conducted a constructive analysis of the research results and drew correct conclusions. What is worth emphasizing is the consistence of conducting the research aimed at solving the established research problem, as well as the fact that the thesis, in addition to its cognitive values, also has a measurable practical effect.

Based on the literature review attached to the doctoral thesis, I also confirm the PhD student's activity in disseminating knowledge through publications, e.g. Matusiak, M.; Sukhbat, O. Influence of Stretching on Liquid Transport in Knitted Fabrics, published in *Materials* in 2023 and Matusiak M., Sukhbat O. Liquid moisture transport in knitted fabrics in relaxed and stretched state, *Communications in Development and Assembling of Textile Products* published in *Autex Research Journal* in 2022, as well as co-authorship of papers presented at international conferences, e.g. Kamińska D., Sukhbat O., Matusiak M. Investigation of The Moisture Transport in Protective Clothing For Firefighters,

Proceedings of the 10th Central European Conference, Lodz 2019 and Matusiak , M., Sukhbat, O., Transport of liquid sweat through the multilayer textile assembly, Clothing-Body Interaction 2023, Berlin March 2023.

The critical remarks presented in the review are polemical in nature and do not detract from the positive assessment of the doctoral dissertation submitted for review.

Based on the above, I confirm that the reviewed doctoral dissertation titled "Shaping the physiological comfort performance of multilayer clothing assemblies for firefighters", prepared by Otgonsuren Sukhbat, M.Sc. meets the requirements stipulated in Article 187 of the Act of 20th July 2018, Law on Higher Education and Science. Consequently, I recommend to the Council for Scientific Degrees at the Lodz University of Technology, in the fields of mechanical engineering and materials engineering, to proceed with the further stages of the doctoral procedure for Otgonsuren Sukhbat, M.Sc.

A handwritten signature in blue ink, appearing to be 'Chap', is centered on the page. The signature is fluid and cursive, with a long vertical stroke extending downwards from the end of the word.