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COMPUTER–AIDED CLOTHING ERGONOMIC DESIGN FOR THERMAL COMFORT

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SUMMARY: Ergonomics is defined as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. Clothing is an essential means for human well-being, existence and survival, which involves study of humans and their environments, including anthropometry, biomechanics, textile engineering, clothing engineering, kinesiology, physiology, thermophysiology and psychology. Clothing provides a portable and personalized thermal environment that is critically important for human survival in extreme conditions and determines the health and sickness of human populations in daily life. Ergonomic design for thermal comfort involves the integration of multidisciplinary knowledge and has been a complex and long process of trial-and-error in traditional means. Utilizing proper mathematic models, computational algorithms, databases and increasing computer power and popularity, we can design and engineer apparel products for thermal comfort in an effective, economical and scientific way by using advanced CAD system. This paper presents a virtual thermal ergonomic CAD system for ergonomic design of clothing, which creates a virtual space for designers and engineers to design and develop apparel products and view their thermal functional performance without making the real garment samples. The thermal bioengineering framework and clothing ergonomic design principles are presented with case demonstrations.

Key words: *thermal environment, thermophysiology, clothing, CAD, thermal function, ergonomic design*

INTRODUCTION

Ergonomics is defined by the International Ergonomics Association ergonomics as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. Ergonomics is employed to fulfill the two goals of health and productivity *(International Ergonomics Association, 2008.)*.

Clothing ergonomic design for thermal comfort is not only critically important for human survival in extreme conditions as reported by G. Havenith *(Havenith, 2010.)*, but also important in active sporting activities *(Holmér, 2008.)* and for human thermal comfort *(Havenith et al., 2010.)*. However, traditionally clothing has been designed and fabricated to achieve required thermal functions largely based on personal

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experiences and semi-quantitative techniques, which is a time consuming and complicated process. Repeated actions of trial-and-error in the design are inventible and the design cycle thus is very long. It seems impossible to preview the dynamic thermal performance of any garment in design stage from available materials such as fibers, yarns and fabric in the interactions among environment, clothing and the human body. Further, it is extremely difficult to get a clear quantitative picture on the dynamic and interactive relationships among the human body, clothing and environment.

In order to accelerate the thermal functional design process, a concept of textile thermal bioengineering design was defined as the application of a systematic and quantitative way of designing and engineering apparel products to meet the thermal biological needs of the human body to maintain an appropriate microclimate for the protection, survival and comfort of the wearer *(Li, 2007.)*. This idea can be realized by integrating the achievements from a number of research areas: (1) development of theories, data and models on heat and moisture transfer behaviors in textile materials and the thermoregulatory behaviors of human body, as well as the thermal interactions between the human body, clothing and environment; (2) development of computational methods, visualization techniques and engineering database; (3) design and engineering of the material and clothing for desirable thermal functions; (4) fabrication of the end products and characterizing their thermal biological functions.

With the growing capability of computing and internet technologies, this thermal bioengineering system is able to be realized and delivered to the users in the world through a virtual thermal ergonomic CAD system. Given the definition of textile thermal bioengineering above, the development of the CAD system indeed involves the integration of multidisciplinary knowledge, including textile design principles, physical mechanisms and physiological mechanisms, mathematical simulation models, computational algorithms, user interfaces and functionalities, material engineering database and project data management techniques.

This paper reviews the development of a thermal bioengineering CAD system for thermal ergonomic design of apparel products, including the integration of multidisciplinary knowledge and the theoretical framework for textile thermal bioengineering. Based on this framework, the CAD system is realized by the development of the interfaces and functionalities of ergonomic design, computer simulation, visualization and project management functions, as well as the supporting engineering database. The user is enabled in a virtual space to design clothing and preview its thermal functional performance before making the garment, which is demonstrated with application cases.

THEORETICAL FRAMEWORK

The conceptual framework of clothing thermal ergonomic design is shown in Fig. 1. The design process focuses on the thermal dynamic interactions between human body, clothing and environment (HCE for short). Three domains of knowledge and information are essential, including: (1) human thermal biological processes, i.e. human thermophysiological mechanisms; (2) heat and moisture transfer processes in clothing; and (3) external thermal environment in terms of temperature, humidity and wind (direction and velocity). In clothing thermal ergonomic design process, it is of critical importance to develop deep understanding of the mechanisms and establish mathematic models to describe the mechanisms quantitatively for the three areas.

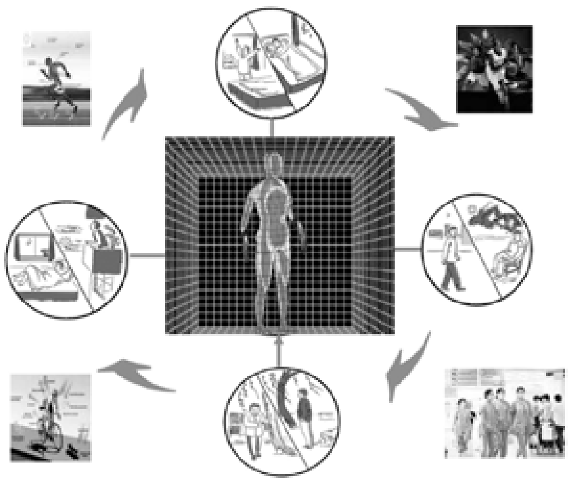

Figure 1. Thermal ergonomics of clothing system

Slika 1. Ergonomija termičkih svojstava odjeće

Heat and moisture transport behaviors in the textile material are the predominant factors that determine the thermal functional performance of apparel products in various wearing conditions. Commonly, the heat and moisture processes in the textile materials involve: (1) heat transfer in terms of conduction, convection and radiation, as well as the latent heat during various phase change processes, such as condensation/ evaporation and freezing/ melting that would occur in the fabric/yarn/fiber materials; (2) moisture transfer, in terms of water vapor diffusion and convection in the fiber interstices, liquid water diffusion through capillary pores in the fabrics/ yarns, moisture absorption/ desorption of fibers, and moisture condensation/ evaporation and freezing/melting. These physical mechanisms need to be described mathematically as equations to form the foundation for computational simulation of the heat and moisture transfer processes in clothing. The key criteria in selecting the mathematical models for developing CAD software include: (1) whether the models have clear physical meanings and (2) whether the key parameters in the equations have specific physical meanings and are measurable using scientific instruments as the basic structural and physical properties of constituting elements such as fibers, yarns and fabrics. By carefully examining the theoretical models published in the last few decades on the heat and moisture transfer processes in textile materials, a series of models were selected as the key solver for the CAD software *(Wissler, 1964., Li and Holcombe, 1992., 1998., Henry, 1939., Farnworth, 1986., Li, 2001., Li et al., 2001., 2004., 1999., 2003., 2004., 2005., Wang et al., 2003., Mao and Li, 2009., Guo et al., 2008.).*

In thermal ergonomic design, the ultimate goal of clothing is to provide effective thermal protection for the human body against various heat/cold environments and create a thermally comfortable portable microclimate for wearers. It is essential to take into account of the thermophysiological status and responses of human body and wearing conditions in computer simulation to predict and preview the thermal performance of the garments. In addition to the thermal function of the clothing, human body has an effective thermoregulatory system for maintaining thermal balance with external environment. When the body feels hot or cold, corresponding regulatory mechanisms such as sweating, skin blood flow changes and shivering will be activated to maintain the core temperature of the body returns to the set up value. The human body maintains thermal balance with the external environment by the means of heat and moisture transfer. A number of mathematical models on the thermoregulatory system of human body have been developed and reported in the last few decades *(Gagge et al., 1971., Stolwijk, 1971., Fu, 1995.).*

During wearing, the interactions between the human body, clothing and environment are dynamic and continuous, through which the thermal status of human body changes accordingly. Therefore, thermal ergonomic design of textile products needs taking account of the physical activities of human body, clothing and external environment in terms of temperature, humidity and wind changes in the four seasons, as shown in Fig. 2.

CLOTHING THERMAL ERGONOMIC CAD

Clothing thermal ergonomic design, as discussed above, needs integration of multidisciplinary knowledge and information from human thermophysiology, heat and moisture transfer in clothing materials and external thermal environmental conditions. To achieve the logic integration, it is essential to analyze the processes of dynamic interactions and develop a software architecture and information system to model, simulate and visualize the physical processes and physiological responses in the HCE system in various wear conditions, so that thermal functional performance of clothing can be previewed, as illustrated in Fig. 2. With the software architecture and information system, the thermal ergonomic design of textile products can be implemented and achieved via computer and internet. The CAD system for clothing thermal ergonomic design can be developed by expressing the knowledge and information involved with computer languages and programmes.

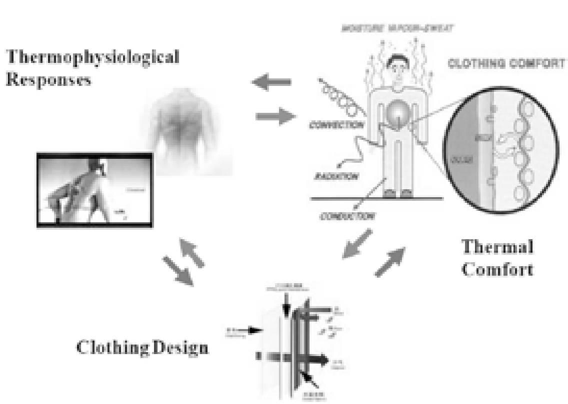

Figure 2. Thermal ergonomic design of apparel products

Slika 2. Ergonomija termičkih svojstava odjevnih predmeta

With the conceptual framework of the textile thermal ergonomic design, a CAD system has been developed as a software tool for end-of-users, which involves completion of a number of tasks: (1) investigating the theories and mechanisms of the complex and interactive thermal processes and behaviors in human body/clothing/environment; (2) development and selection of mathematical models and computational simulation in relation to design principles and procedures; (3) design of software architecture and development of computational algorithms to simulate the dynamic thermal interactions for predicting the thermal functional performance of final products from the basic material compositions, structural features and functional treatments; (4) design and development of user friendly interfaces and functionalities according the design procedures; and (5) design and develop engineering databases to support the ergonomic design process.

The computational algorithms and software architecture are the two key components in the CAD system. Computational simulation is developed on the basis of the physical mechanisms, theories and models that describe the heat and moisture transfer behaviors of fibers, fabrics and garments and thermoregulatory behaviors of human body as well as the dynamic interactions between clothing/human body/environment. Meanwhile, it incorporates the design principles with the physical laws and standards, as well as practices and codes that mostly come from the experiences of designers and engineers in the design decision making process. This component consists of the data characterization and collection, mathematical models and numerical algorithms.

The software architecture of this CAD system plays a very important role in encapsulating the complex models and databases, and computational algorithms that are needed for the computer simulation and preview of product thermal functions into user-friendly interfaces and design flows for general users. The potential users may have different knowledge background such as scientists, academics, engineers and students in the relevant fields and industrial sectors, as well as designer and buyers with abundant experience in fashion design and business operation, as well as ordinary consumers who want making wise purchasing decisions. The potential users may be further extended to other potential users who only understand simple computer operations. To enable these potential users, the CAD system needs to be designed and engineered in a simple flow to introduce the concept of thermal ergonomic design.

CAD SYSTEM REALIZATION

The innovative characteristics of clothing thermal ergonomic design leads to the fact that the development of the final CAD systems should consider the following issues: (1) it should be able to express and realize the concept of thermal ergonomic design of apparel products; (2) it can provide the flexibility to integrate different simulation models, which describe different thermal functions of textile products and thermal balance of human body; (3) it should provide the compatibility between the existing integrated models and the new simulation models developed in the future; (4) it is able to cope with the new user requirements by adding new functionalities into the software system.

The object oriented method was adopted to encapsulate the simulation models and to realize the open architecture of this CAD system. The simulation models *(Li et al., 2006., Mao, et al., 2008.)* were encapsulated into the Classes representing the clothing, human body, external environment and computational solver as individual objects, which were packaged with related properties and computational algorithms into the Class. The functionalities of this CAD system were developed by following the flow of pre-processing, computational simulation and post-processing. Fig. 3 shows the software architecture of clothing thermal ergonomic design CAD system, which has the following features: (1) clothing design is carried out with the parameter-specified virtual human body and wear conditions; (2) the simulation models are integrated with computational algorithms to generate numerical results by iterative computation; (3) the thermal status of the clothing, body and environment is visualized with 2D and 3D charts and 3D animations; (4) performance of the clothing can be analyzed and revealed with the preview of the dynamic temperature and moisture distributions of clothing and thermoregulatory responses of human body.

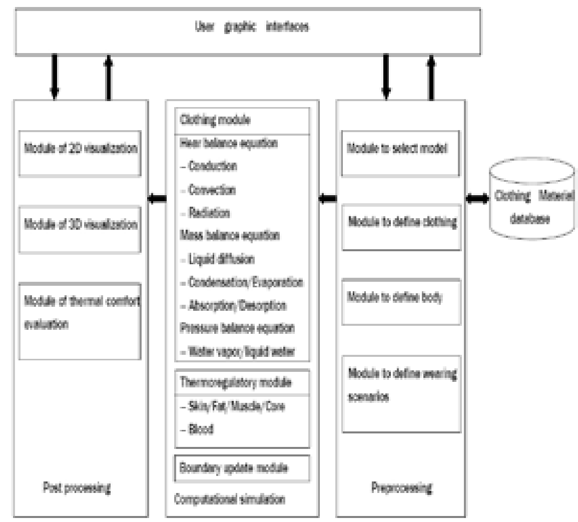

Figure 3. Software architecture in the textile thermal bioengineering CAD system

Slika 3. Prikaz CAD sustava za termički bioinženjering tekstila

In order to provide users with friendly interfaces and design wizards, an innovative concept of ergonomic design is employed in this CAD system to present the clothing design process, which guide the user to complete the thermal ergonomic design of an apparel product by just answering a set of simple questions, such as "What to do", "Environment", "Who" and "Garment". The information behind these questions will help to determine the required values of input variables based on the answers of "What to do", "Environment" and "Who". The user is required to specify what the activity schedule in wearing the clothing is, what are the climatic conditions for the scheduled activities, what is the physical, physiological and psychological status of the wearer before he/she starts to design the garment. The design principle is implemented in the CAD software interface, which is supported by the engineering database. The project data in the system were also managed with the database, including the design configuration of clothing material, human body and climatic conditions, simulation results and visualized files with the project ID.

(1) "What to do"

In this interface, the activities that are going to be performed and the duration of each activity when wearing the clothing are defined. Different typical activities including sports, games, and work are provided in the listed table. The user can arrange an activity schedule with reference to the metabolic rate of each activity.

(2) "Environment"

In this interface, the user is able to locate the virtual wearer in any expected place by setting the local climatic variables of temperature, relative humidity, air pressure, and wind velocity. If the user is not familiar with the climatic conditions of a particular place and time, he can search and retrieve it from the engineering database with the query conditions of location, date and time. Furthermore, each activity scheduled by the user can be specified in different climatic conditions.

(3) "Who"

In this interface, the wearer is defined by a set of physical, physiological and psychological parameters and can be accessed from the engineering database by the categorized conditions of gender, age and race. The virtual human body can be customized for any kind of person by the definition of physical and physiological parameters. This flexibility is very helpful for the designer to design the clothing and analyze the thermal performance of the clothing for any human population.

(4) "Garment"

In this interface, the garment is designed to be worn on the virtual human body with the sequence of wearing garment one by one. In each garment design, the first step for the user is to choose the style and fitting. Following that, the garment is designed by following a bottom-up engineering procedure: fiber→fabric→garment, in which the user can either define new fibers, fabrics and garments through the interfaces by inputting a set of parameters, which describe the structural, physical and thermal features and/or properties, or query the existing materials from the engineering database. The innovative technology/materials, such as membrane, phase change material, heating fabric and moisture management fabric, can also be selected in the garment design by inputting the values to their relevant physical properties that can be measured using available scientific instrument.

CASE DEMONSTRATION

A design case is given to illustrate the clothing thermal ergonomic design in the virtual thermal CAD system. This case compares two sets of personal protective clothing (PPC) for a hospital healthcare worker, who is a male with 61 kg weight and 171 cm height. The styles, fabrics and outlook of the PPC used for the simulation are shown in Fig. 4.

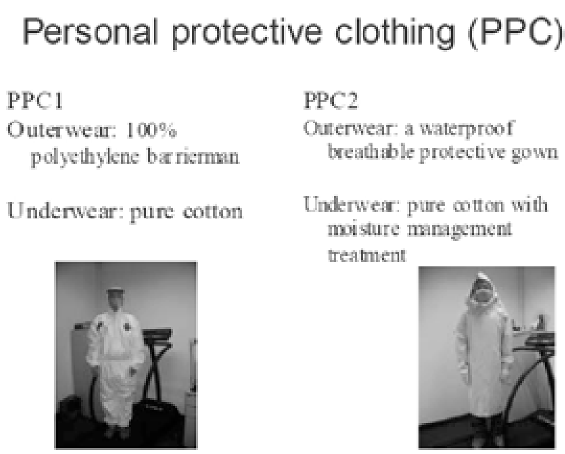

Figure 4. Computational thermal ergonomic design of personal protective clothing

Slika 4. Ergonomijski dizajn termičkih svojstava osobne zaštitne odjeće pomoću računala

The thermal ergonomic design follows the procedure below:

Step 1: Define physical activity protocol at "What to do?" interface.

The activity schedule for wearing this clothing is shown in Fig. 5, which consists of a series of successive activities with the designation of their durations.

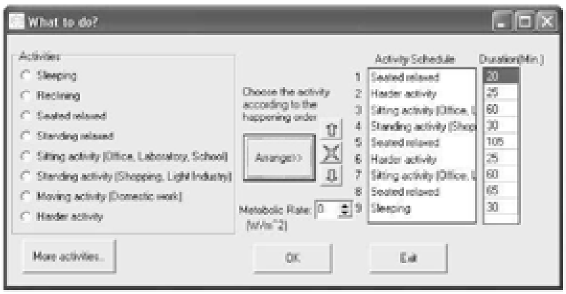

Figure 5. Define activity protocol

Slika 5. Definirati protokol aktivnosti

Step 2: Define environmental conditions at the "Environment?" interface

In this step, the climatic conditions for each activity in the schedule are specified in the Fig. 6, including the temperature, relative humidity of air and wind velocity.

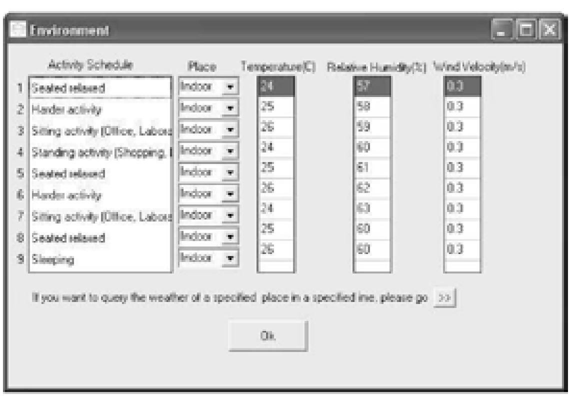

Figure 6. Define environmental conditions

Slika 6. Definirati uvjete okoline

Step 3: Define human body at "Who?" interface

The virtual human body is specified by defining the physical, physiological and psychological specification on the interface for "Who". Fig. 8 shows the interface for human body, in which customized specification of a wearer can be performed by inputting in physical parameters such as height and weight and a series of physiological parameters.

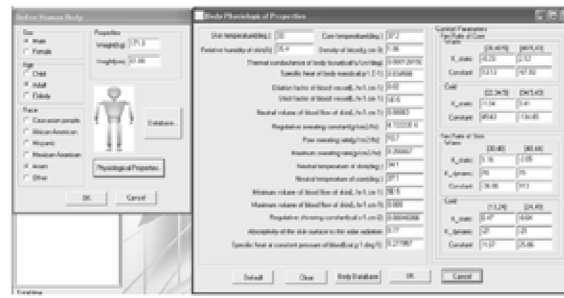

Figure 7. Define human body

Slika 7. Definirati tijelo čovjeka

Step 4: Design clothing at "Garment?" interface

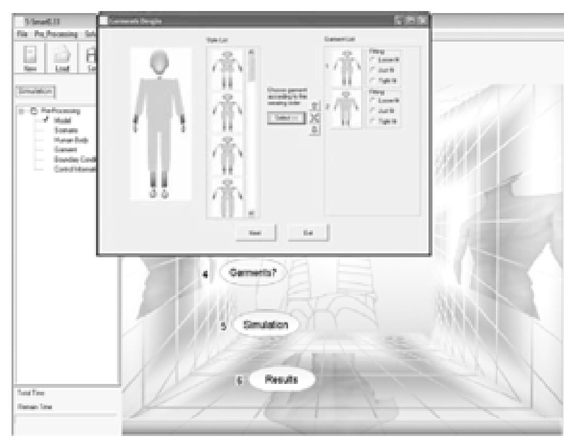

Figure 8. Select garment styles

Slika 8. Odabrati stilove odjevnog predmeta

The clothing design is performed with the accordance to the sequence of clothing style, fitting status and fabric composition. Fig. 8 shows the interface for selecting garment style with different cover ratios and fitness.

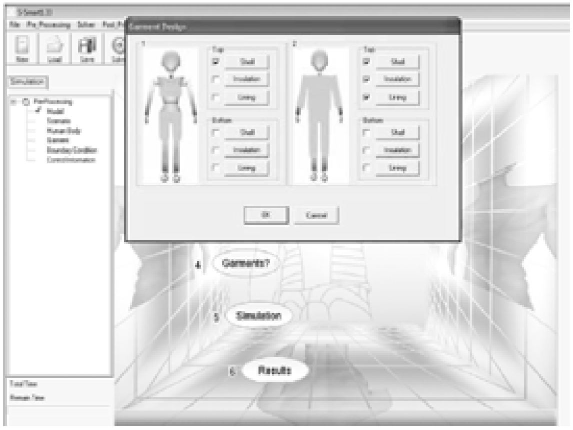

Figure 9. Define garment structure

Slika 9. Definirati strukturu odjevnog predmeta

Further, the garment structure can be defined in terms of number of layers in the garment, as shown in Fig. 9. Maximum of three layers can be selected for each garment.

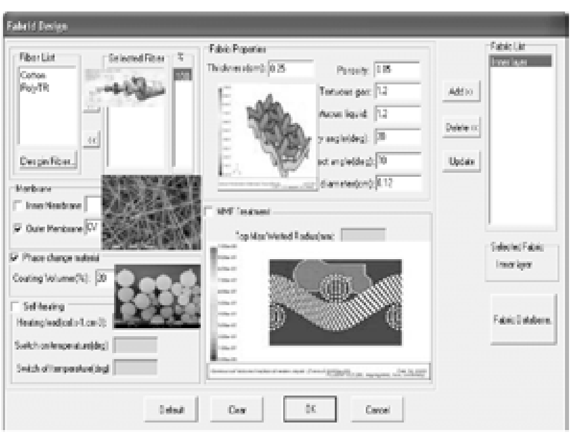

Figure 10. Design fabrics

Slika 10. Dizajn tkanine

The interface for fabric composition design is shown in Fig. 10. Fabric is designed in terms of selection fibers, fabric structural properties such as thickness, porosity, functional properties and compositions such as moisture management properties, water vapor permeability of membrane (e.g. Gore-tex fabrics), melting point and latent heat of PCM microcapsules and heating capability and temperature controlling settings of heating fabric.

Step 5: Define boundary conditions at the "Boundary Condition" interface

The boundary conditions for human body, environment and fabric layers in the garment can be defined, as shown in Fig. 11. The contact status, heat transfer coefficients and moisture transfer coefficients between skin and fabric, between fabric layers in the garment, and between the outmost garment and external environment can be specified. These factors are estimated according to the tightness of the garments, body movements and wind directions and speed in the external environment.

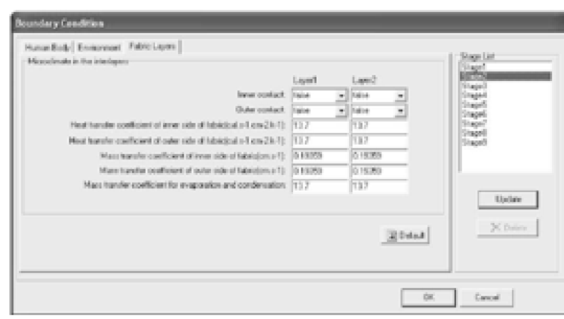

Figure 11. Define boundary conditions

Slika 11. Definirati granične uvjete

Step 6: Define computational control conditions at the "Control Information" interface

Fig. 12 is the interface for the user to define the control information, such as the time step, number of finite grids for fabric and fiber in computations. Importantly, the user also can change the cover ratio of clothing on skin surface according to the mode of wearing clothing, body movement and body postures in different stages.

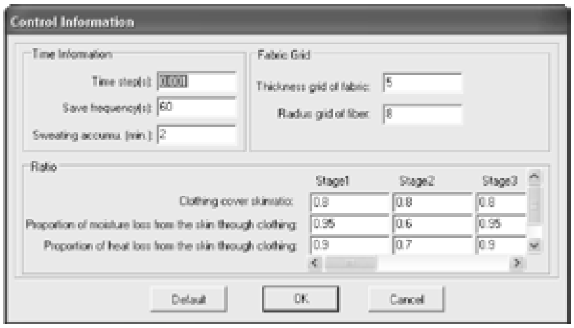

Figure 12. Define computational control conditions

Slika 12. Definirati kontrolne uvjete

Step 7: Computational simulations

After defining all the relevant parameters, the user can click the bottom "Simulation" to order the computer to start computational simulations, as shown in Fig. 13. After the simulation is completed, the users will be informed and the relevant data is generated and ready for view.

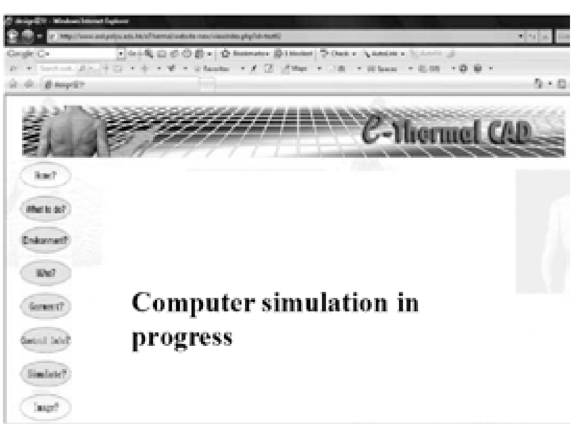

Figure 13. Interface of computational simulation

Slika 13. Sučelje za računalnu simulaciju

Step 8: Preview garment thermal functions with scientific data

The thermal functional performance of the garment designed can be previewed in terms of temperature and moisture distributions in the clothing, sweating rate, temperature and moisture distributions at the skin surface, as well as the thermophysiological responses of the human body such as skin blood flow and shivering rate and core and skin temperatures.

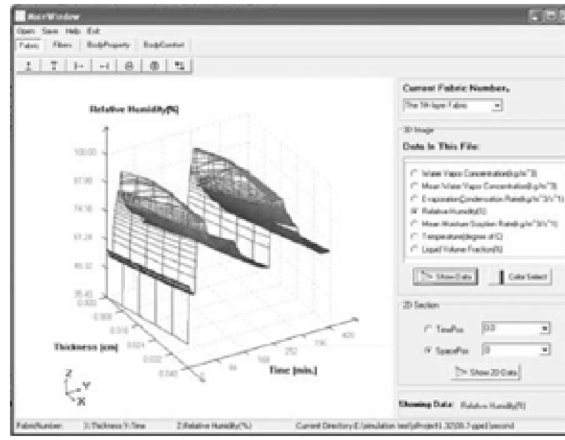

Figure 14. Relative humidity distribution at the first layer of garment in PPC1

Slika 14. Distribucija relativne vlažnosti prvog sloja odjevnog predmeta u OOZ1

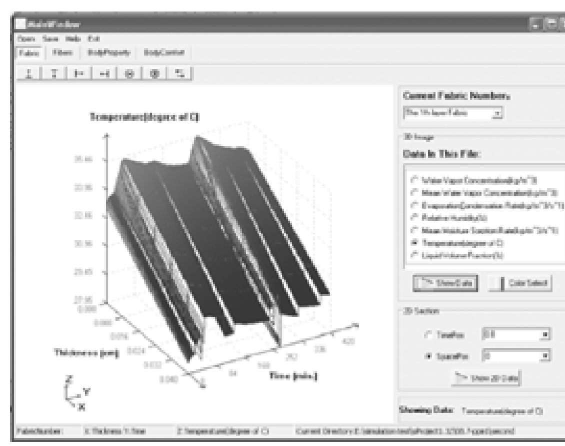

Figure 15. Temperature distribution at the first layer of garment in PPC1

Slika 15. Distribucija temperature prvog sloja odjevnog predmeta u OOZ1

As examples, the distributions of relative humidity, temperature at the first layer of garment in PPC1 are shown in Fig. 14 and Fig. 15, which are presented as scientific curves/surfaces along with the garment thickness from the skin to outer layer and alone with time duration of excises. Fig. 16 illustrates the dynamic relative humidity at the skin surface, outer surface of garment and outer surface of garment 2 by means of color mapping onto the virtual human manikin. This presentation can be viewed as animation movies to show the time effects.

Fig. 14 and Fig. 15 show the simulated temperature and water vapor concentration distributions in outwear during the wearing process. From which it can be observed that the temperature of outerwear changes during the whole day working protocol corresponding to the increased or decreased metabolic rates in different working period. The microclimate humidity was increased almost simultaneously with the start of exercise in the morning and falls in the afternoon after starting to work on the computer, and then was kept at a lower level during other working periods.

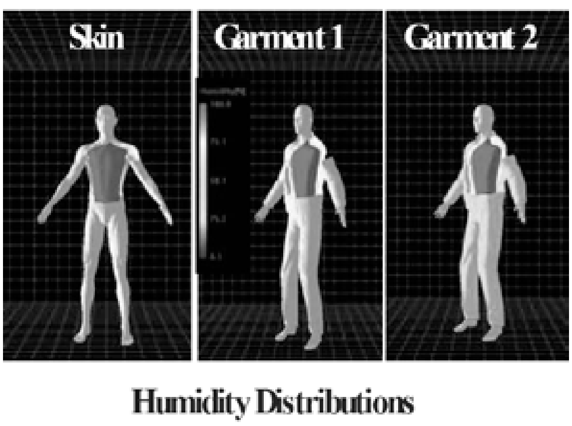

Figure 16. Humidity distributions at the skin surface, the first garment surface and the second garment surface of in PPC1 visualized on the 3D human manikin

Slika 16. Distribucija vlažnosti na površini kože, površina prvog odjevnog predmeta i površina drugog odjevnog predmeta u OOZ1 vizualizirano na 3D ljudskog manekena

Fig. 16 illustrates the 3D presentation of the humidity distributions at skin surface, at the surface of garment 1 and at the surface of garment 2 on virtual human thermal manikin in a virtual thermal environment.

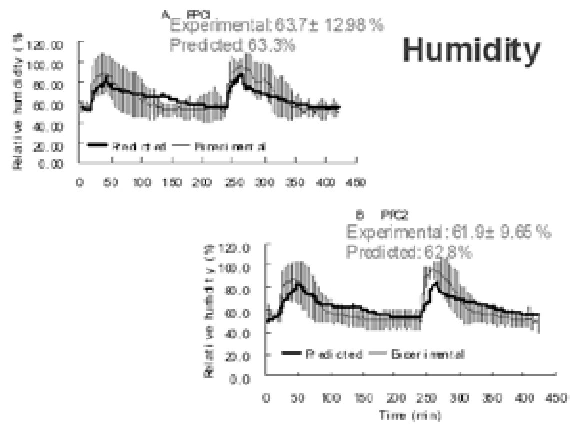

Figure 17. Comparison between simulated and measured RH distributions in PPC1 and PPC2

Slika 17. Usporedba između simuliranih i izmjerenih distribucija relativnih vlažnosti OOZ1 i OOZ2

The real wear trial study was carried out by using human subjects in a climatic chamber, which was controlled according to the same experimental protocol in the CAD design specification. The sensors were placed on the skin and clothing and in the deep ear canals to record temperatures and humidity continuously in the experiment (*Guo et al., 2008.*).

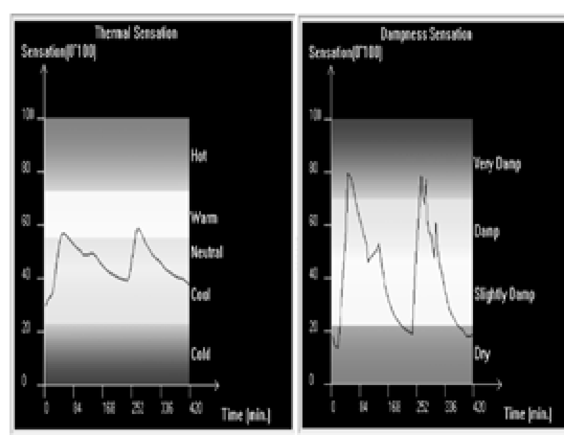

Figure 18. Predictions on thermal sensations, moisture sensation

Slika 18. Predviđanje osjećaja topline i vlage

Fig. 17 compares the simulation results (solid lines) with experimental results (error bars) of relative humidity at the skin surface, which shows that the simulation results have the same trends of the experimental curves and fall within the error bars, indicating that the simulation results of this computer aided system is acceptable.

Fig. 18 shows the predictions of the thermal sensation and moisture sensations for PPC1. The patterns of the thermal sensation and moisture sensation follow the changes of relative humidity shown in Figure 17.

CONCLUSION

This paper reviews a thermal CAD system for ergonomic design of apparel products. The concepts of thermal bioengineering engineering and thermal ergonomic are introduced. The theoretical framework for ergonomic design of clothing for thermal comfort is discussed. A CAD system is developed to realize the framework and guides the users to perform thermal ergonomic design with systematic specification of the input variables from human body, clothing and environment by following a simple and logic design procedure. A design case is illustrated to show the design and visualized results implemented with this CAD system with comparison with experimental curves derived from wear trials using human subject. This is our first version of CAD system developed for clothing thermal ergonomic design, which is accessible through Internet via the web address: Visit: http://www.asd.polyu.edu.hk/eThermal. All are welcome to use the on-line CAD software and give your feedback comments.

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RAČUNALNI ERGONOMIJSKI DIZAJN ODJEĆE ZA TERMIČKU UDOBNOST

SAŽETAK: Ergonomija je definirana kao znanstvena disciplina koja proučava interakcije između ljudi i ostale elemente sustava, te kao profesija koja primjenjuje teoriju, načela, podatke i metode dizajna kako bi optimizirala ljudsko stanje i ukupnu aktivnost sustava. Odjeća je ključna za ljudsku dobrobit, postojanje i preživljavanje, što uključuje proučavanje ljudi i njihovu okolinu, uključujući antropometriju, biomehaniku, tekstilno inženjerstvo, kineziologiju, fiziologiju, termofiziologiju i psihologiju. Odjeća pruža prenosivo, osobno toplinsko okruženje bitno za preživljavanje u ekstremnim uvjetima te utječe na zdravlje i obolijevanje ljudi u svakodnevnom životu. Ergonomijski dizajn za termičku udobnost uključuje integraciju multidisciplinarnog znanja i predstavlja jedan kompleksan i dugi proces koji se zasniva na pokušajima i pogreškama u tradicionalnom značenju. Primjenom matematičkih modela, računalnih algoritama, baze podataka i povećanjem moći računala i popularnosti, možemo dizajnirati i konstruirati odjevne predmete za termičku udobnost na učinkovit, ekonomičan i znanstveni način pomoću naprednog CAD sustava. Ovaj rad prikazuje virtualni CAD sustav za ergonomijsko dizajniranje termičkih svojstava odjeće. CAD sustav formira virtualni prostor za dizajnere i inženjere za dizajn, razvija odjevni predmet i prikazuje njegove termičke funkcije bez izrade stvarnog odjevnog predmeta. Termički bioinženjering i načela ergonomijskog dizajna odjeće su, također, prikazani.

Ključne riječi: *termička okolina, termofiziologija, odjeća, CAD, termička funkcija, ergonomijski dizajn*

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