Establishment of Computational Models for Clothing Engineering Design

MAO AIHUA
Institute of Textile and Clothing
Hong Kong Polytechnic University
Hung Hom, Hong Kong,
CHINA
Edward.mao@polyu.edu.hk

LI YI* (Corresponding author)
Institute of Textile and Clothing
Hong Kong Polytechnic University
Hung Hom, Hong Kong
CHINA
tcliyi@ polyu.edu.hk

WANG RUOMEI
Institute of Textile and Clothing
Hong Kong Polytechnic University
Hung Hom, Hong Kong
CHINA
tcruomei@inet.polyu.edu.hk

LOU XIAONAN
School of information science and technology
Sun Yat-Sen University
Guang Zhou, Guang Dong, CHINA
lnslxn@mail.sysu.edu.cn

Abstract: - Clothing design achieved by engineering framework and method is a newly interest in the state of art of textile research, which may create many advantages, such as improving the design efficiency and strengthening the ability to consider more issues. The mathematical models describing the behind physical and chemical mechanisms of the involved various behaviors inside the textile materials and the interactions at its boundary with external environment play an significant role in the clothing engineering design system, since they are able to offer designers/users an advanced ability to simulate and preview the function performance of the textile products. Whereas, the assumptions and simplifications of the development of computational models determine their potential/suitability to be developed as CAD/simulation software for engineering design applications. Considering this issue, the criteria for selecting suitable computational models for engineering design purposes is of enormous importance in the development of engineering design CAD system, and the communication sockets between the boundaries of different models integrated for simulating the different functions in the human body-clothing-environment system need to be developed with scientific and accurate data flows. In this paper, with the development of the framework of engineering design of textile product, the discussion of models selection criteria is presented considering the behind physical mechanism, application limitation, parameters measurability and data availability. A critical analysis of the well known models for the thermal behaviors in the clothing is conducted, and thermal functional engineering design systems for textile products with the integration of different computational models as well as boundary communication sockets are demonstrated.

Key-Words: - Computational models, selection criteria, engineering design, thermal functions, clothing

1 Introduction

Engineering design of textile products has been a major interest in the art of clothing design and production, which includes the concern of production engineering and innovated technologies treatment, the investigation of the mechanism and description models of involved behaviors and processes, the simulation the functions of the product, as well as the CAD/simulation system helping to achieve the design concepts and products. With this novel design method, new advantages are demonstrated in terms of continuously shorten the design cycle, saving time and money by avoiding realistic design trials, affording the ability to consider more issues related to the design process and functions of textile products. In the realization process of the engineering design of textile product, computational models describing the involved thermal behaviors in the textile materials are an important component to achieve the simulation of thermal performance of the textile product. Many mathematical models have been developed to simulate the heat and moisture transfer processes in textile materials, which take into account of moisture absorption/desorption, various phase change processes, and the effect of innovative materials such as waterproof breathable fabric, smart temperature regulating fabrics, heating fabric in the literature [1-8]. These efforts have laid down the foundation of computational simulation of thermal performance of textile products. However, in the development of these models many assumptions were made to define the problems and might be validated in special conditions, which in some degree causes the simplification of the considered issues and directly determine their potential/suitability to be developed as CAD/simulation software for engineering design applications. How to select the suitable models for engineering design purposes is a critical issue in the development of engineering design CAD system.

This paper firstly reports the development of a framework for thermal functional engineering design of textile products. With the presentation of the framework, the criteria for selecting suitable computational models are discussed with the considerations of the physical mechanisms behind the models, their application limitations and measurability of parameters in the models, as well as the availability of the data needed. A critical analysis of the well known models for the thermal behaviors in the clothing is conducted and thermal functional engineering design systems for textile products that were developed on the basis of different computational models are presented.

2 Framework of engineering design of textile products

The apparel products play an important role in the healthy lifestyle of human beings by providing the functions of thermal comfort and protection. In the microenvironment between clothing and human body, the biological/physiological status of body and the thermal performance of clothing are highly interactive and influence the psychological/ emotional feelings of human. Considering the close relationship between the functions of apparel products and the healthcare and psychological comfort of human beings, the design and engineering process of textile products should not only consider the thermal functional performance of clothing, but also the biological responses and comfort feeling of human body, as well as the interaction between the clothing and human body, which also involves the effects from the wearing environment. Thus, the engineering design of textile products can be regarded an interdisciplinary collaboration work from a diversity of fields, which may integrate physical, chemical, biological, physiological and psychological knowledge, computational and simulation science, as well as engineering principles in a systematic, quantitative way.

Before building up the framework of engineering design for textile products, it is necessary to put the light on the thermal behaviors happening in the human body-clothing-environment system, which is illustrated in Fig.1, from which it can see the close interaction between the body, clothing and external environment. Predominantly, involves the following behaviors of heat and moisture transfer process in textile materials and biological thermoregulations in human body:

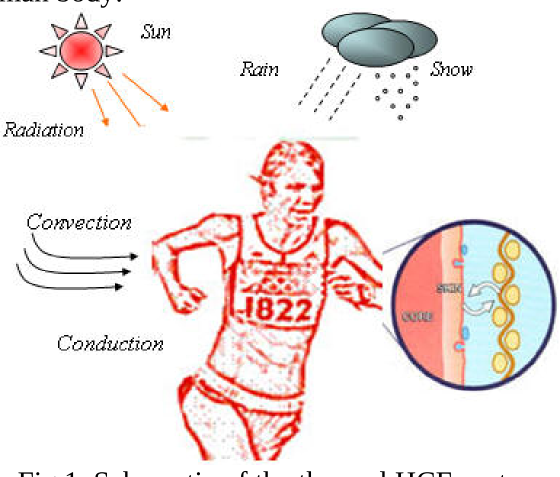

Fig.1 Schematic of the thermal HCE system

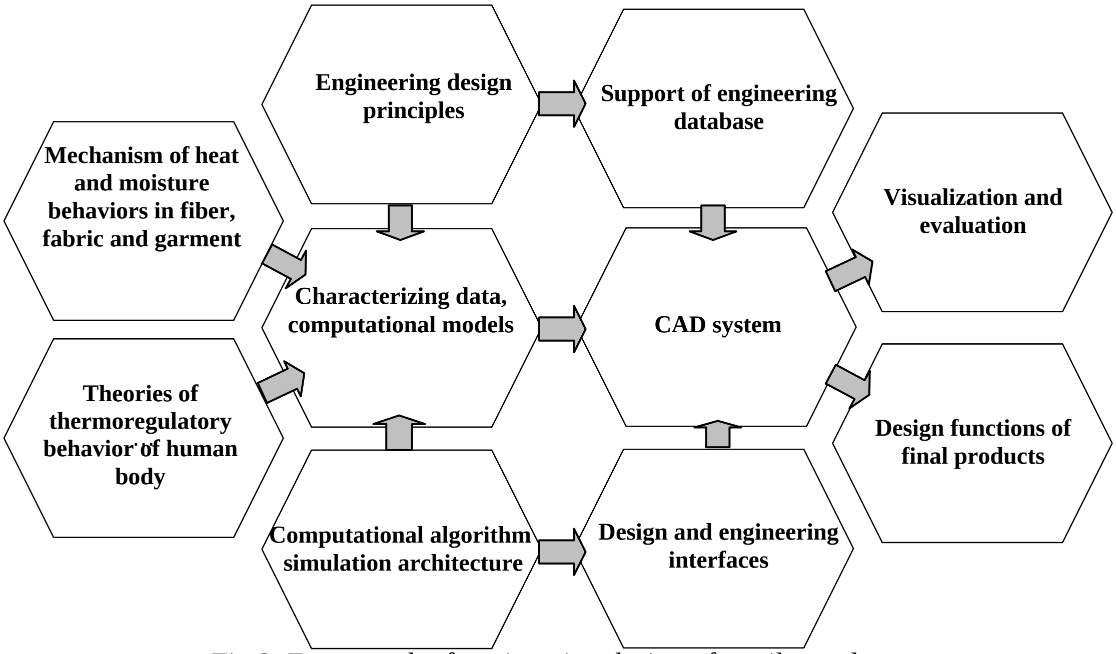

Fig.2 Framework of engineering design of textile products

1) The heat transfer process in clothing materials, which usually happens in the ways of heat conduction, convection and radiation across the textile material, and may be influenced by the latent heat of various phase changes in clothing materials, such as the heat release/absorption by the processes of condensation/evaporation and freezing/melting.
2) The biological thermoregulations in human body, such as the metabolic heat generation by muscles and organs, energy transferred by blood circulations, sweating and shivering, heat loss through skin in terms of heat conduction, convection and radiation, as well as heat evaporation of moisture through perspiration and sweating.

   The moisture transfer process in clothing, which involves moisture transferred by convection, moisture diffusion in the void space of textile material through capillary pores, moisture absorption/desorption in fibers, as well as moisture transformed by condensation/ evaporation and freezing/melting.
3) The interactions between the human body, clothing and environment, including the heat and moisture transfer through the boundaries between the clothing and the skin, the clothing and external environment, and the skin and external environment. The most inner and outer layers of the clothing undertake the formation of the boundary with the skin an external environment.

Considering the above analysis, the design and engineering process of the thermal functional textile product can be realized with the following framework, as shown in Fig.2, which demonstrates the involving knowledge and technologies from diverse fields. Under this framework, the engineering design of textile products starts from investigating the theories and mechanism of involving complex and interactive thermal processes and behaviors in clothing and human body, follows the development of the computational models and simulation and design principles, finally achieves the thermal functional products with the aid of the CAD system, which is the friendly presentation of the engineering design process with computer graphic interfaces and computations

3 Selection criteria for computational models

From the framework illustration, it can be seen that the computational models play a particularly important role in the engineering design process of textile products, which are utilized to describe and simulate the involved thermal behaviors in computational way by characterizing the complex thermal processes and properties of clothing and human body with measurable/experimental data, meanwhile is a core component to develop the CAD system with the corresponding computational algorithm and simulation techniques. However, during the development process of these computational models, a number of hypothesis and assumptive conditions were given to define the special considered issue and might be validated in the special configurative cases. When thinking about the potential/suitability of these models to be directly integrated to the engineering design process and system for general and free design and applications purpose, there are some considerations need to be taken into:

- Whether was the computational model developed with clear physical meanings such as reasonable scientific hypotheses? Are the parameters in the models related to the real structural and physical properties/process of the materials? Are the parameters involved in the models measurable in industrial engineering processes?
- Whether is there close interaction between the human body models and clothing models so as to enable the integration between them with smooth communication sockets?
- Do the computational algorithms/simulation programs are developed with a clear engineering design framework and are user-friendly as simulation tools?
- Whether are the computational algorithms/ simulation programs suitable for industrial participants to use in designing and engineering their products and validate their predictions and simulation results?
- Whether is the simulation program supported by a good engineering database that contains the fundamental technical specifications of the raw materials, semi-products and final products?

With the judgment balance provided by these criteria, it is able to create a more scientific and systematic view to employ the suitable and robust computational models to the engineering design system and enable the design and simulation of the textile products to be more applicable and effective.

Table 1 Critical analysis of the computational models

Computational models	Hypothesis /application limitation	Parameters/data availability in the models	Interaction of clothing and body models	Computational algorithms/simulation programs
Farnworth model [1]	Radiation heat transfer	Estimated by other theories	No	Applied/ inherited into other research work
Henry model [9]	• Coupled heat and moisture transfer • Ignored moisture sorption	• Decided by linear relationship • Experiential data	No	Only valid over small ranges of the conditions
Fan and Luo model [4]	• Coupled heat and moisture transfer • Considered radiation effect • No clear description of mechanism of condensation/evaporat ion process	• Measurement • Calculated by some assumptions	No	Simulated with different fibers in specified conditions
Li and Zhu model [6]	• Coupled heat and moisture transfer • Liquid diffusion • Condensation/evapo ration • No radiation effect	• Experimental data • Measurement • From other references	No	Validated by comparison between simulation and experimental results
Li and Holcombe model [10]	• Coupled heat and moisture transfer • Water vapor two-stage sorption of wool fiber • 1D body thermal balance	• Calculated by rules • Experimental data • Measurement	Interaction at whole level	Validated by comparison between simulation and experimental results
Li f. model [11]	• Based on Li and Zhu model • Body thermal balance in multi-parts	• Experimental data • Measurement • Referred to other reference	Multi-parts interaction	Validated by comparison between simulation data and results from other reference

4 A critical analysis of computational models

A critical analysis of the well known computational models for describing the complex heat and moisture behaviors in clothing material and biological thermoregulatory activities of human body is conducted according to the above discussed criteria, as listed in Table1.

These models explored the computational approaches to describe and simulate the thermal behaviors in the textile materials in various considered conditions. Though most of them have been developed into simulation programs for validation purpose, no engineering design framework can be found in them and no engineering database support is presented.

5 Development of CAD systems

Under the framework of engineering design of clothing, various CAD systems achieving for different design requirements and principles are able to be developed by the application of different computational models, which need to be employed and integrated with the condition of right boundaries and smooth data flow, as well as scientific communication sockets. The final presentation of the engineering design system with different CAD software tools can illustrate different functionalities and capacities for clothing functional design and simulation, as well as the results visualization and analysis.

5.1 1D clothing thermal functional design system

A CAD system which integrates the clothing and human body simulation models referring to Li and Zhu's model [6] and Li and Holcombe's model [10] is developed according to the engineering design framework. It is able to carry out 1D clothing thermal functional design, and analyze the thermal performance of individual fabric layer on the whole level.

In this system, the clothing heat and moisture models are composed by a series of partial differential equations, whose numerical solution is obtained by developing computational algorithm with specification of the boundary conditions. By analyzing the interactions in the Human body-clothing-environment system, the development of the boundary condition equations for the clothing models is accomplished by reference to the thermal status of the external environment and body. For instance, for the clothing heat and moisture equation, at the inner side of the clothing close to the skin surface, the sweat evaporation from the skin and dry heat loss of body are concerned and calculated respectively for the clothed area and unclothed area, which was infused into the data flow built up between the human body and clothing models on the purpose of communication. Furthermore, concerning the gap between the clothing and body skin, the contact and non-contact states, which are judged by the volume of sweat accumulation, are distinguished. The boundary conditions in these two states are different due to the change of the heat and moisture transfer media.

With this integration between models, the design and simulation of body, clothing and environment thus are able to be considered systematically and carried out as a highly interactive work in a virtual space. During the simulation of the thermal performance of clothing, the communication between the clothing and environment is executed dynamically to update the thermal statuses of clothing and human body at the boundary. As illustrated in Fig.3, communications between the human body, clothing and environment primarily happen at the boundary of the inside and outside fabric layer of clothing, and the body skin, which could be covered by clothing or expose directly to environment.

The CAD system, named with P-smart, as the presentation of the engineering design system delivered to users and designers, was developed with computational algorithm based on the mathematical models and computer technologies. Fig.4 shows the interface of fabric design in the CAD system, which includes the basic structure information and various functions treatments, also the supports of engineering database. Fig.5 shows the 1D visualization of the simulation results, relative humidity distribution of clothing and body skin during the wearing scenario.

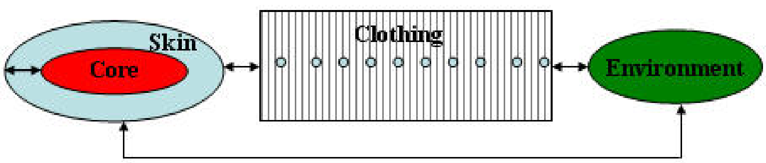

Fig.3 Communication between body, clothing and environment

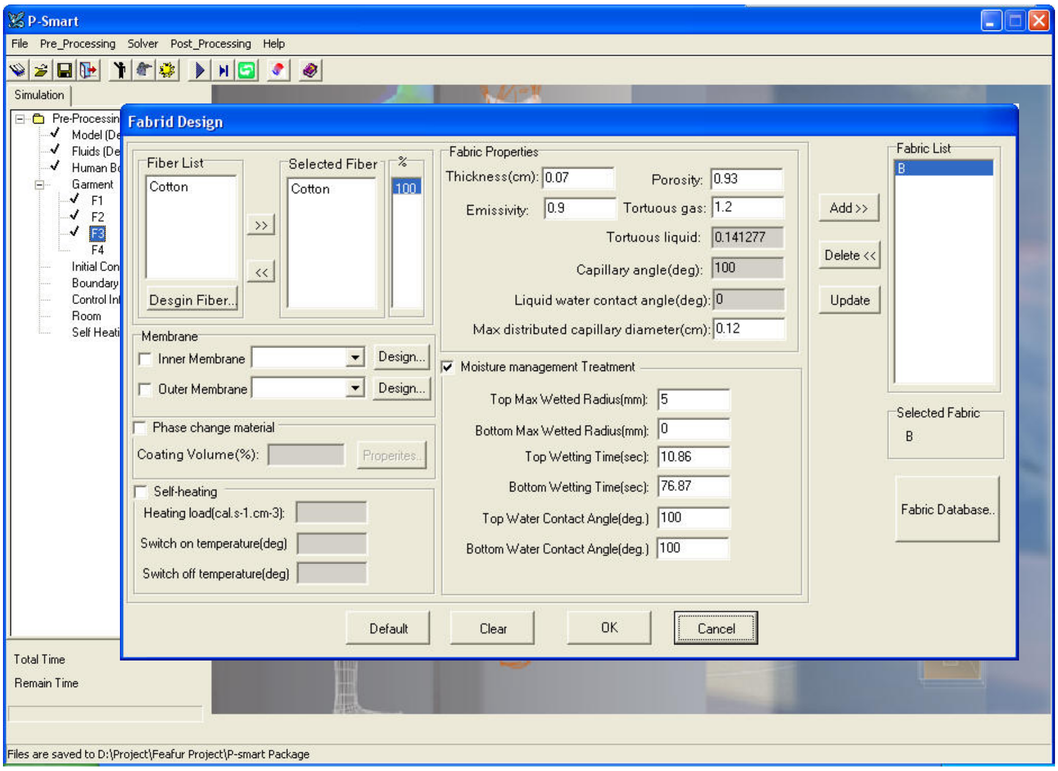

Fig.4 1D thermal engineering design CAD system

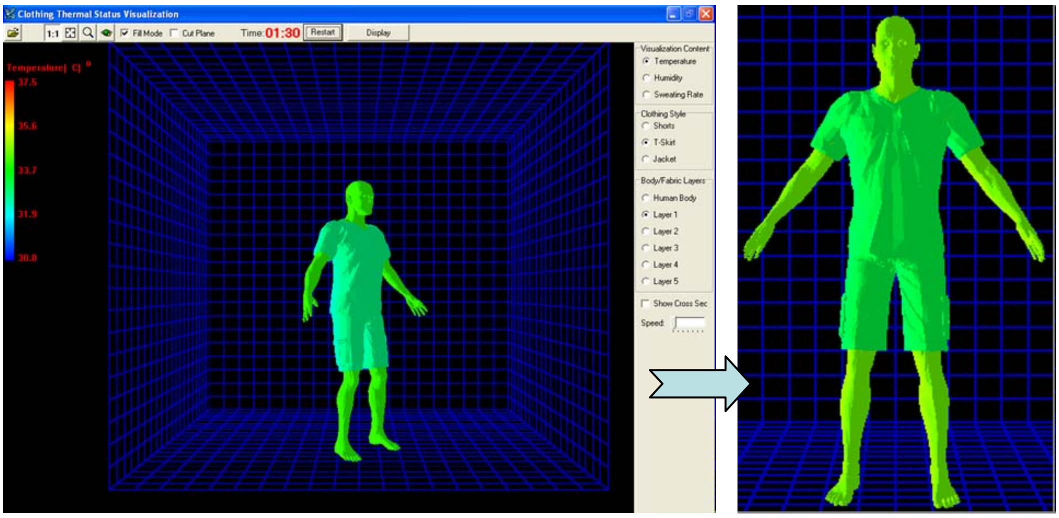

Fig.5 Visualization of the 1D simulation results

With the capacity provided by this virtual system, the traditional clothing design procedure of try-and-error to verify the design concept by repeated sample making and wear trials is improved by the application of new numerical method, which enable the users to preview the performance of clothing and test/optimize the design before they making any real garment. In this virtual environment, it allows the users to design multi-layer clothing assembly with consideration of the fundamental and measurable properties of clothing materials from fiber diameters, structural features of fabric to functional treatments, such as PCM microcapsules, nano coating and shape memory coatings. It effectively speeds up the design process, save time and money and increase productivity.

P-smart system is the first software to transform the highly theoretical modeling work into an operational computer aided design tool, which is friendly for designers who have little/limited background knowledge on the technical information and complex multidisciplinary knowledge. It shows its advances in the overall thermal functional design, new material creation and functional treatment with parametric method in numerical way.

P-smart system is developed on the basis of two-node human regulation model, from which the thermoregulation and heat balance of human body at different body parts cannot be simulated. Therefore, it can only simulate and predict the overall thermal performance of clothing and the thermal responses of human body, which is good enough for designing multi-layer clothing system, as reported previously.

The major weakness/limitation of the P-smart system, however, is that it was developed on the basis of two-node human regulation model, which presents the thermoregulation and heat balance of human body in the whole level. This limitation of mathematical models rises to the fact that P-smart system is better in one-dimensional multi-layered assembly clothing design and predicting the overall thermal performance of clothing and thermal comfort of human body.

5.2 multi-style clothing thermal functional design system

In order to satisfy the requirements of multi-style design and considerate function treatments, another CAD system is developed to present the multi-style engineering thermal design of clothing. The multi-dimensional computational models including the clothing model and 25-node human body model with the reference to Li and Zhu's model [6] and Li f.'s model [11] are integrated in the engineering system, which enable the multi-style design and simulation, as well as visualization.

The significant feature of the integrated models is that it regards the human body-clothing-environment system as multi-parts, including head, trunk, arms, legs, hands and feet, and the interactions between the clothing, human body and environment are detailed to each part for chasing a particular and scientific simulation. The thermal physiological status of the body is able to be generated in detail pertaining to each body part due to the multi-division of the body into a 25-node model to fully represent the human body, which enables the communication between models of clothing and body to happen at each part.

The numerical algorithm for solving the integrated models of human body and clothing is developed with the multi-communication structure, as illustrated in Fig.6, in which the center blood node represents the blood flow in the large arteries and veins of the body accounting for the heat exchange between all the body parts. Meanwhile the thermal value of each volume of the clothing is prescribed as the boundary condition for its adjoining ones.

Table 2 Data flow in the communication

	Human body	Clothing	Environment
Communication variables	• Sweat evaporation flux • Heat flux • Sweat volume • Water vapor Pressure • Heat transfer coefficient • Moisture transfer coeffici	• Water vapor flux • Heat flux • Liquid volume • Water vapor pressure • Heat transfer coefficient • Moisture transfer coefficient	• Air temperature • Air relative humidity • Air pressure • Wind velocity

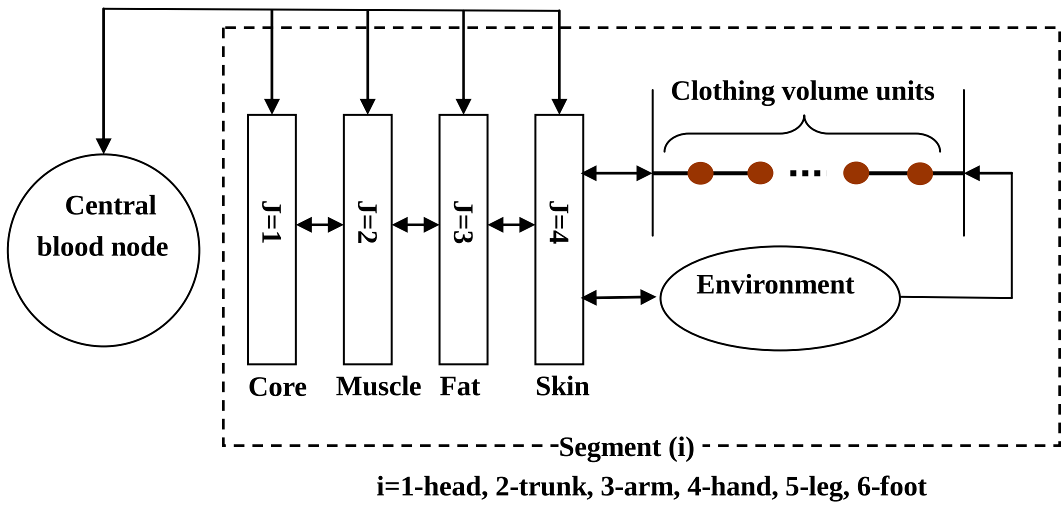

Fig.6 Communication between human body, clothing and environment at each part

The boundary interactions between the clothing, human body and environment are dynamically updated in each round of computation. The finite volume control method is employed to discretize the mathematical clothing models, which are composed in terms of a series of finite differential equations. The detailed information about the discretization method and solution of the integrated model of clothing and human body can be found in a number of publications [12-16]. During the iterative computation, the solution of the thermal variables of clothing and human body is recorded to data files for post-processing.

In order to driven these communications, it is necessary to build up connective sockets through which the data flow can be transferred into and out from the mathematical models with a scientific and accurate configuration. The involved variables in the data flow, illustrated in Table 2, exchanged their value dynamically during the simulation process with the simulation results generation at each time step.

Furthermore, due to the fact that the interactions between the clothing and human body are considered at all divided body parts, the socket for connecting the models of clothing and human body has to be developed to enable integration within the models respectively for head, trunk, arms, hands, legs and feet.

The final CAD system (T-smart) based on the computational algorithm of the involved mathematical models is present to the designers with the functionalities of wearing scenario design, simulation solver and results visualization. All the interfaces are designed concerning the multi-style design principles and engineering methods. And an engineering database is supported during the design process to manage the fundamental technical specifications of the raw materials, semi products and final products. Furthermore, with the advantages of engineering database, it is able to preview the thermal performance of the clothing on different people with different gender, age and race, even the individual person by giving value of the personal physical and physiological parameters.

Fig.7 is the garment design interface in the multi-style CAD system, which provides the users/designers the space to design different styles and textile materials for different body parts and fabric layers. It affords the flexibility and diversity for the clothing design utilizing the computer system.

Fig.8 shows the graphic visualization of the simulation results with 3D axes, which is the water vapor distribution of the fabric layer covered on the trunk of human body with time and thickness direction. From the distribution, it is easy to observe the thermal performance of clothing during the wearing scenarios and determine if the clothing is suitable for this wearing application.

. Fig.9 illustrates 3D visualization of the simulated temperature of multi-style clothing and human body during the wearing process. It can be seen that the more detail information of simulation at the head, trunk, arm, hands, leg and feet. Analyze of the thermal performance of clothing and thermal comfort thus can be furthered to each body part, which enable

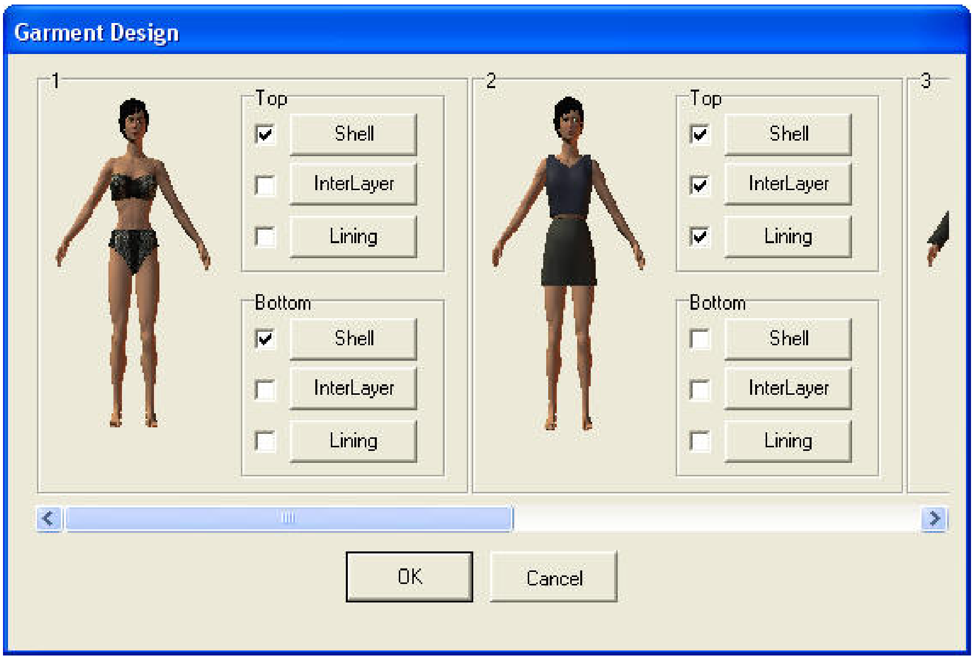

Fig.7 multi-style thermal engineering design CAD system

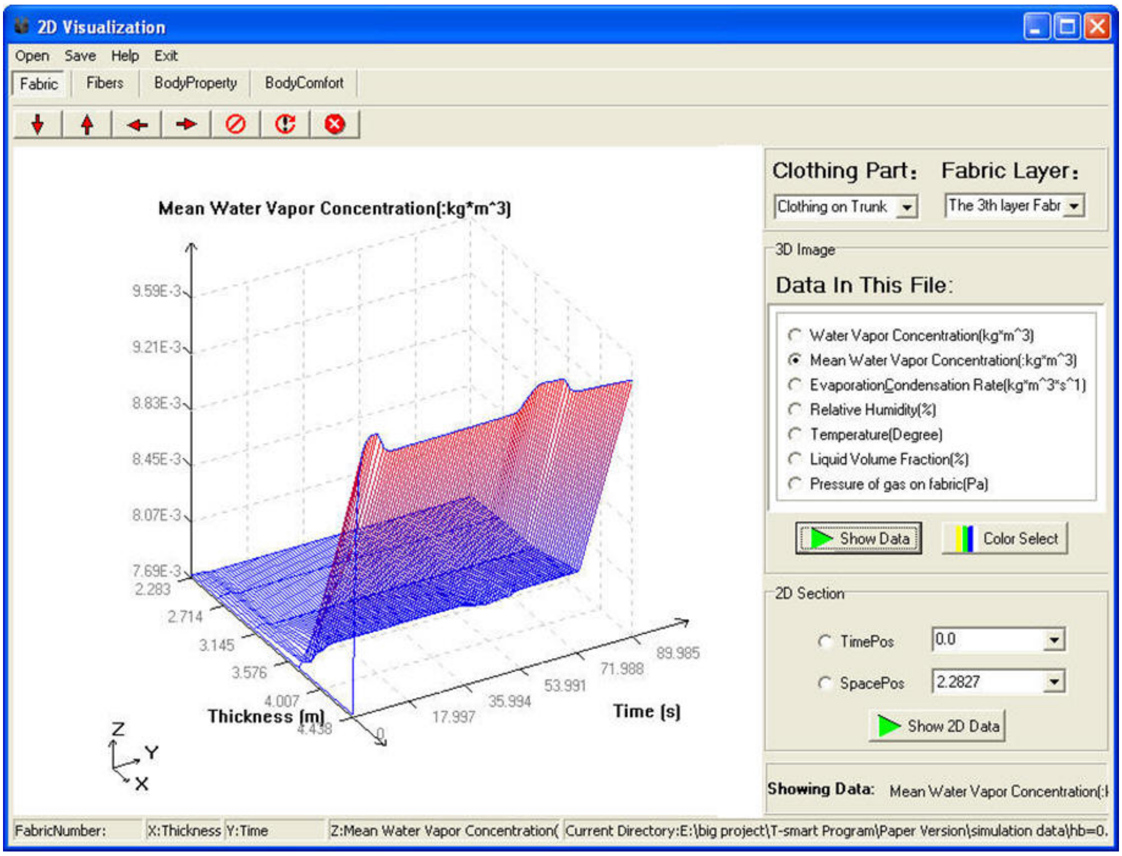

Fig.8 water vapor distribution of the fabric layer on the body trunk

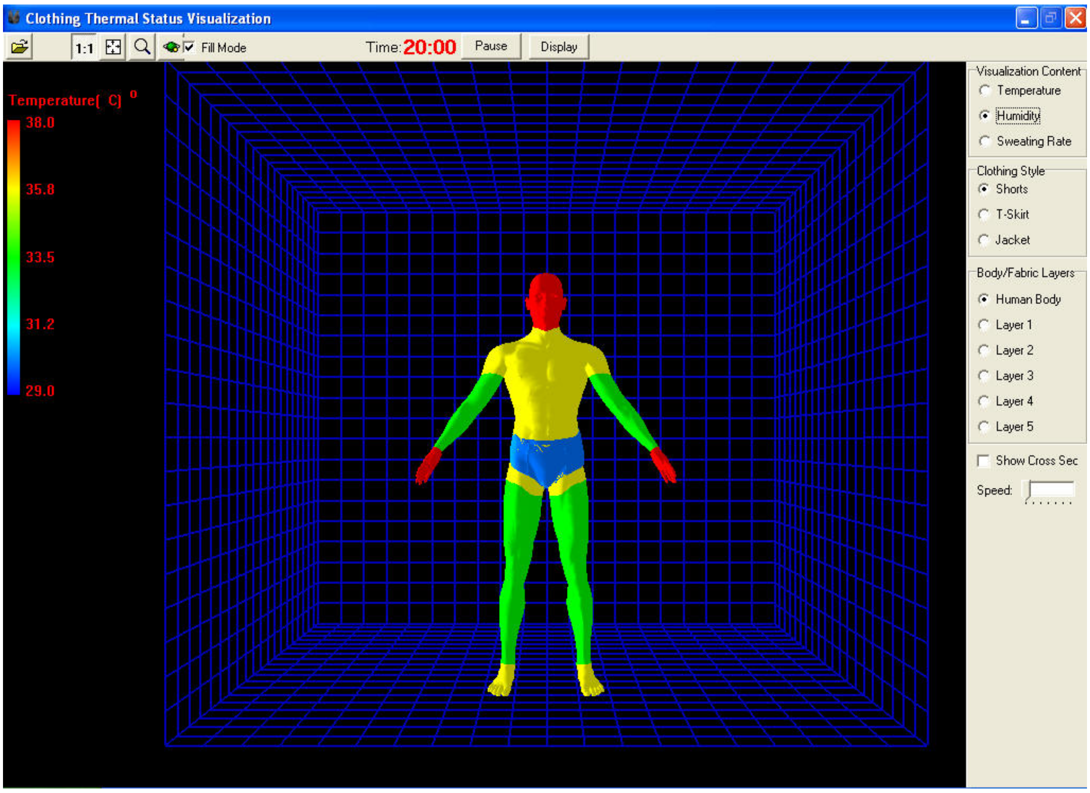

Fig.9 multi-style visualization of simulated temperature of clothing and body the designers obtain more particular feedback and make more reasonable improvement for the design scheme.

With these features, T-smart offers the new functionalities that the designers can design multi-style clothing with the specification of wearing scenarios in any expected place and time with available climatic information, and preview the thermal performance of clothing during the scenarios by direct visualizations after the computation simulation. The designers, thus, extend their ability to consider more flexible and considerate design for different people and different environments.

6 Conclusions

The computational models play an important role in the engineering design system of textile products. Due to the assumption and simplification of the models will determine their potential/suitability to be integrated in the engineering system, the selection criteria become quite significant and is discussed in this paper after the presentation of the engineering and design framework of textile products. A critical analysis of the well-known models of clothing thermal functions is provided according to the selection criteria. Two CAD systems employing different computational models are illustrated, which indicates the impact of computational models on the design and simulation of the engineering design system.

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