Journal of Fiber Bioengineering & Informatics 4:1 (2011) 71–82
http://www.jfbi.org | doi:10.3993/jfbi04201108

M-Smart—An Improved Multi-style Engineering Design CAD System for Clothing Thermal Functions

Yi Teng [a], Ruomei Wang [a,b], Yi Li [a,*], Xiaonan Luo [b], Jie Li [a]
Jiao Jiao [a], Aihua Mao [c], Yueping Guo [a]

[a] *Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hong Kong, China*

[b] *Department of Computer Science, Sun Yat-sen University, Guangzhou, China*

[c] *Department of Computer Science, South China University of Technology, Guangzhou, China*

Abstract

A virtual CAD system for thermal functional design is reported in this paper. An improved multi-style garment design and segmental condition specification was achieved in this system. Moreover, this system predicted the thermal status of human and clothing system while the predicted results correspond well with the experimental results. Both 3D static and dynamic visualization were presented to the users to get a feedback for the design case.

Keywords: Thermal Functional Engineering Database; Multi-style Garment Design; Cad System; Segmental Specify

1 Introduction

With the application of CAD technologies in thermal functional design area, designers can perform virtual garment design on a computer instead of doing experimental tests in laboratories. This does not only reduce the development period but also saves significant costs involved in conducting testing experiments. Published papers and models can be found extensively, describing the heat and moisture transfer process between human and multi-layer fabrics which provides the theoretical foundations and possibilities for CAD functional design.

In previous researches, a CAD system named P-smart for multi-layer clothing thermal engineering design had been developed to predict the thermal status of both human and clothing during a serious of activities [1]. With P-smart system, designers can design the clothing in a virtual environment with the assigned activities and predict the thermal status of both human body and clothing. Compared to the traditional clothing testing methods, P-smart allowed designers to perform the clothing design on a computer which reduces the design period. Moreover, P-smart

*Corresponding author.
Email address: `tcliyi@polyu.edu.hk` (Yi Li).

April 2011

system proposed a basic framework for thermal functional design for human and clothing system especially for multi-layer garments design.

However, the thermal regulation of human is a two-node model which means that the whole body is still viewed as two layers, core and skin. This two-node human model [2-4] has many limitations, for example the entire clothing covering different segments is the same including the material and the fabric layers. So, multi-style garment design such as short sleeve and short pants cannot be realized with P-smart system. Afterwards, a software named T-smart [5] was published and reported that each segment can be simulated individually. The calculation model in T-smart for human regulation is a 25-node model [6] in which the whole human body is divided into six parts and the clothing on each part can be defined by designers. Moreover, it allows the designers to take the effect of multi-style design into consideration. However, the limitation of T-smart also comes in terms of multi-style design. The T-smart cannot realize the true status of multi-style because all the segments share similar temperature, wind velocity, cover ratio and effect of convection. As shown in Fig. 1 in a real situation, different segments may suffer from a distinguished velocity and this can cause an entirely different thermal sensation on the segment.

In this paper, an improved CAD system which allows designers to perform real multi-style design with the consideration of boundary condition for each segment individually is reported. The new software can specify the scenarios for each segment individually. Moreover, the 3D static and dynamic visualization are designed in this system to present the simulation results.

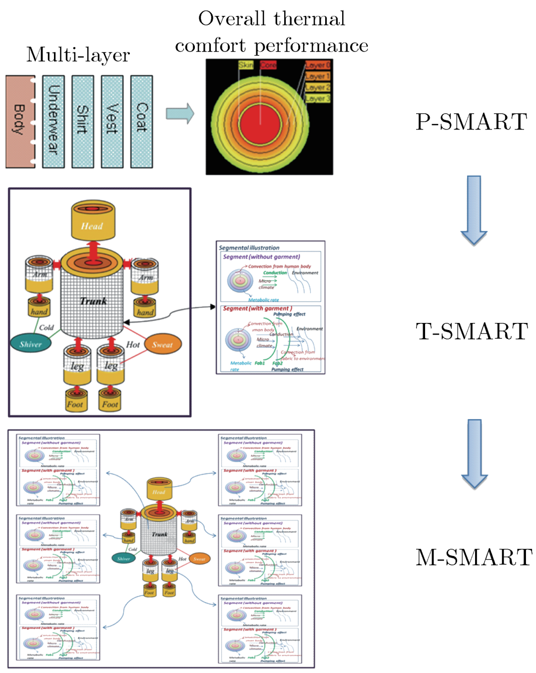

Fig. 1: Analysis of P-smart and T-smart

2 Integrated Mathematical Model for Human and Clothing System

The computational models for M-smart includes two parts which are 25-node thermal regulation model for human body and a mathematical model describing the heat and moisture transfer process through multi-layer garments.

2.1 Human Regulation Model

In the passive system of Stolwijk's model (Stolwijk and Hardy, 1997), the body is composed of head, trunk, arms, hands, legs and feet segments which are subdivided into four concentric layers representing the core, muscle, fat and skin layers. An additional note called center point denotes the central blood pool which executes the communication among the six segments via convection heat exchange occurring within the blood flow of each node.

Passive system:

$$\begin{cases} C_n \dfrac{\mathrm{d}T_n}{\mathrm{d}t} = Q_i - B_i - D_i - E_i \quad n = 1, 2, \cdots, 24 \\ C_b \dfrac{\mathrm{d}T_b}{\mathrm{d}t} = \displaystyle\sum_{n=1}^{24} B_n \end{cases} \tag{1}$$

$$\begin{cases} \text{Core layer: } Q(N) = QB(N) \\ \text{Muscle layer: } Q(N+1) = QB(N+1) + WORKM(I) * (WORK) + \\ \qquad CHILM(I) * CHILL \\ \text{Fat layer: } Q(N+2) = QB(N+2) \\ \text{Skin layer: } Q(N+3) = QB(N+3) \end{cases} \tag{2}$$

$$\begin{cases} \text{Core layer: } BF(N) = BFB(N) \\ \text{Muscle layer: } BF(N+1) = BFB(N+1) + Q(N+1) - BFB(N-1) \\ \text{Fat layer: } BF(N+2) = BFB(N+2) \\ \text{Skin layer: } BF(N+3) = \dfrac{BFB(N+3) + SKIVN(I) * DILAT}{(1 + SKINC(I) * STRIC) * 2^{(ERROR(N+3)/10)}} \end{cases} \tag{3}$$

In the controlling system of Stolwijk's model (Stolwijk and Hardy, 1997), four types of thermal reactions of the body are considered which include shivering, sweating, vasoconstriction and vasodilatation process. Based on the computational results, the effects of the metabolic rate, blood flow, sweating and shivering can be obtained. The controlling system can be described as follows.

Controlling system:

$$\begin{cases} \mathrm{SWEAT} = \mathrm{CSW} * \mathrm{ERROR}(I) + \mathrm{SSW} * (\mathrm{WARMS} - \mathrm{COLDS}) + \\ \qquad \mathrm{PSW} * \mathrm{WARM}(I) * \mathrm{WARMS} \\ \mathrm{DILAT} - \mathrm{CDIL} * \mathrm{ERROR}(I) + \mathrm{SDIL} * (\mathrm{WARMS} - \mathrm{COLDS}) + \\ \qquad \mathrm{PDIL} * \mathrm{WARM}(I) * \mathrm{WARMS} \\ \mathrm{CHILL} = -\mathrm{CCHIL} * \mathrm{ERROR}(I) + \mathrm{SCHIL} * (\mathrm{COLDS} - \mathrm{WARMS}) + \\ \qquad \mathrm{PCHIL} * \mathrm{COLD}(I) * \mathrm{COLDS} \\ \mathrm{STRIC} = -\mathrm{CCON} * \mathrm{ERROR}(I) + \mathrm{SCON}(\mathrm{COLDS} - \mathrm{WARMS}) + \\ \qquad \mathrm{PCON} * \mathrm{COLD}(I) * \mathrm{COLDS} \end{cases} \tag{4}$$

$$\begin{cases} \mathrm{ERROR}(N) = T(N) - \mathrm{TEST}(N) + \mathrm{RATE}(N) * F(N) \\ \mathrm{WARM}(N) = \mathrm{ERROR}(N) \quad \mathrm{ERROR}(N) > 0 \\ \mathrm{COLD}(N) = \mathrm{ERROR}(N) \quad \mathrm{ERROR}(N) < 0 \\ \mathrm{WARMS} = \mathrm{SKINR}(1) * \mathrm{WARM}(4) + \mathrm{SKINR}(2) * \mathrm{WARM}(8) + \\ \qquad \mathrm{SKINR}(3) * \mathrm{WARM}(12) + \mathrm{SKINR}(4) * \mathrm{WARM}(16) + \\ \qquad \mathrm{SKINR}(5) * \mathrm{WARM}(20) + \mathrm{SKINR}(6) * \mathrm{WARM}(24) \\ \mathrm{COLDS} = -\mathrm{WARMS} \end{cases} \tag{5}$$

2.2 Mathematical Models for Heat and Moisture Transfer Process in Clothing

When a water vapor concentration gradient exists across the multi-layer textile, the moisture flux can be re-distributed due to the diffusion process through the void space in the textile. The governing (Burley's model) equation describing the vapor transfer process is given based on the diffusion law and Li and Luo's two-stage absorption model.

$$\frac{\partial(\varepsilon_a C_a)}{\partial t} = \frac{D_a \varepsilon_a}{\tau_a} \cdot \frac{\partial^2 C_a}{\partial x^2} \frac{\varepsilon_a}{\varepsilon} \varepsilon_f \cdot \frac{\partial C_f}{\partial t} + \tau_{\mathrm{lg}} \tag{6}$$

The liquid water diffusion through textile can be attributed to a capillary process through fabrics. The mathematical descriptions for the process of liquid transfer, moisture sorption/desorption and condensation/evaporation can be expressed as follows.

$$\frac{\partial(\rho_1 \varepsilon_1)}{\partial t} = \frac{\partial}{\partial x}\left(D_1(\varepsilon_1)\frac{\partial(\rho_1 \varepsilon_1)}{\partial x}\right) - \frac{\varepsilon_1}{\varepsilon}\varepsilon_f \cdot \frac{\partial C_f}{\partial t} - \tau_{\mathrm{lg}} \tag{7}$$

The heat transfer process happens along with the process of conduction, convection and radiation while the conduction and radiation of heat plays a predominant role in energy transfer. The governing equation for heat transfer process can be written as follows.

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_{\mathrm{mix}}(x)\frac{\partial T}{\partial x}\right) + \frac{\partial F_R}{\partial x} - \frac{\partial R_L}{\partial x} + c_r \cdot \frac{\partial C_f}{\partial t}\left(\frac{\varepsilon_a}{\varepsilon} \cdot \lambda_v + \frac{\varepsilon_1}{\varepsilon} \cdot \lambda_1\right) - \lambda_{\mathrm{lg}} \cdot \tau_{\mathrm{lg}} \tag{8}$$

3 M-smart System Introduction

To design M-smart system, the architecture and computation flow are the key points. Based on a thermal functional database, which includes human model databases and functional garment database, the designed class structure illustration figure shows the relationship between different kinds of objects.

3.1 M-smart System Architecture

The CAD system is built on thermal engineering database which includes two parts: human model and multi-style garments. The architecture of the CAD system is demonstrated in Fig. 2. It can be found that the pre-simulation process is related to the database of the human and garment definition steps. Moreover, the human model and garments in the visualization process are also downloaded from the thermal engineering database.

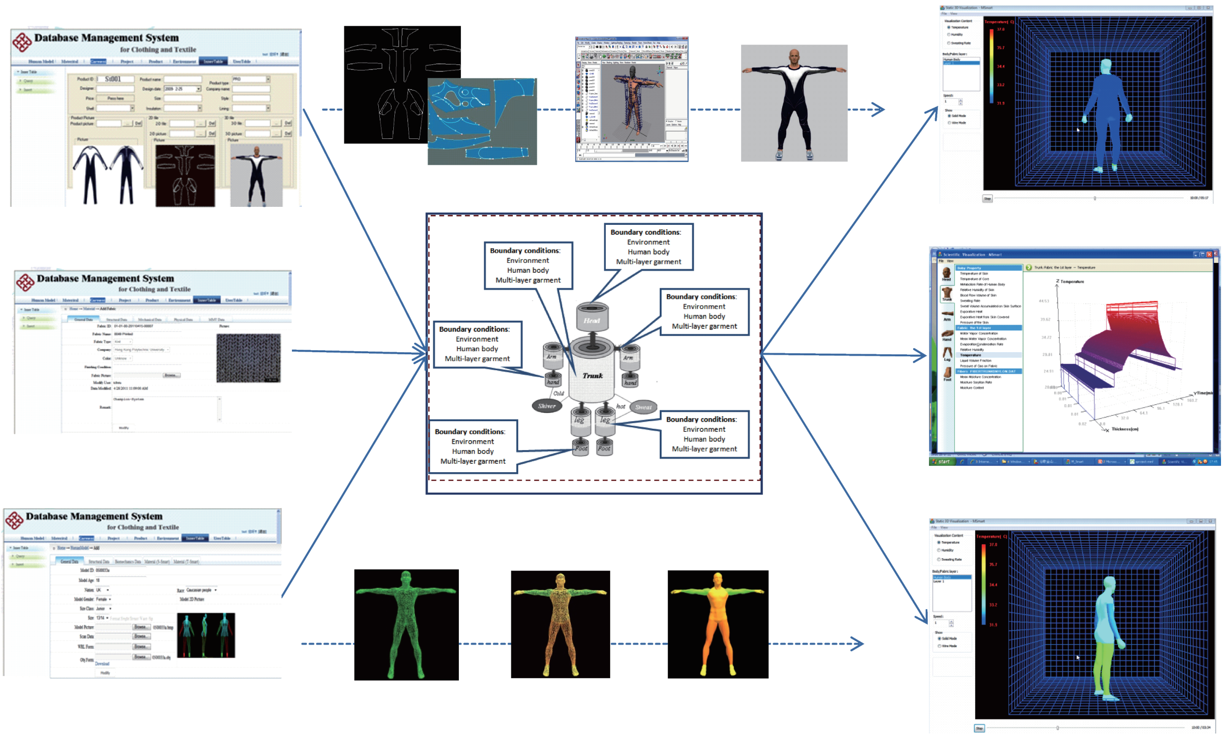

Fig. 2: Architecture of M-smart system

3.2 Numerical Simulation Flow Chart

With the pre-simulation process, the parameters for the calculation process are prepared. The calculation for the heat and moisture transfer process in clothing is based on a finite volume method. The human regulation calculation can be translated into linear equations computation. The thermal status of the human skin surface can be the boundary condition for the dynamic calculation of clothing. The simulation flow chart can be understood from Fig. 3.

3.3 Class Design

This CAD system is programmed in C++ language and classes design is also adopted in this system. The class relation is illustrated in Fig. 4.

4 Design Case

In order to illustrate the thermal comfort predictability of this CAD system, a case of summer running protocol is introduced and a comparison of simulation results and experimental results with body core temperature and skin temperature is evaluated.

4.1 Case Design Specification

In order to investigate an athlete's running process, a serious of activities is extracted from the experiment process. With the environment in the chamber maintained as 30C and 50% RH, the

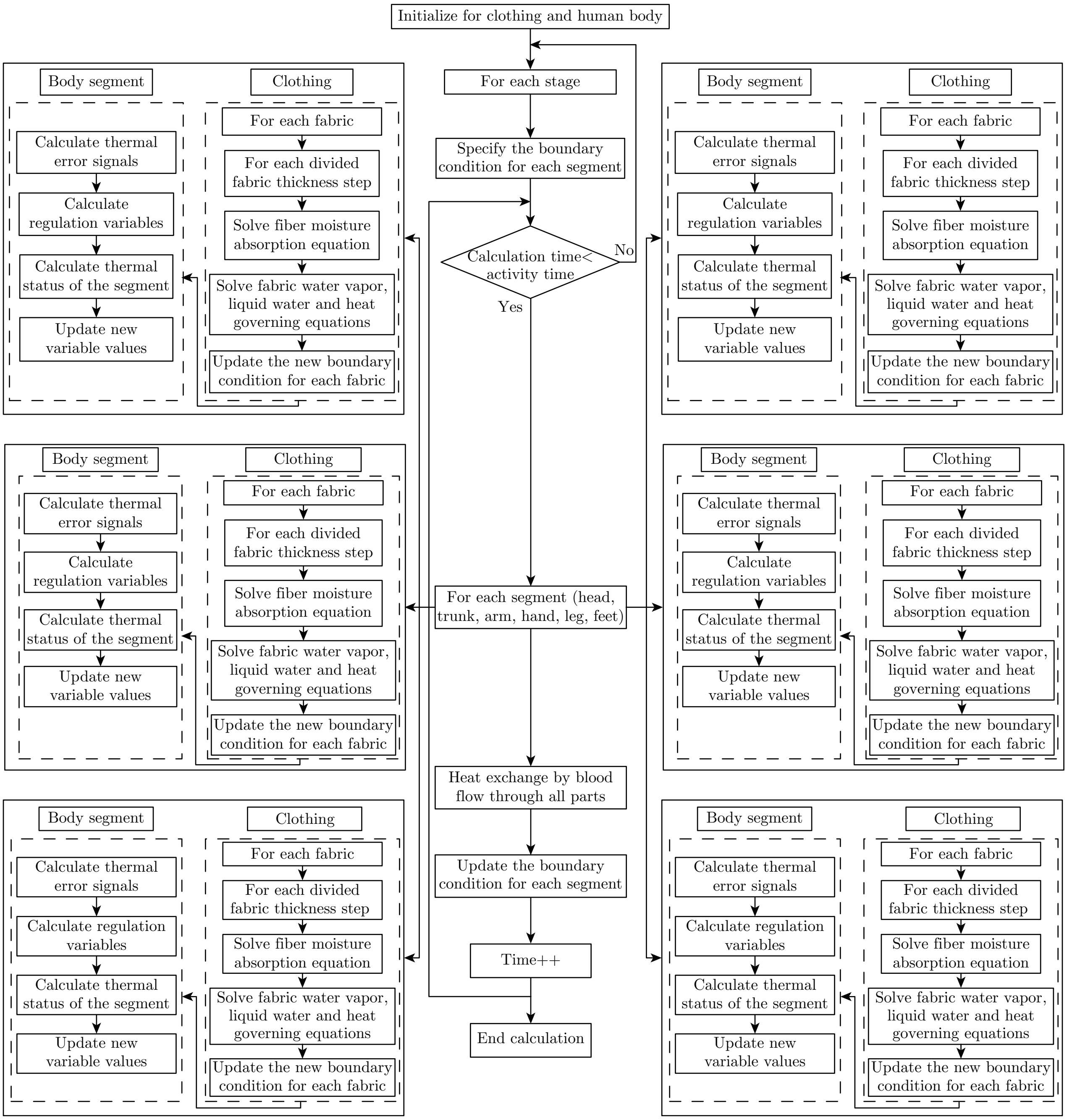

Fig. 3: Simulation flow chart of M-smart system.

velocity during the resting process is 0.2 m/s, whilst during the whole running process the velocity is 3.5 m/s (positive going to the athlete). The experiment can be described by five continuous motor processes which are: seated resting for 30 min at a metabolic rate of 58 W/m^2, warm up running for 10 min at 400 W/m^2, 70% VO_2 max running for 45mins at a metabolic rate of 550 W/m^2, 1500 performance running for 5min at a metabolic rate of 650 W/m^2, then recovery for 30 min at a metabolic rate of 60 W/m^2. The wind velocity during the first and last stages is 0.2 m/s while the wind speed during the other three running processes is 3.0 m/s. Fig. 5 illustrates the running protocol.

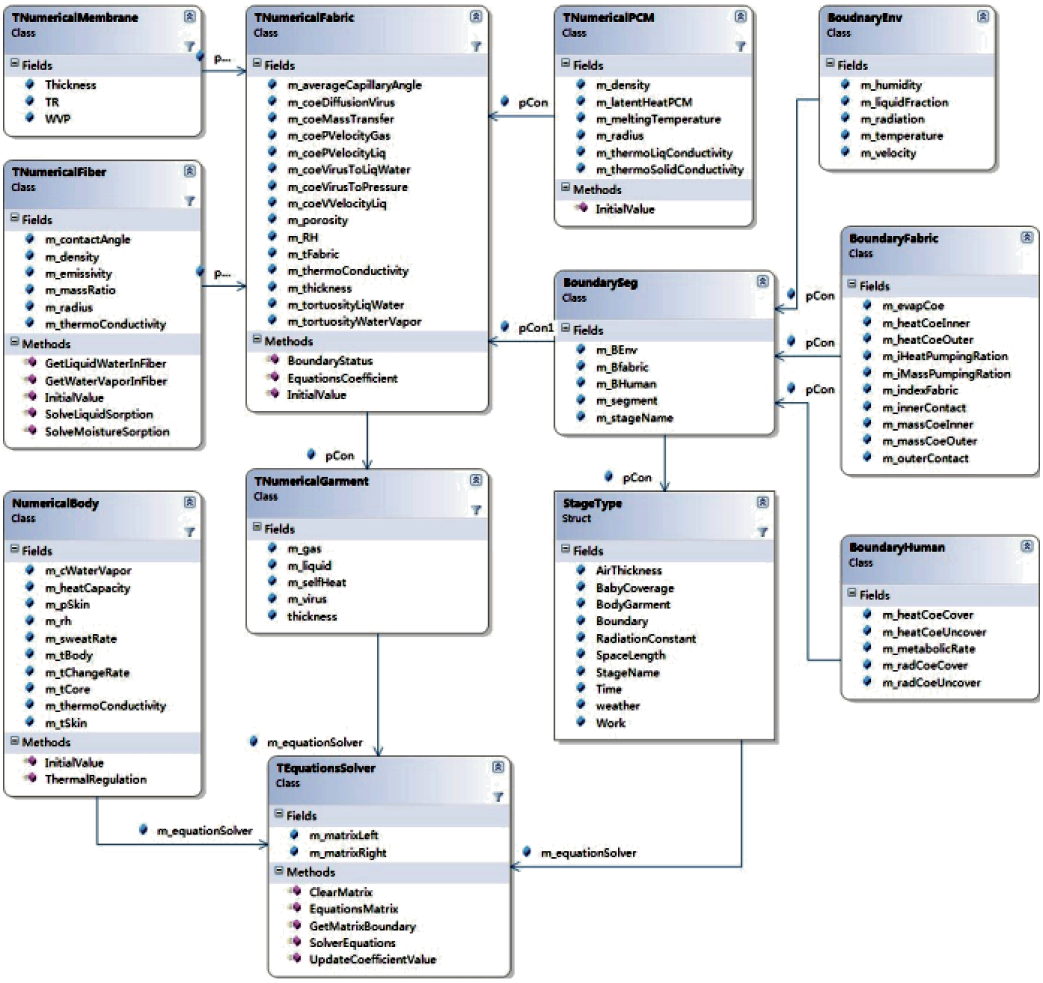

Fig. 4: The class relation diagram of M-smart.

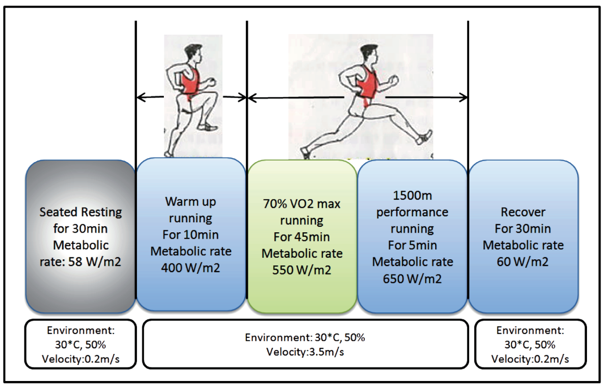

Fig. 5: Experimental protocol.

4.2 Multi-style Simulation Case Design

Based on the experimental testing, the simulation case design process can be divided into six steps.

Step 1: Define the activity stages including the activity clarification, metabolic rate and duration. The interface can be found in Fig. 7.

Fig. 6: The main interface of M-smart system

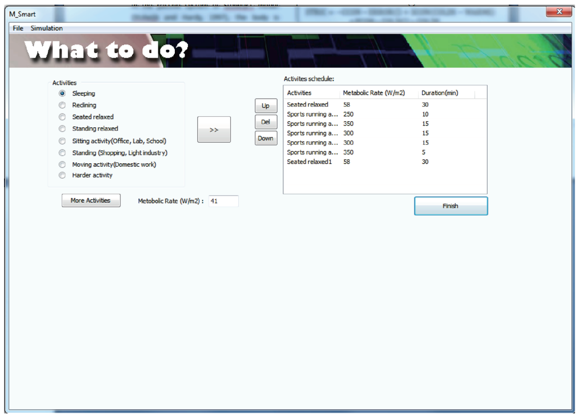

Fig. 7: Step 1: What to do?

Step 2: Define the environmental condition for each stage including temperature, relative humidity, wind velocity and air pressure. These values will be default values for the boundary condition specification.

Step 3: Choose the human basic condition then search from the database to obtain a close human model and identify the physiological data according to the human size.

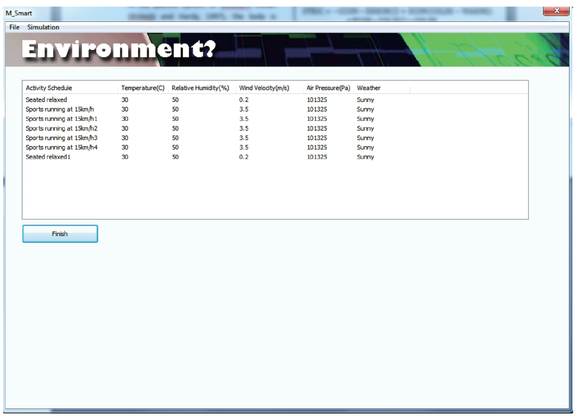

Fig. 8: Step 2: Environment?

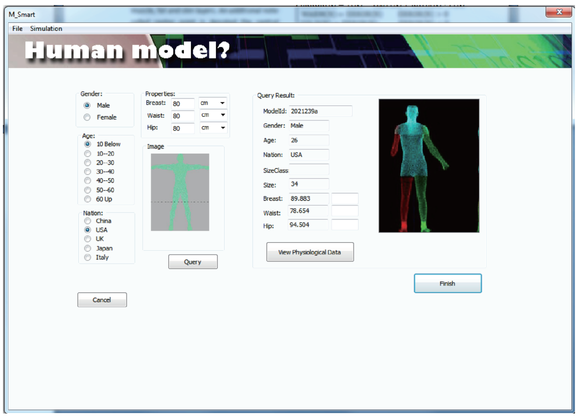

Fig. 9: Step 3: Human model selection panel

Step 4: Define the multi-style garment. Choose the garment from the garment list. All the garments are downloaded from the garment database while the size of the garment is the same as the human model chosen in step 3.

Then, define the garment one by one. For one garment, this CAD system seperates into six parts. Each part can have at most three fabric layers and a cover ratio.

Specify the fabric parameters to a layer on one segment. The fabric information includes the fiber ingredient, the fabric thickness, radius, the contact angle and MMT characters.

Step 5: Segmental boundary condition specification. For each stage and each segment, set the speicified value according to the intensity of the activity.

After completion of the above mentioned steps, the simulation process can start.

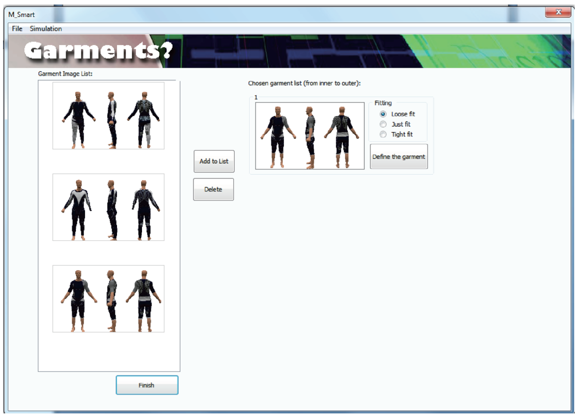

Fig. 10: Step 4: Multi-style garment definition panel

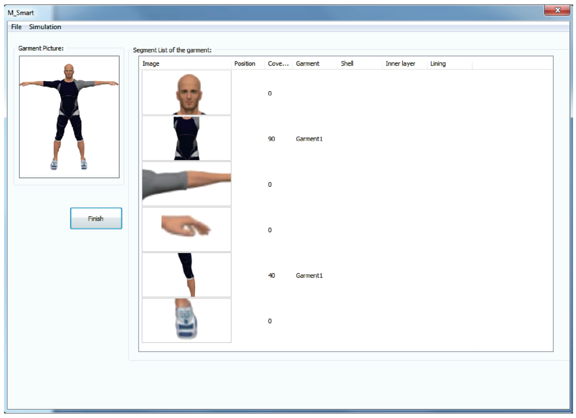

Fig. 11: One garment definition panel

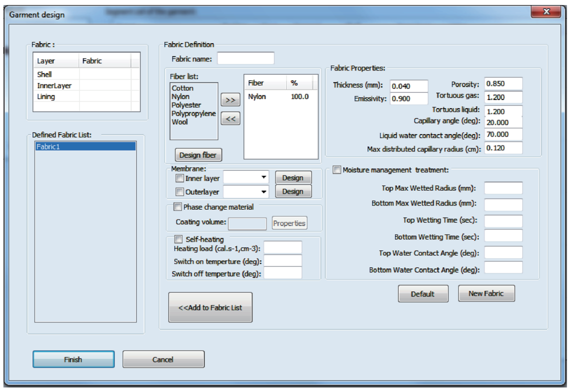

Fig. 12: Fabric definition panel

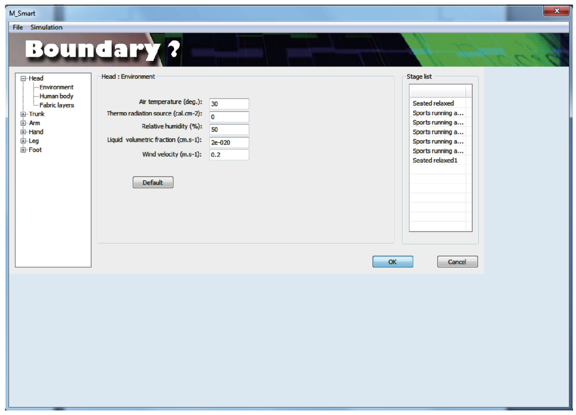

Fig. 13: Step 5: Boundary conditon specification

4.3 Validation of the Simulation Case

In the previous steps, the running protocol, environment, human model, multi-style garments and boundary conditons are specified. The thermal status which demonstrates the thermal status changing tendency of human body is presented. The key index of human thermal status is the core temperature of human body. From Fig. 14, it can be found that the predicted data agrees well with the experimental data at each stage.

From Fig. 15, the changing tendency of the mean skin temperature is almost the same as the value changes in the 5% error bar range.

4.4 3D Visualization

A three dimensional visualization is provided in M-smart system. Fig. 16 shows a 3D human model which is selected from the human model selection module downloaded from the human model database. The cross section shows the core and skin temperature of the selected segment.

The 3D human model with the selected garment can also be shown in this panel. Choose the garment and watch the thermal status changes during this process (Fig. 17).

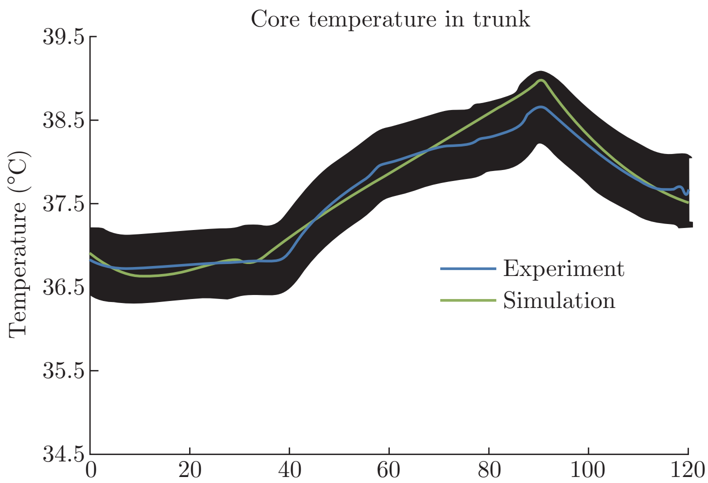

Fig. 14: Core temperature comparison

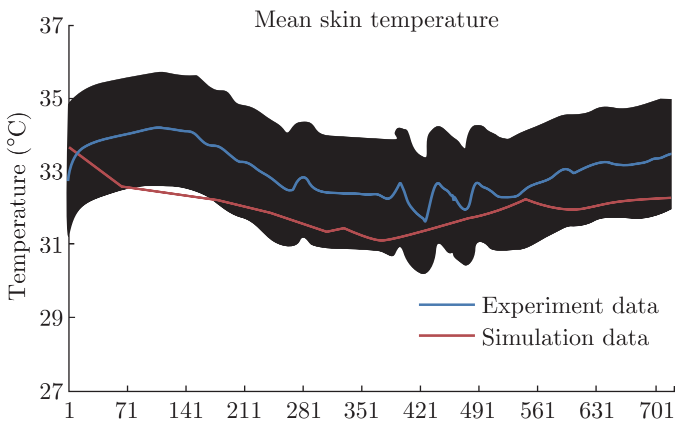

Fig. 15: Mean skin temperature comparison

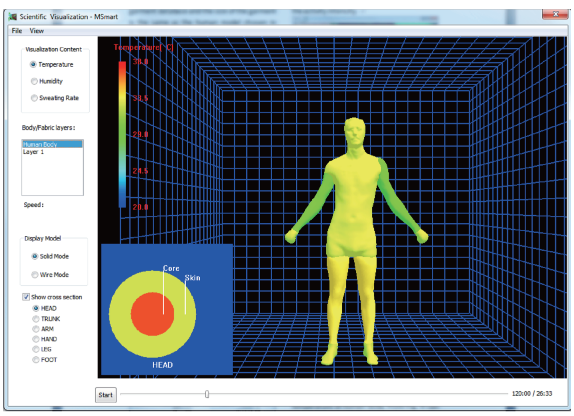

Fig. 16: Static 3D human model visualization presentation

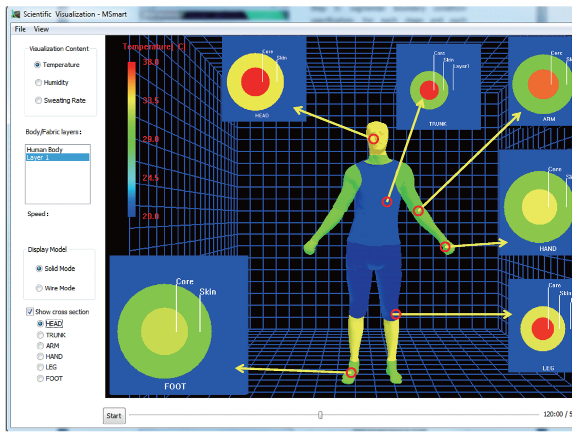

Fig. 17: Static 3D human model with garment visualization presentation

Fig. 18 shows a 3 dimensional visualization. The human model is a standard human model from 3D software. As the 3D model can do a series of activities which is called dynamic, choose the human model to observe the thermal status changes during the motor process.

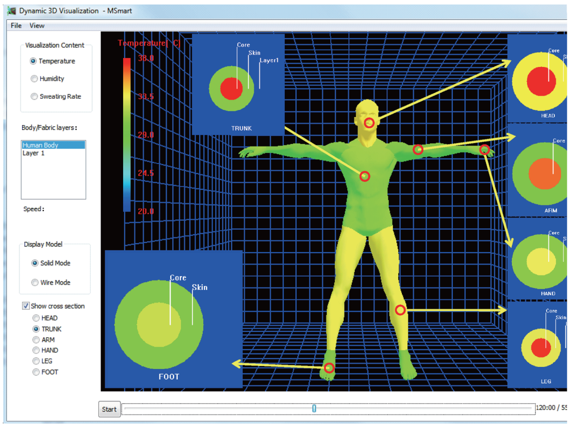

Fig. 18: Dynamic 3D human model visualization

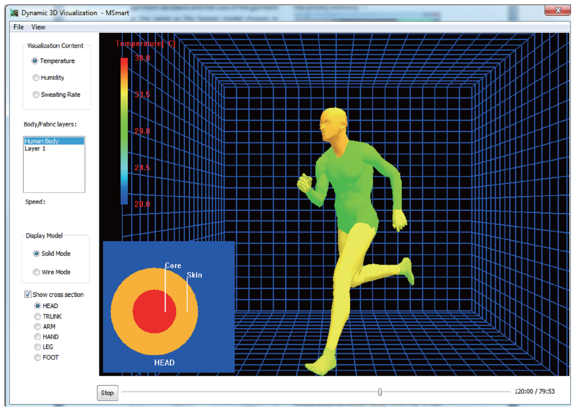

Fig. 19: Dynamic 3D human model visualization at running status

5 Conclusion

The simulation results show different responses to different scenarios. The comparison between simulation results and experimental results indicates that the improved CAD system can predict the heat and moisture process in human-clothing system.

This improved system includes four parts: thermal functional engineering database, friendly user interface, simulation calculation and visualization. The relationship among these four parts can be described as: the thermal functional database is the basic platform for the whole system. The pre-simulation process is to collect all the calculation parameters and store them into a pre-simulation file. Then, pass the file to calculation process to obtain the simulation results, which will be presented in the visualization part.

The CAD system can realize a true multi-style garment design. Moreover, segmental garment design and calculation is adopted in this CAD system.

Acknowledgements

We would like to thank the Hong Kong Innovation Technology Commission and Hong Kong Research Institute of Textiles and Clothing for funding the research through the projects ITP/030/08TP.

References

[1] Li Y, Mao A H, Wang R M, Luo X N, Wang Z. P-smart–a virtual system for clothing thermal functional design. Computer-Aided Design 2006, 7, 726-739

[2] Gagge A P, Stolwijk A J, Saltin B. Comfort and thermal sensations and associated physiological response during exercise at various ambient temperatures. Environmental Research 1969, 2, 209-229

[3] Gagge A P, Stolwijk A J, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Trans 1971, 77, 247-262

[4] Gagge A P. Rational temperature indices of man's thermal environment and their use with 2-node model of his temperature regulation. Fed. Proc 1973, 32, 1572-1582

[5] Mao A H, Li Y, Luo X N, Wang R M. A CAD system for multi-style thermal functional design of clothing. Computer-Aided Design 2008, 40, 916-930

[6] Stolwijk A J, Hardy J D. Temperature Regulation in Man-A theoretical Study. Physiol 1966, 291, 129-162