Study on the Moderate Thermal Environment Comfort Evaluation Using Thermal Manikin

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Abstract. A new manikin can be used to simulate heat transfer and thermal sensation of Chinese human body in moderate thermal environment. Local (t_eqlocal) and whole body equivalent temperature (t_eqwhole) had been measured in a uniform environment using it and compared with corresponding environmental temperatures. Objective/subjective evaluation trial was carried out in an air-conditioned climate chamber where 12 Chinese males sat to mark their sensation. By comparison it could be found: (1) after 100 min manikin thermodynamic state tended to become stable and t_eqwhole was 20.6 °C which approximately equaled to air temperature 20.7 °C in the uniform environment. Therefore, its measurement accuracy is verified to be very high. (2) in the chamber, PMV index measured by manikin was –0.8 which was close to subjective sensation vote (–0.917 ± 0.996), indicating that it is reasonable and credible to evaluate environment comfort by means of this manikin.

Keywords: Moderate thermal environment · Thermal manikin · Equivalent temperature · Objective evaluation · Subjective evaluation · Thermal sensation

1 Introduction

The word manikin is believed to originate from the Dutch word “Manneken” [1], a small man. The first thermal manikin was a one-segment copper manikin made for the US Army in the 40’s. Belding first built a headless and armless manikin from pipes and metal sheets with an internal heater and fan to distribute the heat. The need for more detailed information about heat transfer characteristics of convection and thermal radiation between environment and human body brought forward the construction of manikins with several, independently controlled segments over the body surface. Almost all manikins today provide for more than 15 segments. Another significant step forward was taken with the introduction of digital regulation techniques. This allowed for more flexible applications and accurate measurements.

Manikins are complex, delicate and expensive instruments with many advanced and useful features. The heat transfer characteristics of convection and thermal

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radiation between environment and thermal manikin are identical with that of the human body. A human shaped thermal manikin measures convective, radiative and conductive heat losses over the whole surface and in all directions. By summing up the area weighted values, a value for whole body heat loss is determined.

Significant performance features of thermal manikins:

- relevant simulation of human body heat exchange, whole body and local
- measurement of 3-dimensional heat exchange
- integration of dry heat losses in a realistic manner
- objective method for measurement of clothing thermal insulation
- quick, accurate and repeatable
- cost-effective instrument for comparative measurements and product development
- provide values for prediction models; clothing insulation and evaporative resistance, heat losses

For the same exposure conditions, a thermal manikin can measure heat losses in a relevant, reliable and accurate way. The method is quick and easily standardized and repeatable. Due to the nature of the method, values obtained can serve directly as input for mathematical models for prediction of thermal responses. In other words, manikin can be used to simulate real body heat transfer and thermal sensation, and then to evaluate thermal environment comfort of human therein.

There are many relevant international standards of non-uniform thermal environment measurement and evaluation applying in kinds of fields, for instance, the vehicle thermal environment. Nevertheless, those standard terms from ISO are always not suitable to Chinese people. Aiming to solve this deficiency, a manikin system was created to specialize in thermal environment measurement and evaluation technology of Chinese people in Beihang University. It is made up of a thermal manikin, software for clothing thermal resistance measurement in sitting posture and in standing posture, and software for thermal environment measurement and comfort evaluation in sitting posture and in standing posture.

The thermal manikin was developed with 26 divisions heated individually interiorly, shown as Fig. 1.

Softwares were developed for Chinese to control manikin heat state, measure clothing insulation, measure inhomogeneous environment and evaluate thermal environment comfort.

In this paper, the accuracy and reasonability of manikin system were verified in air-conditioned moderate thermal environment. The results provide the basis for the thermal environment control approach to meet the demand of human comfort in ergonomics field.

2 Methods

The evaluative process of studying moderate thermal environment comfort by the manikin system is shown as Fig. 2. It is composed of 3 main parts: manikin heating process control, thermal environment measurement and thermal environment comfort evaluation.

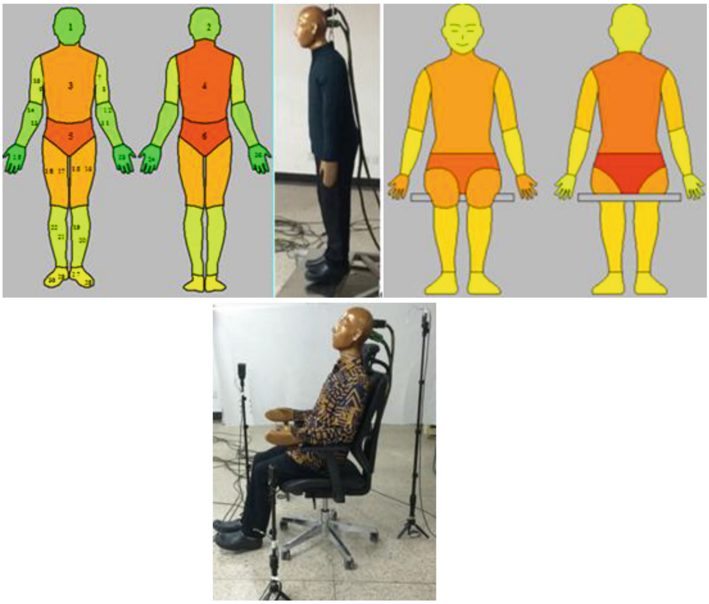

Fig. 1. Thermal manikin zones and postures

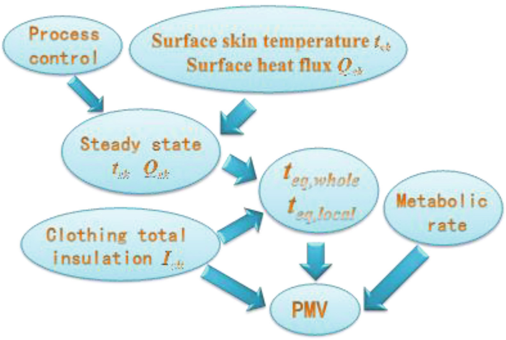

Fig. 2. Moderate thermal environment comfort evaluation schematic diagram

2.1 Process Control

During the actual heating process, surface temperatures of manikin segments were controlled to rise gradually and satisfy the equation t_sk = 36.4–0.054Q_sk respectively when manikin reached steady state eventually, different from existing constant surface temperature and constant surface heat flux control mode. It was achieved by variable integral PID control algorithm [2].

2.2 Environment Measurement

Real ambient environments had been found to be asymmetrical anywhere, there is an integrated temperature index which names equivalent temperature t_{eq} [3] to synthesize the effects of all environmental factors to non-evaporative heat loss from human body. Total thermal resistance [4] of clothing covering whole body I_{clt} and each zones $I_{(clt,local)}$ were calibrated in an uniform thermal environment with still air. $t_{(eq,local)}$ [3] for 26 independent segments and $t_{(eq,whole)}$ [3] for whole body were calculated by measurements of t_{sk}, Q_{sk} in manikin steady state, I_{clt} and $I_{(clt,local)}$ as shown in Fig. 2. Software for thermal environment measurement and comfort evaluation was shown as Figs. 3 and 4.

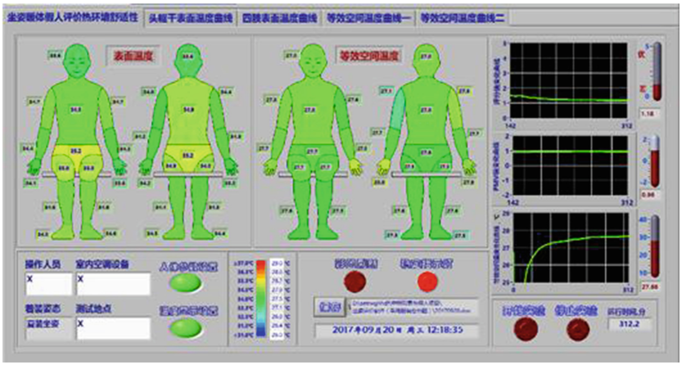

Fig. 3. Software interface of thermal environment comfort evaluation in sitting posture

Basing on heating process control above, Trial 1 was performed to test moderate thermal environment using manikin and verify its measurement accuracy by comparison: the manikin was dressed in summer clothing including vest, long-sleeved shirt, short underwear, thin trousers, sports shoes and socks. It was seated and activated in a fairly homogeneous climate room where the wall temperature was the same as that of air, there were no air flow and no other heat radiation. Room air temperatures at the height of manikin head, check, leg, lower leg and foot were measured during the trial as shown in Fig. 1, average of these temperatures was considered as the room air temperature. Thermal manikin was controlled as described above using software shown in Fig. 3, entire trial was continuing 6 h to get a more reliable measurement of t_{eq}.

2.3 PMV

Equivalent temperature t_{eq} of thermal environment and I_{clt} were measured by thermal manikin, body metabolic rate M and external mechanical work W were determined by subject activity in the environment. Thermal environment comfort could be evaluated by following equation deriving from The HEAT BALANCE EQUATION [5]:

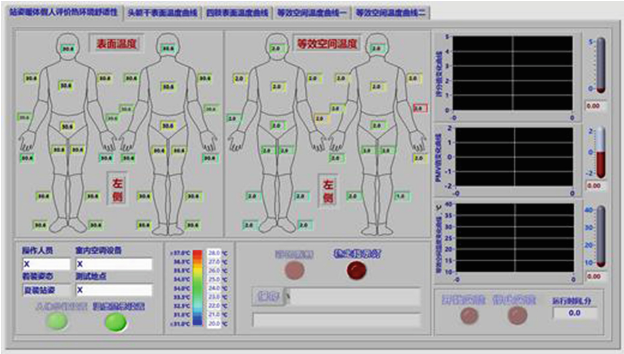

Fig. 4. Software interface of thermal environment comfort evaluation in standing posture

$$
\begin{aligned}
\mathrm{PMV} = {} & [0.303 \cdot e^{\wedge}((-0.036 \cdot M)) + 0.028] \cdot \{(M - W) \\
& - 3.05 \times [\![10]\!]^{\wedge}(-3) \cdot [5733 - 6.99(M - W) - p\_a] \\
& - 0.42 \cdot [(M - W) - 58.15] - 1.7 \times [\![10]\!]^{\wedge}(-5) \cdot M \cdot (5867 - p\_a) \\
& - 0.0014 \cdot M \cdot (34 - t\_eq) - [(35.77 - 0.028 \cdot M) - t\_eq]/I\_clt\}
\end{aligned}
\quad (1)
$$

The PMV index is commonly used in moderate thermal environment comfort evaluation. It represents the subjective response of thermal sensation from human body and indicates that whether a body feels acceptable and comfortable.

2.4 Comfort Evaluation

Basing on environment measurement by manikin above, *Trial 2* was carried out in a climate chamber to verify reasonability and credibility of using this manikin in Chinese thermal comfort evaluation. *Objective Evaluation:* Outdoor environment was controlled to become summer condition where t_a was 35 ± 0.5°C and relative humidity was 50% and indoor environment was the same as outdoor at the beginning of the trial. Indoor air-conditioner was activated with setting condition at 26°C and stabilized gradually, then air-conditioned environment was measured and evaluated firstly by manikin with the same clothing as that in *Trial 1* at a fixed position around chamber center where subjects would stay later. PMV and t_(eq,whole) were obtained from comfort evaluation software with sitting metabolism, 1.2 met (70 W/m^2) [6] and used clothing thermal resistance.

Subjective Evaluation: 12 male Chinese were recruited who were 31.75 ± 6.30 years old and 172.83 ± 7.59 cm tall, mean ± SD. In this trial, conditions were same as that in objective evaluation, such as chamber outdoor environment, indoor air-conditioned climate, summer clothing, chair and its position. Every participant would take a rest, fill in the blank of personal basic information, wear the unified summer clothing and be explained the experimental procedure in a preparation room before entering the chamber.

Then participant entered the chamber, sat in the chair and kept reading as shown in Fig. 5 so that his metabolism rate also could be maintained at 1.2 met. Duration of this experiment was 90 min, participants were asked to mark their thermal sensation per 15 min in the questionnaire according to 7-point thermal sensation scale shown as Table 1.

Fig. 5. Subjective evaluation trial scene

3 Results and Discussions

Trial 1: After heating manikin about 100 min, the thermal state of manikin tended to become stable with surface temperature, heat flux of its surface respectively 33 °C and 62 W/m^2, shown as Fig. 6. After 2 h from the beginning of *Trial 1,* the heating process was completely constant and there was no longer any temperature rise or steady heat flux variation on the manikin surfaces.

Room air temperature t_a and equivalent temperature t_eq were compared in Fig. 7, t_a was stabilizing at 20.7 °C averagely. It could be found that t_a maintained stable during trial. In this room wall temperature equaled approximately to t_a, there were no horizontal temperature differences, vertical temperature differences between floor and height of 3 m less than 0.5 °C, and no air flow. In consequence, the room could be considered as a standard indoor environment to verify the thermal manikin system where t_eq equals to t_a.

Room t_(eq,whole) measured by thermal manikin system increased very quickly during a short period less than 90 min, then rose to stable temperature of 20.6 °C gradually within 30 min or so, and had a little bit fluctuation with the slight change of environment during the followed test. The control process of this manikin was rapid and stable. As shown in Fig. 7, t_(eq,whole) was extremely close to t_a, deviation between t_a and t_(eq,whole) was less than 0.3 °C, and the small deviation lasted a very long time during the whole stable stage. So equivalent temperature measurement of thermal manikin system was accurate and reliable.

Trial 2: The sitting manikin t_(eq,whole) in the chamber obtained from software was about 22 °C when the air-conditioner refrigerant condition was set at 26 °C. The t_eq measured by manikin system was 4 °C lower than the indoor t_a controlled

Table 1. 7-point thermal sensation scale.

Vote	–3	–2	–1	0	+1	+2	+3
Sensation	Cold	Cool	Slightly cool	Neural	Slightly warm	Warm	Hot

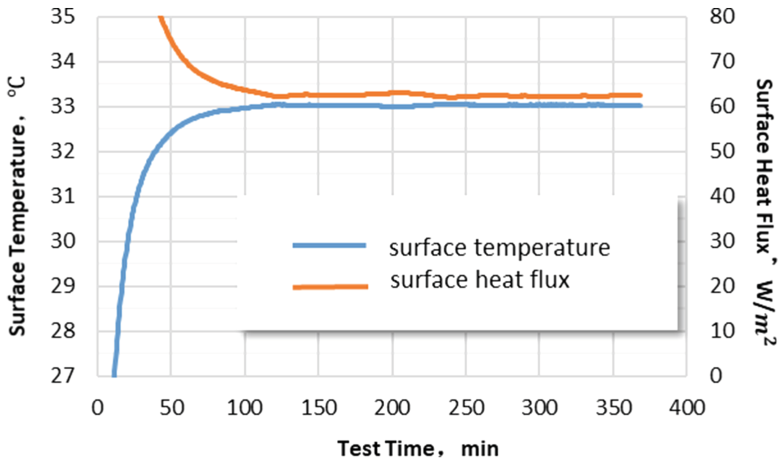

Fig. 6. Thermal state of thermal manikin

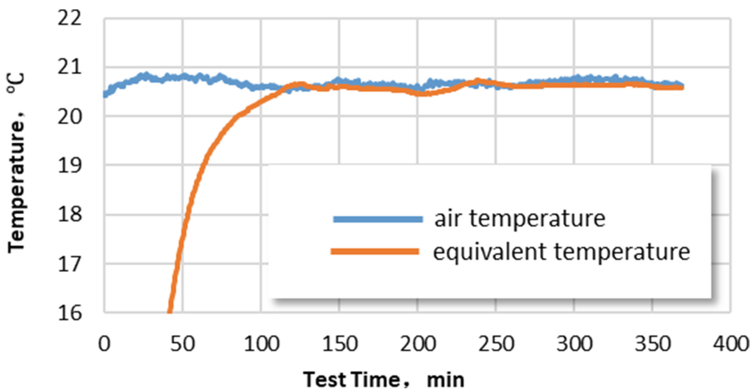

Fig. 7. Equivalent temperature measurement curve comparison with air temperature in climate room

by air-conditioner, reason for this was that the cold wind from air-conditioner blowing to human body or the manikin affected heat loss to environment and then reinforced the feeling of coolness.

The sitting manikin PMV in the chamber obtained from software was –0.8, which was relatively close to the subjective thermal sensation vote (–0.917 ± 0.996) investigated from 12 subjects while they kept sitting or reading over 90 min. The statistical standard deviation 0.996 was considered a little large in the view of statistics. It might depend on account of a limited sample, subjects likely had distinctly different thermal preference so that they would generate discrete mental sensations even in the same condition.

However, the relative tolerance between statistical mean thermal vote (MTV) and measured predicted mean vote (PMV) was merely 13% and both of them could be considered as slightly cool but comfortable status according to the 7-point thermal sensation scale.

4 Conclusions

In summary, after heating manikin about 100 min, the thermodynamic state of manikin tended to become stable. After heating manikin 2 h, the heating process was completely constant and there was no longer any temperature rise or steady heat flux variation on the manikin surfaces. Consequently, the control process of manikin system is not only rapid but also quite stable by variable integral PID controller.

The surface temperature distribution of completely heated manikin behaves close proximity to real human body surface at the near range of 33 or 34 °C. The deviation of t_eq and t_a in a same standard uniform environment is just 0.1 °C which can be considered negligible because of the tiny relative tolerance (0.5%). Therefore the measurement accuracy of manikin has been proved to be really high through Trial 1, which has led a solid foundation for its profound application and popularization in the future research to predict the thermal sensation of Chinese body precisely. The manikin system developed in this paper can be used to evaluate thermal comfort in moderate environment.

Furthermore, the result of objective evaluation with this manikin system is very close to the statistical data from subjective evaluation in Trial 2 with a certain number of subjects in the same environmental condition. In summarize, it is reasonable and credible to evaluate Chinese thermal comfort in moderate environment by means of this integrated manikin system consisted of a segment-heated thermal manikin, a clothing thermal resistance measurement software and a thermal environment comfort evaluation software.

References

1. Nilsson, H.O.: Comfort Climate Evaluation with Thermal Manikin Methods and Computer Simulation Models. National Institute for Working Life, Stockholm (2004)
2. Xia, Y., Guo, X., Liu, Y.: The research and application of temperature control system based on gearshift integral PID algorithm. Comput. Knowl. Technol. **10**, 3921–3922 (2014)
3. Ergonomics of the Thermal Environment - Evaluation of Thermal Environments in Vehicles - Part 2: Determination of Equivalent Temperature. ISO 14505-2:2006(E) (2006)
4. Ergonomics of the Thermal Environment - Estimation of Thermal Insulation and Water Vapor Resistance of a Clothing Ensemble. ISO 9920:2007 (2007)

5. Fabbri, K.: Indoor Thermal Comfort Perception - A Questionnaire Approach Focusing on Children. Springer International Publishing, Switzerland (2015)
6. Ergonomics of the Thermal Environment – Determination of Metabolic Rate. ISO 8996:2004 (2004)