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Abstract: Thermal manikins are frequently used for testing and product development by sports science and human excises field, by the building industry and by the automobile industry for evaluation of the performance of heating and ventilation systems. The multi-segment sweating thermal manikin “Newton” and one-segment thermal manikin “Walter” were described in the paper. The calculation methods on clothing thermal insulation and moisture vapour resistance were briefly introduced. The advantages and disadvantages of those two typical thermal manikins were also illustrated.

Keywords: thermal manikin; thermal insulation; moisture vapour resistance

Introduction

The interest of using thermal manikins in researches and measurements has been steadily growing since 1945. At present, there are more than 100 thermal manikins in use in worldwide. Thermal manikins become more multi-functional as the development of the modern science and technology. Thermal manikins provide a useful and valuable complement to direct trials with human subjects. In conditions where the heat exchange of is complex and transient measurements with a thermal manikin produce relevant, reliable and accurate values for whole body as well as local heat exchange. Such values are useful for assess thermal stress in environments with human occupancy, determine heat transfer and thermal properties of clothing, predict human responses to extreme or complex thermal conditions, validate results from human experiments regarding thermal stress, as well as simulate thermal responses in human exposed to various environments.

Thermal manikins are traditionally used for the climate research. Recently, manikins are increasingly used in many practical applications. Today, thermal manikins are frequently used for testing and developing products by the building industry and by the automobile industry for evaluation of the performance of heating and ventilation systems. The clothing industry uses

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manikins for development of clothing systems with improved thermal properties. Those kinds of research work results in continuous improvement of environments and products of importance for comfort, health and safety in working life.

In this paper, two typical sweating thermal manikins were described. The features and principles of the sweating thermal manikin "Newton" and the fabric manikin "Walter" were presented. Finally, the advantages and disadvantages of those two manikins were compared and summarised.

The Feature of Thermal Manikins

Among all of thermal manikins in use worldwide, the sweating thermal manikin "Newton" and perspiring fabric thermal manikin "Walter" are the two most important ones. The thermal manikin "Newton" was produced by the Measurement Technology Northwest Company (MTNW) in the United States, which is constructed of a thermally conductive aluminium filled carbon epoxy shell with embedded heating and sensor wire elements, as shown in Fig.1.

Fig.1 20-zone sweating thermal manikin "Newton"

There are three types of multi-segment "Newton" at present, 20, 26 and 34 zones. "Newton" was developed using an advanced CAD digital modelling to ensure repeatability in manufacturing. The system is built in accordance with ASTM and ISO standards to meet the garment evaluation needs of testing institutes, clothing, and sleeping bag manufacturers. Also, it is fully jointed, providing motion at the ankles, elbows, knees, and hips to allow virtually any possible body poses. The details of a 20-segment "Newton" are shown in Table 1.

Table 1 Details of thermal manikin “Newton”

Zone No.	Zone name	Surface area(m^2)	Flow conductance(ml/psi-hr)
1	face	0.04569	23.73
2	head	0.09687	42.50
3	right upper arm	0.08356	24.51
4	left upper arm	0.08356	23.98
5	right forearm	0.06483	22.73
6	left forearm	0.06483	23.79
7	right hand	0.04604	23.77
8	left hand	0.04604	23.48
9	chest	0.12096	38.17
10	shoulders	0.10089	38.66
11	stomach	0.11915	42.25
12	back	0.09395	37.16
13	right hip	0.07604	24.05
14	left hip	0.07604	20.51
15	right thigh	0.15193	39.50
16	left thigh	0.15193	36.58
17	right calf	0.13510	37.85
18	left calf	0.13510	35.24
19	right foot	0.05965	20.62
20	left foot	0.05965	24.21

The thermal manikin “Walter” was invented and manufactured by the Hong Kong Polytechnic University in 2001. “Walter” is the world first manikin made of fabric and water, as shown in Fig.2. Obviously, it is a one segment sweating manikin.

Fig.2 One-segment thermal manikin “Walter”

“Walter” simulates perspiration using a piece of waterproof but moisture permeable fabric “skin”, which holds the water inside the body, but allows moisture to pass through the skin. Walter achieves a body temperature distribution similar to a person by pumping warm water at the body temperature from its centre to its extremities. However, the Gore-tex skin can only be used to simulate insensible sweating. The main dimensions of this type manikin are listed in Table 2.

Table 2 Dimensions of the manikin "Walter"

Body Height	172 cm
Neck Circumference	45 cm
Chest Circumference	95 cm
Waist Circumference	89 cm
Hip Circumference	100 cm
Body surface Area	1.79 m^2

The mean skin temperature of "Walter" can be adjusted by regulating the pumping rate of the four pumps inside the manikin body. The regulation is performed by altering the frequency of the power supply to the pumps. Water is supplied automatically and the water loss by 'perspiration' is measured in real time. Walter's arms and legs can be motorised to simulate 'walking' motion. The 'walking' speed may be changed from 0 m/s to 2.7 km/h by adjusting AC frequency of the power supply to the motor that drives the motion.

Calculation of Thermal Comfort Parameters

Clothing thermal insulation and moisture vapour resistance are the two most important physical parameters of clothing ensembles. They are intrinsic properties of clothing depending on the fabric properties, garment style and fitting, and are affected by body posture, body motion and environmental conditions.

The thermal insulation and moisture vapour resistance can be measured by taking measurements on human subjects. This subjective method gives realistic results, but requires sophisticated equipment and is time consuming, and the measured values may also have large variability. Also, human trials are costly and the ethical issue may be involved. Human shaped thermal manikins which can simulate the heat and mass transfer between a human body and the environment have therefore been developed for the purpose. Moreover, measurements on thermal manikins are more repeatable. Therefore, the thermal manikin is an ideal tool to measure clothing thermal insulation and moisture vapour resistance.

Under the heat equilibrium, Woodcock had assumed that the direct heat loss H_d (W/m^2) and the evaporative heat loss H_e (W/m^2) are independent of each other and can be measured independently, therefore the total rate of heat transfer through the clothing H_t (W/m^2) then can be expressed as:

$$H_t = H_d + H_e \qquad \text{Eq. (1)}$$

According to the Flicks law, the evaporation heat loss H_e can be expressed by

$$H_e = \lambda \times \frac{D\Delta C}{d} \qquad \text{Eq. (2)}$$

where, λ is the heat of evaporation for liquid (water or sweat), J/g; D is the diffusion coefficient for water vapour in the air, the value is 2.68×10^{-5} m^2/s, ΔC is the vapour concentration difference, g/m^2, d is air equivalent, m.

The direct heat loss H_d is including conductive heat loss, convective heat loss and the radiative heat loss. Those three types of heat losses are dominated by the temperature difference between the skin surface and the environment.

The total thermal insulation I_t (m^{2o}C/W) and the total moisture vapour resistance R_e (Pa ^{o}C /W) of the clothing system can be expressed by equations (3) and (4):

$$I_t = \frac{A_s(T_s - T_e)}{H_d} \qquad \text{Eq. (3)}$$

$$R_e = \frac{A_s(P_s - P_e)}{H_e} \qquad \text{Eq. (4)}$$

where, (T_S-T_e) and (P_S-P_e) are the temperature difference and difference of water vapour pressure between the skin and environment, respectively.

The body surface area A_S (m^2) is given by Dubois equation:

$$A_s = 0.07673 W^{0.425} H^{0.725} \qquad \text{Eq. (5)}$$

where, W is the body weight (kg) and H is the human body height (m).

It should be noted that the heat loss method specified on ASTM F2370-05 cannot be applied on the thermal manikin “Walter”. This is because “Walter” cannot determine the dry heat loss except a non-sweating skin is provided. This makes measurements complicated due to two fabric skins should be used to determine one clothing physical parameter.

A comparison study with a dry thermal manikin “Tore” showed that the thermal insulation value measured on such a sweating manikin “Walter” should be corrected. The amount of condensed heat inside the tested garments during the test period accounts for the differences. Therefore, a suggestion for the manikin “Walter” to solve that problem is that usage of lesser sweating fabric skin (i.e., the pore size of the laminated layer is smaller to prevent more moisture molecules through).

Advantages and Disadvantages of “Newton” and “Walter”

The thermal manikin “Walter” can measure clothing thermal insulation and moisture vapour resistance at one step. However, the manikin “Newton” can only measure clothing thermal insulation in the dry test or the moisture vapour resistance by the wet test based on previous dry test at a non-isothermal condition. That means it takes two steps to measure clothing moisture vapour resistance on the manikin “Newton”. In addition, the measured thermal insulation by dry tests is only an ideal value.

The thermal manikin “Newton” can control any part of the body at the set temperature or the set heat flux. However, thermal manikin “Walter” can only control the whole body temperature or skin surface temperature at set value. The ways of sweating is also quite different. “Walter” can sweat actively according to different temperature, humidity and clothing, which can simulate a true human insensible sweating. However, different types of fabric skin must be used in order to change the sweating rate. And many studies demonstrated that the sweating rate tends to be greater than the actual value for a real man in hot conditions. “Newton” sweats negatively, which means sweating rate should be controlled by an operator. Moreover, the sweating rate for just fully wet the fabric skin is also difficult to set and most important, the flow rate to fully wet the skin should be changed with different clothing materials and clothing layers.

The skin of “Walter” might be leaking after several times of worn on and took off. It’s difficult to repair the fabric skin when there are too many leaking points, and the price of such one suite of the fabric skin is expensive. The pipe which connects the manikin water body and the water container on the balance can be easily blocked if the water is not clean enough or has bubbles inside. Thus, the perspiring rate might be inaccurate (i.e., the perspiration rate curve shown on the program is not a linear line at one specific test condition), which can greatly influence the final results on clothing moisture vapour resistance. The sweating thermal manikin “Newton” has no such leaking problems due to a different sweat simulation principle.

At present, thermal manikin “Walter” cannot be operated at extremely low temperature due to the siphon pipe might be frozen, especially the whole body in low perspiring condition. The structure of one segment can also limit the simulation of human body temperature. For thermal manikin “Newton”, each segment of the body can be individually controlled. With this structure, the program can control the whole body temperature or heat flux more accurately.

Conclusions

In this paper, two sweating thermal manikins “Newton” and “Walter” were introduced. Their advantages and shortcomings were compared and addressed. It is important to know the basic principle of each different type of thermal manikins in order to well operate them. It is expected that more advanced thermal manikins will be appeared in the near future as the development of modern technology.

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