ISSN:1306-3111
e-Journal of New World Sciences Academy
2008, Volume: 3, Number: 1
Article Number: A0057

NATURAL AND APPLIED SCIENCES
TEXTILE ENGINEERING
Received: August 2007
Accepted: December 2007

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THERMAL MANIKINS: AN OVERVIEW

ABSTRACT

Thermal comfort is the state of mind that expresses satisfaction between the clothes and the surrounding environment. This definition is very important for both the users of clothes and the manufacturers in textile and apprel sectors. In many years, thermal manikins have been used to measure clothing insulation and to evaluate the relationship between thermal environment and thermal comfort. Thermal manikins are complex, delicate and expensive instruments. These are also designed for researches which are used for simulating of human body. The interest in using them in research and measurement standards has grown in recent years. The aim of this paper is to present an overview of thermal mankins by the support of the scientific researches which were published in last 10 years. For this aim, the general informations, measurement methods and the working areas of thermal manikins are given.

Keywords: Thermal Comfort, Thermal manikin,
Measurement Methods of Thermal Manikins,
Textile and Apparel Industry

ISIL MANKENLER: GENEL BİR BAKIŞ

ÖZET

Isıl konfor, kişinin giysileri ve içinde bulunduğu çevre arasındaki durumdan memmuniyet durumu olarak adlandırılabilir. Bu tanımlama, hem giysilerin kullanıcıları için, hem de tekstil ve hazır giyim sektöründeki üreticiler için oldukça önemlidir. Isıl mankenler, uzun yıllardır giysilerin ısıl izolasyon değerlerinin ölçülmesinde ve ısıl konfor ile ısıl çevre arasındaki ilişkinin değerlendirilmesinde kullanımkatadırlar. Isıl mankenler karmaşık, hassas ölçüm yapan ve yüksek fiyatlara sahip sistemlerdir. Isıl mankenler, aynı zaman da insan vücudunun simülasyonu ile ilgili yapılacak çalışmalar için geliştirilmişlerdir. Bu sistemleri bilimsel araştırmalarda kullanmaya yönelik ilgi, son yıllarda oldukça artmıştır. Bu makalenin amacı, bu alanda son 10 yılda yayınlanmış bilimsel çalışmalardan yararlanarak ısıl mankenlerin detaylı tanıtımını sunmaktır. Bu amaç için; ısıl mankenler hakkında genel bilgiler, ısıl mankenlerin ölçüm metodları ve çalışma alanları makale kapsamında verilmiştir.

Anahtar Kelimeler: Isıl Konfor, Isıl Manken,
Isıl Mankenlerin Ölçüm Metodları,
Tekstil ve Hazır Giyim Endüstrisi

1. INTRODUCTION (GİRİŞ)

Clothing itself has three different aspects, which are physiological, social-psychological, and cultural. One property that influences to the clothing's physical utilixation comfort is thermal comfort, which means user's subjective satisfaction to the thermal environment. It is a neutral state, in which a user does not want to take off or add any garments and any part of the body is not too cold or hot [1].

The thermal properties of clothing materials, which relate thermal comfort of the user, involve the heat and mass transfer between a clothed body and the environment. The thermal resistance of a clothing system represents a quantitative evaluation of how good the clothing provides thermal barrier to the wearer. The water vapor permeability of clothing materials is a critical property for a clothing system, which must maintain the human body at thermal equilibrium for the wearer. Clothing materials with high water vapor permeability allow the human body to provide cooling due to evaporation. At high activity levels or in hot environments, the insulating value alone is inadequate for characterizing and comparing thermal properties of clothing systems. Evaporation of sweat becomes an important avenue of heat loss. Therefore, both the thermal resistance and evaporative resistance of clothing are required to assess the heat exchange of human body with the environment [2]. The thermal insulation properties of clothing systems can be defined through physical measurements using thermal manikins or through wear trials using human test subjects [3].

In many years thermal manikins have been used to measure clothing insulation and to evaluate the thermal environment. The first thermal manikins were developed for testing of the military clothing and space suits, but the increasing demand for a better thermal indoor environment during the 1960s, caused a need for information about the insulation values of common daily clothing. At the same time it was found that the best instrument for measuring the human sensation of the thermal environment is a body-model of the same size and shape as the human body. The model is heated to body temperature and wears the actual clothing. Measurement of the heat loss from different part of such a model indicates the expected degree of thermal comfort for a person in the same position and wearing the same clothing as the measuring manikin [4].

The history of the thermal manikins started with the one-segment copper manikin made for the US Army in the early 40's. The building of the first working thermal manikin for the U.S. military is attributed to Dr. Harwood Belding in 1941, who was working as a civilian contractor for the military at the Harvard Fatigue Laboratory testing protective clothing and equipment using human volunteers. Belding was inspired by a store window fashion manikin to build a crude, headless and armless manikin from stovepipe and various sheet metals. The manikin had a simple internal heater and fan to distribute the heat [5]. A significant step forward was taken with the introduction of digital regulation techniques in 1972. This allowed for more flexible protocols and accurate measurements. So far all manikins measured heat losses, but a French manikin was constructed with a cooling technique that allowed measurements of heat gain. It was used for the assessment of heat protective clothing. A similar application field was aimed for with the "Thermo-man" manikin. It is a passive manikin equipped with sensors for detection of surface temperatures during exposure to intensive convective or radiative heat [6].

Figure 1. Thermal manikin made of copper-1951
(Şekil 1. Bakırdan yapılmış ısıl manken-1951)

Until 1989, all manikins have been men and the first female manikin appared in this year. For the following reasons, female model has been chosen.

- There is more variation in female than in male clothing. This gives more need for measurement of clo-values.
- A female model is smaller and lighter and therefore easier to move in and out of for instance a car [4].

Manikins are complex, delicate and expensive instruments. These properties are balanced, however, by many advanced and useful features. Table 1 provides a list of arguments for the use of thermal manikins [7].

Table 1. Significant performance features of thermal manikins
(Tablo 1. Isıl mankenlerin önemli performans özellikleri)

1	Relevant simulation of human body heat exchange
2	Whole-body and local heat fluxes
3	Measurement of three-dimensional heat exchange
4	Integration of dry heat losses in a realistic manner
5	Objective method for measurement of clothing thermal insulation
6	Quick, accurate and repeatable
7	Cost-effective instrument for comparative measurements and product development
8	Provide values for prediction models

Recently manikins have been developed where perspiration across the skin surface and walking speed can be controlled in some laboratories. However, a two-layer model consisting of a core layer and a shell layer whose temperatures can be independently controlled by a computer has, until now never been developed or tested. Depending on some situation, for example, in the case when wearing cold-weather gear in cold conditions, existing thermal manikins are limited to a uniform temperature distribution across the skin surface even though the human body’s extremities experience large drops in skin temperature. This inevitably leads to an overestimation of heat loss from the extremities in the result obtained using the thermal manikin [8]. Nowadays thermal manikins have unquestionable priority as instruments for determining thermal clothing insulation. The number of manikins is still increasing (there are about 100 working thermal manikins in the world), as is the scope of their applications. Because they are designed and built by different groups, usually associated with universities or research institutes, an enormous diversity of technical characteristics for these devices exists, resulting from the use of different construction materials, differences in shape, structure and the number of segments [9].

2. RESEARCH SIGNIFICANCE (ÇALIŞMANIN ÖNEMİ)

Clothing comfort includes many aspects such as freedom of body movement, tactile comfort and thermal comfort. Among them, thermal comfort is of primary importance since clothing is worn in various thermal conditions. In some extreme and hazardous environments, such as polar regions, high mountains, deep caves etc, thermal comfort may be a matter of life or death. Therefore, the evaluation of clothing thermal comfort and the understanding of the effects of garment design and clothing materials is important for optimization of functional clothing design. The thermal comfort of clothing systems may be evaluated by subjective wearer trials or objective simulation tests. Subjective wearer trials can relate the results directly to the clothing in actual use, but tend to be inconsistent and costly and can sometimes expose the subjects to danger when testing under extreme conditions. Objective simulation tests include flat plate methods (e.g. guarded hot-plates), cylindrical methods (e.g. guarded hot cylinders) and thermal manikins. Thermal manikins have therefore been considered as the most useful tools for evaluating thermal comfort of overall clothing systems [10]. In this paper, the detailed explanations of thermal manikins, measurement methods and the working areas of thermal manikins are given.

3. THE WORKING PRINCIPLES OF THERMAL MANIKINS (ISIL MANKENLERİN ÇALIŞMA PRENSİPLERİ)

Thermal manikins developed by different countries like USA, Germany, Japan, Canada, Denmark, Finland and China are of different characteristics. The difference in material, shape, structure of divided parts, method of temperature control and testing conditions has brought about different testing results. Although these differences, the main principles as follows are the same to each other.

3.1. Body Segments (Vücut Bölümleri)

It is an extremely important factor that the manikin is able to react on the thermal environment in the same way as a human being in the same situation and wearing the same clothing. For doing this, the manikin is divided in 15 or more thermally independent sections, such as head, chest, abdomen, back, buttocks, arms, hands, etc; each with its own heating and computer control system (Figure 2).

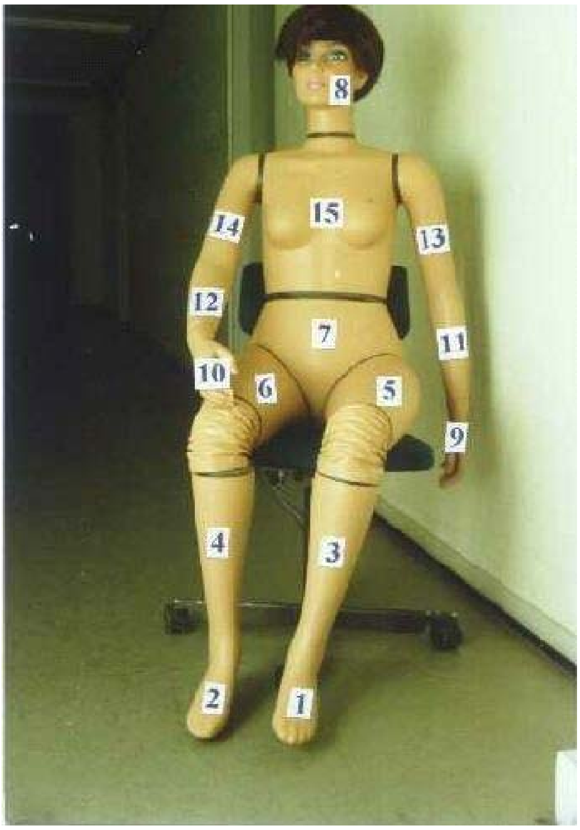

Figure 2. The body segments of a thermal manikin
(Şekil 2. Isıl mankenin vücut segmentleri)

The control system must be designed in a way which gives the correct correlation between surface temperature and dry heat loss. This correlation is given in ASHRAE - as well as in ISO - standards. It is based on Fangers comfort equation:

Skin temperature= 35.7 - 0.028 * heat loss (°C).

or when only the dry heat loss is simulated:

Skin temperature= 36.4 - 0.054 * dry heat loss (°C).

These equations give the mean values for the total body surface. In order to overcome this, all the body parts of the manikin are individually controlled [4].

The body height of the manikin is approximately (1,70±0,15) m, with a body surface area of (1,7±0,3) m^2 (ISO 15831, 2004). It is possible to see the body segments and respective areas of an average thermal manikin in Table 2.

3.2. Surface Temperature (Yüzey Sıcaklığı)

The manikin is constructed so as to maintain the same average constant temperature of (34,0±0,2)°C measured at all segment surfaces of its nude body. The surface temperatures of the manikin are be measured by at least one appropriate temperature sensor (e.g. thermocouples, thermistors, resistance temperature devices) per body segment. The sensors is not protrude more than 0,5 mm from the manikin's surface and shall be well bonded, both mechanically and thermally, to the manikin's surface. Lead wires are bonded to the surface, or preferably pass through the interior of the manikin. When calculating the mean skin surface temperature of the manikin's body, each sensor temperature is area-weighted, considering the portion of the body surface area covered by the sensor [11].

3.3. Heating System (Isıtma Sistemi)

Generally, the nickel windings on the parts of the body of the manikin distribute the heating effect homogeneous so the effect per square meter of the body is the same in all parts at the same voltage. The wire is used for both heating and measuring. Heating is performed by pulse lengths of 0-24 ms over 1024 steps. The frequency is 40 Hz, supplied from the internal controllers. The effect from the heating wire is controlled by means of time modulated pulses from zero to about 24 milliseconds. All body parts are switched on and off separately. All control, measurements and calculations are done in a build in computer in each part. All parts work alone if connected to a computer. The heating period is maximum 24 milliseconds. In the next 1 millisecond the temperatures of all parts are measured and the heating effect calculation is updated. The temperature is calculated from the resistance of the heating wire, which is measured by the controller. After this measuring period the heating period starts again. The software inside the controllers can be updated from the computer. The supply voltage is continuously measured. Therefore the manikin will work with full accuracy on a car battery changing from max 30 V to min 15 V [4].

Table 2. The body segments and respective areas of an average thermal manikin
(Tablo 2. Isıl mankenin ortamana alanları ve vücut segmentleri)

No	Name of body segments	Area (m^2)
1	L. foot	0.0430
2	R. foot	0.0430
3	L. low leg	0.0900
4	R. low leg	0.0900
5	L. front thigh	0.0850
6	R. front thigh	0.0880
7	L. back thigh	0.0750
8	R. back thigh	0.0780
9	Pelvis	0.0550
10	Back side	0.1100
11	Skull	0.0500
12	L. face	0.0258
13	R. face	0.0258
14	Back of neck	0.0248
15	L. hand	0.0380
16	R. hand	0.0370
17	L. forearm	0.0500
18	R. forearm	0.0500
19	L. upper arm out	0.0419
20	R. upper arm out	0.0436
21	L. upper arm in	0.0319
22	R. upper arm in	0.0336
23	L. chest	0.0700
24	R. chest	0.0700
25	L. back	0.0650
26	R. back	0.0650
Total		1.479

3.4. Measurement System (Ölçüm Sistemi)

The manikin is placed in a controlled climatic chamber, at least 2 m × 2 m × 2 m (length × width × height). The manikin is dressed with the clothing ensemble to be tested, with each garment arranged on the appropriate part of its body as in practical use. The air flow in the chamber is horizontal or vertical. The mean air temperature in the climatic chamber is 22,5 °C. The test time of each measurement for clothing ensembles is nearly 60 minutes. The serial and parallel calculation models are used to obtain thermal insulation and thermal conductivity values. At the end of each measurement, the heat loss (P), thermal resistance (R) and thermal insulation (Clo) values are obtained and saved by the computer [11].

3.4.1 Serial model (Seri Model)

The total thermal insulation, *I*t, or the resultant total thermal insulation, *I*tr, is calculated on the test results gained with the manikin respectively either stationary or moving its legs and arms, using Equation (1).

$$I_t \ \mathbf{or} \ I_{tr} = \sum_i f_t \times \left[\frac{(T_{si} - T_a) \times a_i}{H_{ci}} \right] \text{ in square metre kelvins per watt} \quad (1)$$

$$\text{where } f_i = \frac{a_i}{A} \quad (2)$$

3.4.2. Parallel model (Paralel Model)

The total thermal insulation, *I*t, or the resultant total thermal insulation, *I*tr, is calculated on the test results gained with the manikin respectively either stationary or moving its legs and arms, using Equation (3).

$$I_t \ \mathbf{or} \ I_{tr} = \left[\frac{(T_{si} - T_a) \times A}{H_c} \right] \text{ in square metre kelvins per watt} \quad (3)$$

where

$$T_s = \sum_i f_i \times T_{si} \text{ in degrees centigrade}$$

$$H_c = \sum_i H_{ci} \text{ in watts}$$

where

*I*t is the total thermal insulation of the clothing ensemble with the manikin stationary, in square metre kelvins per watt;
*I*tr is the resultant total thermal insulation of the clothing ensemble with the manikin moving, in square metre kelvins per watt;
*T*s*i* is the local surface temperature of section *i* of the manikin, in degrees centigrade;
*T*a is the air temperature within the testing chamber, in degrees centigrade;
ai is the surface area of section *i* of the manikin, in square metres;
*H*c*i* is the local heat loss from section *i* of the manikin, in watts;
A is the total body surface area of the nude manikin, in square metres;
fi is the area factor of section *i* of the nude manikin;
*f*cl is the clothing area factor [11].

3.5. Application Areas of Thermal Manikins (Isıl Mankenlerin Uygulama Alanları)

A thermal manikin is a useful tool to evaluate thermal environments such as clothing, houses and others [7]. The main application fields for thermal manikins are as follows:

- Evaluation of clothing
  - thermal properties (insulation and evaporation. resistance)
  - protection (fire, radiation, rain)
- Evaluation of HVAC-systems
  - buildings
  - vehicles
  - incubators
- Evaluation of indoor air quality
- Simulation of human occupancy
- Physiological simulation
- Other applications [6].

4. RESULT (SONUÇ)

Thermal manikins are necessary instruments for measuring the thermal insulation and thermal conductivity of clothing systems, which are important parameters relevant to clothing thermal comfort. Tests with thermal manikins are frequently used to determine the thermal insulation of clothing ensembles. Thermal manikins need to have the some properties like correct body shape and size, control of heat emission, control of the distribution of heat across the skin surface, emission of the skin, control of the distribution of perspiration across the skin surface etc. in order to accurately simulate the human body. Thermal manikins can react as a human being and some thermal manikins can also simulate human perspiration. The new techmologies in this area make possible them to do also the walking position. For all these advantages, textile and apparel industry will attach more importance to thermal manikins especially for the field of thermal comfort.

The history of thermal manikins begins in the early 1940's. Until our modern day, lots of researches and applications have been done in all over the world by using thermal manikins. USA, Japan, Denmark, Finland, Sweden and China are the leader countries in this area. In Turkey, it is really hard to find some scientific researches in the area of textile and apparel by using thermal manikins. It would be quite reasonable to assume a significant increase in the implementation and in the acceptance of the thermal manikins in the textile industry since they are being recognized as functional and convenient tools.

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