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Development of a Human-Clothing-Environment Simulator for Dynamic Heat and Moisture Transfer Properties of Fabrics

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Abstract: A vertical skin model with two detachable environmental chambers was developed to simulate a Human-Clothing-Environment system and to evaluate heat and moisture transport properties of textile materials under severe conditions and during transient states. The construction of the system was described and data reproducibility and accuracy of the instrument were verified by using PEG treated nonwovens. Also advantages over a traditional static type experiment were demonstrated based on a series of experiments.

Keywords: Human-Clothing-Environment simulator, Dynamic heat and moisture transport properties, Vertical skin model, Transient condition, Environmental condition effect

Introduction

Novel technologies have been introduced to develop innovative textile materials and/or finishes that meet customer demands. Such multi-functional textile materials require different methods to properly assess their performance. While wearing comfort is one of the most important properties to be considered, there have not been many studies on the apparatus and techniques to measure this variable. This is because the significance of comfort has been underestimated while the complex mechanism and the variables involved in heat and moisture transfer processes within the microclimate of a testing apparatus cannot be controlled readily.

There have been many attempts to determine the mechanisms of heat and moisture transfer through textile materials [1,2]. In doing so, researchers have been confronted by limitations in establishing an ultimate model to predict real wear situations on account of the numerous variables, which are attributed to various wearing conditions of garments as well as manufacturing processes of the material itself. Several efforts in developing measurement techniques for wearing comfort by using appropriate apparatuses have been made in order to attain reliable results wherein the microclimate in a real wear situation is represented in terms of heat and moisture transport properties [3-6]. Most of these studies adopted horizontal type skin simulators as heat and moisture sources for simulating the temperature regulation system of human skin. In order to determine the effects of material characteristics on comfort, it is necessary to consider the wearing circumstances, environmental conditions, and human activity levels. Accordingly, researchers have introduced apparatuses such as sweating manikins and movable manikins in order to simulate complex thermodynamic mechanisms and the movement of the human body effectively. The skin models provide useful information on material properties but are insufficient for prediction of the performance of a garment under real wearing situations. While sweating/movable manikins provide tangible advantages from the point of view of assessing material properties, they still have some limitations in terms of cost, operational complexity, and availability.

Combining the advantages of the skin model and the sweating manikin, a Human-Clothing-Environment (HCE) Simulator was developed in this study. The simulator is a vertical skin model with two detachable chambers that can be utilized to measure heat and moisture transfer properties through textile materials under various environmental conditions as well as garment construction effects, such as layering and openness, and movement effects such as ventilation. The construction and the features of the HCE simulator are described and the reproducibility/accuracy and the advantageous characteristics over existing apparatuses are verified from a series of experiments in this study.

Construction of the Human-Clothing-Environment Simulator

The Human-Clothing-Environment Simulator (Korea patent pending: 03-19136) consists of a power supply with a temperature control unit, a hot plate, two environmental chambers, and a data logging system, as shown in Figure 1.

Environmental Control Chambers

Two detachable environmental chambers are installed to investigate the effects of cyclic environmental changes and severe climatic conditions. The chambers are individually controlled from $-30\,^{\circ}C$ to $18\,^{\circ}C$ for the low temperature range and from $18\,^{\circ}C$ to $50\,^{\circ}C$ for warm conditions. The control accuracy of the temperature and humidity is $\pm 0.5\,^{\circ}C$ and $\pm 2\,\%$, respectively. Two separated chambers make it

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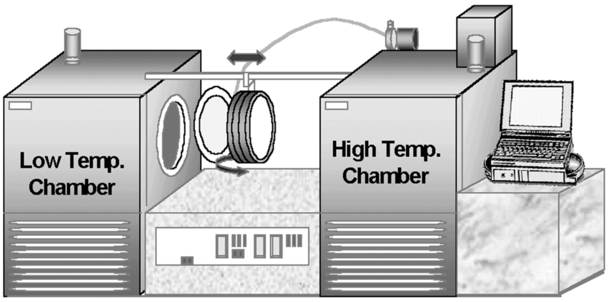

Figure 1. Human-Clothing-Environment simulator.

possible to provide a wider control range than the conventional type so that the performance of functional textiles can be studied with a range of extreme outdoor conditions and transient conditions.

The vertical test plate can be rotated and has access to each chamber so that different conditions can be achieved in a very short time by quickly moving the test plate from one chamber to the other by way of a bar that connects the two chambers. The wind speed inside the chambers ranges from 0.2 to 0.7 m/s depending on the condition of temperature and humidity.

Vertical Skin Model

The skin model is vertically constructed so as to simulate the body-clothing-environment system more precisely, whereas most other skin simulators are horizontal types. Figures 2 and 3 show a schematic diagram and a photograph of the vertical skin model, respectively. The vertical skin model consists of two parts: a hot plate and a sweat-distributing layer. The hot plate temperature is maintained at mean skin temperature, generally 33 °C, and the control range is 22 to 42 °C. The required input power to maintain the temperature constant is recorded in real time.

The sweat-distributing layer is attached onto the hot plate and the moisture level can be controlled with consideration of activity level and/or environmental conditions (Figure 3). The testing area is a circle of 20 cm diameter and is covered with a functional fabric that absorbs moisture quickly and dries rapidly so that the supplied moisture can be distributed throughout the test area evenly without dripping. The maximum absorbent capacity, the rate of absorption, and the drying rate of the moisture distributor are summarized in Table 1. Based on the moisture management properties of the functional fabric, the appropriate amount of supplied moisture and the number and location of nozzles were determined.

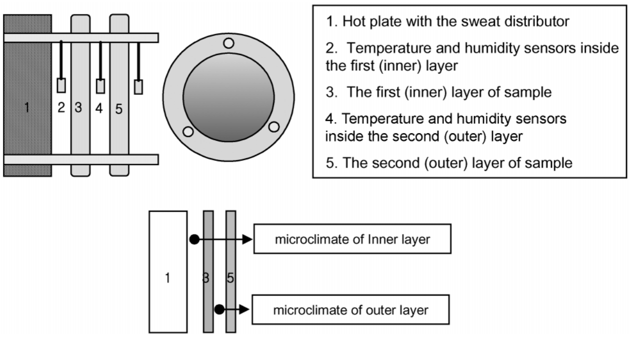

Figure 2. Schematic diagram of the vertical skin model and the measurement location

Figure 3. Picture of the vertical skin model and sensors.

Table 1. Moisture management properties of the sweat distributing layer

Maximum absorbent capacity (g/cm^2)	Drying rate (g/cm^2)	Rate of absorption of 1 m*l* drop (cm/10 sec)		
		Vertical upward	Vertical downward	Horizontal
5.53×10^{-2}	1.3×10^{-4}	2.2	4.5	4.5

The vertical skin model contains temperature and relative humidity sensors (CHS-APS, TDK) located in each layer to monitor the microclimate within the garment, as shown in Figure 2. The data from the temperature and humidity sensors are collected in the computer for further analysis.

More than one layer of the specimen can be tested to determine the layering effects by using sample mounting frames with gaskets. The thickness of the air gap between the layers can be controlled by manipulating the thickness of the sample mounting frames from 0 to 30 mm and there can be several openings for simulations of various garment designs.

The skin model can rotate 360 ° and move between the two chambers. For example, if one wants to predict the comfort of a skiwear ensemble consisting of underwear, innerwear, and outerwear, three layers of test fabrics could be mounted over the vertical skin model and the two chambers could be set to room temperature and an outdoor skiing environment mean temperature, respectively. The skin model with test fabrics would be connected to the room temperature chamber and the temperature and humidity inside each layer for a certain amount of time would be

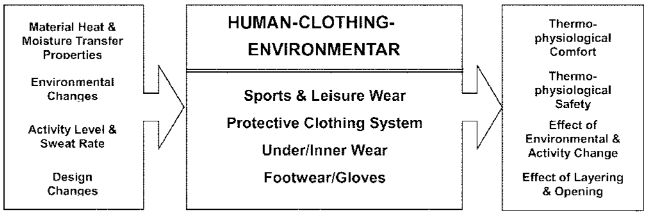

Figure 4. Application range of the Human-Clothing-Environment simulator.

measured. Subsequently, the model would be moved to the lower temperature chamber for a designated period of time to investigate the features of heat and moisture transfer properties through each layer when the environmental conditions change.

Application of HCE Simulator

The information that can be obtained from the HCE simulator is summarized in Figure 4. The advantages of the HCE simulator relative to the existing methods are as follows.

First, utilizing two independent chambers, the effects of cyclic changes of environmental conditions are monitored when a test material is subjected to the two different sets of conditions consecutively. For example, endothermic and exothermic phenomena of temperature adaptable fabrics, which are well known as phase changing materials, can be investigated with environmental temperature changes.

Second, a broader range of temperature control (–30 °C~ 50 °C) makes it possible to investigate the performance of functional textiles that otherwise could not be assessed under standard conditions. Microporous membrane laminated fabrics are known as breathable under standard conditions. The breathability is the critical factor in their functioning and for that reason most customers and manufacturers consider such material to be the optimal choice for sports and leisure wear. There is plentiful data for standard conditions supporting this assumption. However, when breathable materials are used under arctic conditions, a freezing of the moisture from the body on the surface of the membrane blocks the micropores and deteriorates the breathability of the membrane. For this case, a chamber with arctic conditions can simulate the real wearing environment to provide information on the effects of environmental conditions on the material heat and moisture transfer properties.

Third, by controlling the water supply to the sweat-distributing layer, the effects of sweat rate attributed to activity levels and/or strenuous environmental conditions on the heat and moisture transfer properties of the textile materials can be assessed.

Fourth, layering effects and the role of each layer on the heat and moisture transfer properties of a garment system can be investigated by manipulating the sample mounting frames. The garment design factors such as opening area and location can be considered in this system as well.

Table 2. Comparison of comfort evaluation methods

	HCE simulator	Human test	Sweating manikin	Skin model	Walk-in chamber
Cost	●	△	△	●	△
Preparation	●	△	△	●	-
Speed	◎	△	○	◎	-
Reproducibility	◎	△	◎	◎	-
Accuracy	◎	△	◎	◎	-
Information	●	○	◎	△	-

●: excellent, ◎: very good, ○: good, △: not good.

Table 2 shows a comparison of the HCE simulator and the existing evaluation methods.

Experimental

Control Accuracy and Data Reproducibility

In order to verify the accuracy of the apparatus and reproducibility of the test results, a series of cyclic tests were made using a test sample. A nonwoven fabric treated with polyethylene glycol was used as a test material. Polyethylene glycol is known as a temperature adaptable material that has endothermic and exothermic characteristics near skin temperature and at reasonable environmental temperatures for human activities [7,8]. These temperature-buffering characteristics vary according to the molecular weight and the amount of add-on of the polyethylene glycol.

For the test, polyethylene glycol with molecular weight 1500 was added onto a polyester nonwoven fabric with 120 g/cm^2 weight. The amount of add-on was 50 %. Test conditions were 25 ± 0.5 °C, 50 ± 1 % RH for one chamber and –20±0.5 °C for the other. The skin model with the test samples was connected to each chamber for 30 minutes at a time. For the outer layer, a wind-proof fabric was used to minimize the wind effect.

Dynamic Insulation Properties

As an important feature of the HCE simulator, dynamic heat and moisture properties of a temperature adaptable fabric can be determined under transient conditions. To investigate temperature-buffering properties under different environmental conditions, two test samples were prepared: nonwovens treated with PEG with molecular weights of 1500 and 400, respectively. Nonwovens rather than woven fabrics were selected for the samples in order to apply the maximum amount of temperature adaptable materials on the test fabric and nonwovens are superior to woven fabrics from this point of view. The same amount of add-ons and procedure were applied to identical nonwovens for both samples. Upper part of the Table 3 shows the samples layout

Table 3. Layout of test samples

Experiment	Inner layer	Outer layer
Dynamic insulation property	PEG 400 treated nonwoven PEG 1500 treated nonwoven	Windproof fabric
Effect of environmental condition	150 denier polyester knit	Microporous membrane laminated Polyester fabric Wool fleece fabric

Table 4. Thermal properties of specimens with different molecular weight of PEG

Molecular weight of PEG	Thickness (mm)	Weight (g/cm^2)	T_m (°C)	T_c (°C)	ΔH_f (J/g)	ΔH_c (J/g)	Thermal conductivity (W/cm°C)
400	2.44	120	-	-	-	-	1.9×10^{-4}
1500	2.45	120	47.36	20.89	40.65	34.76	1.9×10^{-4}

used in this experiment. To determine thermal properties of the samples Differential Scanning Calorimeter (DSC) and the Thermo Labo II(KES-F7) were utilized. The results of DSC and thermal insulation properties at 20 ± 1 °C were summarized in Table 4. There was no difference in the thermal conductivity between the samples at the steady state but DSC test result shows that the PEG 400 treated sample, which does not have phase changing property, showed neither endothermic nor exothermic characteristics as expected. The sample treated with PEG 1500 had a heat absorbing peak at 47 °C and a heat releasing peak at 21 °C.

The hot plate temperature of the skin model was maintained at the mean skin temperature (33 °C) and the PEG treated nonwovens were mounted on the inner layer. Since nonwoven fabrics usually have larger pores than woven fabrics, a windproof material was mounted for the outer layer to block the effects of the wind speed inside the chambers. Test conditions and times are summarized in Table 5. After the samples mounted skin model was connected to the warm chamber, temperature and humidity of each layer were measured during a 30 minute period. It was quickly moved to the cold environment and measured the microclimates for 30 minutes. The same procedure was repeated twice for a total of 2 hours. The data on the temperature and the relative humidity inside each garment layer were collected and recorded every 10 seconds through the data logging system. If the amount of calories released or absorbed during phase changing is sufficient, some differences in microclimate temperatures between the two samples are anticipated.

Effects of Environmental Condition

The effects of environmental temperature on the heat and moisture transfer properties of textile materials were investigated. For this experiment, a microporous membrane laminated polyester fabric and a wool fleece fabric were compared.

Using a syringe, 8 m*l* of distilled water was supplied to the sweat-distributing layer of the skin model. The two chambers were set at 25 °C, 50 % RH and −10 °C, respectively. For the inner layer, 150 denier polyester knit fabric was used as innerwear for both test samples. Test conditions and the procedure are described in Tables 5 and 6. After moisture was supplied to the sweat-distributing layer, the sample was connected to the warm-conditioned chamber for 15 minutes (period 1) and then switched to the cold chamber for 30 minutes (period 2). The microclimate within each layer was measured for both samples and the effects of environmental temperature on the moisture transfer properties of the microporous membrane and wool fleece fabric were compared.

Table 5. Test protocols

Experiment	Period	Test condition	Testing time (min)
Dynamic insulation property	1	25 ± 0.5 °C, 50 ± 1 % RH	30
	2	−20 ± 0.5 °C, 15 ± 1% RH	30
	3	25 ± 0.5 °C, 50 ± 1 % RH	30
	4	−20 ± 0.5 °C, 15 ± 1% RH	30
Effect of environmental condition	1	25 ± 0.5 °C, 50 ± 1 % RH	15
	2	−10 ± 0.5 °C, 19% ± 1% RH	30

Table 6. Moisture accumulation within each sample after the test

Outer fabric	Inner layer (polyester knit)	Outer layer
MPM	0.50 g	-
Wool fleece	0.29 g	0.67 g

Results and Discussion

Control Precision and Data Reproducibility

Figure 5 shows the results of a series of cyclic tests and displays the temperature between each layer. The temperature of the inner layer was measured between the PEG treated nonwoven and the skin simulating hot plate and the outer layer temperature was taken between the inner and outer

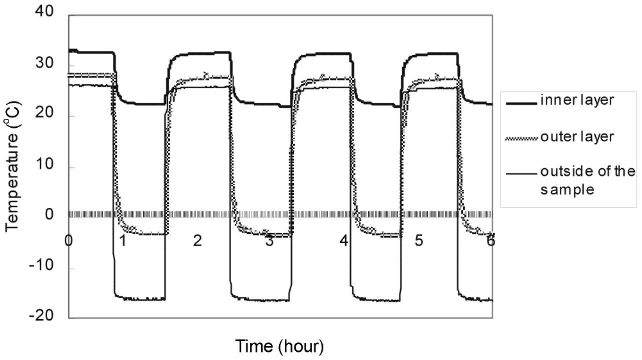

Figure 5. Consistency of transient test results obtained in two different conditions: warm condition: 25 ± 0.5 °C, 55 % RH, cold condition: −20 ± 0.5 °C, 15 % RH.

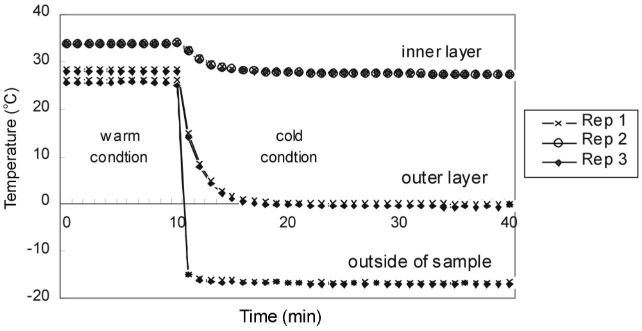

Figure 6. Data reproducibility of Human-Clothing-Environment simulator: microclimate temperatures of PEG 1500 treated nonwoven at transient conditions (warm condition: 25 ± 0.5 °C, 55 % RH, cold condition: −20 ± 0.5 °C, 15 % RH).

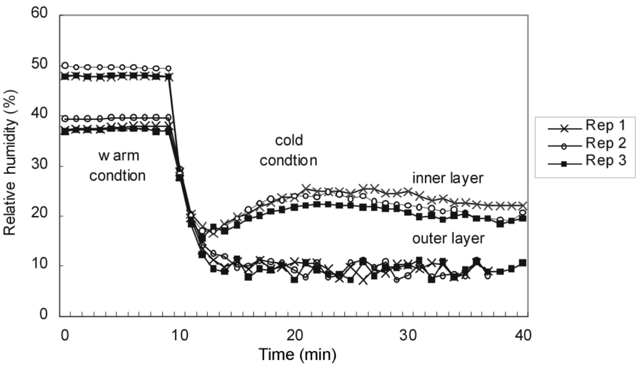

Figure 7. Data repeatability of Human-Clothing-Environment simulator: microclimate humidity of PEG 1500 treated nonwoven at transient conditions (warm condition: 25 ± 0.5 °C, 55 % RH, cold condition: −20 ± 0.5 °C, 15 % RH).

layer. The graph shows data reproducibility, sensitivity of the sensors, and the control accuracy of the chambers. Immediately after the skin model was moved and connected to the different condition chamber, the temperature sensors detected the differences without any time delay and the reading was stable throughout the 30 minute test period. The results also show the stabilized temperature control system of the chambers. For the duration of the test, the chambers regulated the temperature in a consistent range. Therefore the pattern of the graph shows identical paths for each change. Figures 6 and 7 show the data reproducibility of the HCE simulator. Three test replications were made using the same test material. In the case of temperature, reproducibility of the data was verified within the control range of the control chamber (±0.5 °C) in every layer and microclimate humidity also showed good consistency with only 1~2 % standard deviation.

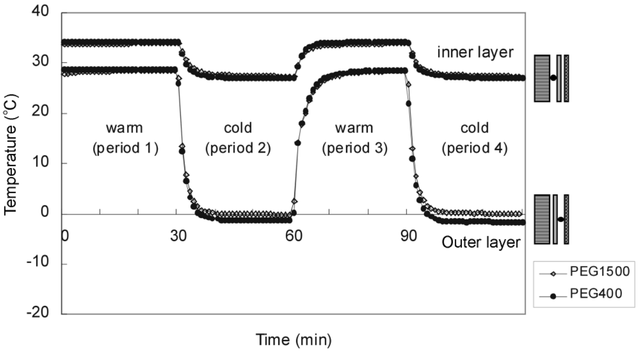

Figure 8. Microclimate temperature of the PEG treated sample within each layer at transient conditions (inner layer: PEG 1500 or PEG 400 treated nonwoven, outer layer: waterproof fabric, warm condition: 25 ± 0.5 °C, 55 % RH, cold condition: −20 ± 0.5 °C, 15% RH).

Dynamic Insulation Properties

Figure 8 shows the microclimate temperatures of the test samples under dynamic conditions. In the warm condition (periods 1, 3), there was no difference in temperature between the samples. When the skin model was moved to the cold condition (periods 2, 4), the PEG 1500 treated sample, which was expected to have exothermic characteristics, showed higher temperature than the PEG 400 treated sample, both in the inner and the outer layers. The differences were greater in the outer layer (1.3 °C) than in the inner layer (0.5 °C). This is because that the temperature of the inner layer (29~30 °C) is higher than the peak temperature of thermal release from the PEG 1500 treated sample, which is 20~21 °C. The thermal release properties could be more effective in the outer layer than in the inner layer because of the cooler microclimate temperature. Therefore it is reasonable to propose that a phase changing material with this range of effective temperature be applied to the second or third layer rather than the innermost layer to get more effective thermal buffering properties at lower temperature.

Useful information can also be obtained by determining how differences in microclimate temperature in the HCE

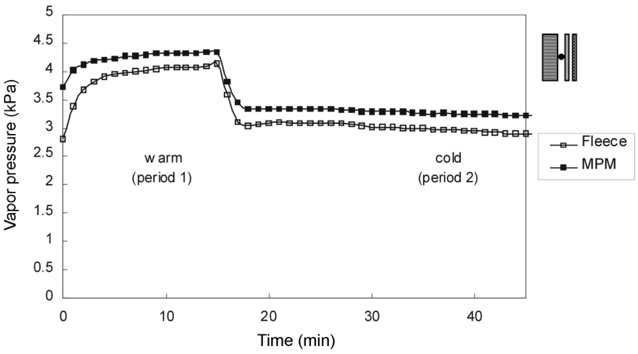

Figure 9. Vapor pressure inside the inner fabrics when applying two different outer fabrics at transient conditions (inner fabric: 150 denier polyester knit, warm condition: 25 ± 0.5 °C, 55 % RH, cold condition: –20 ± 0.5 °C, 15 % RH).

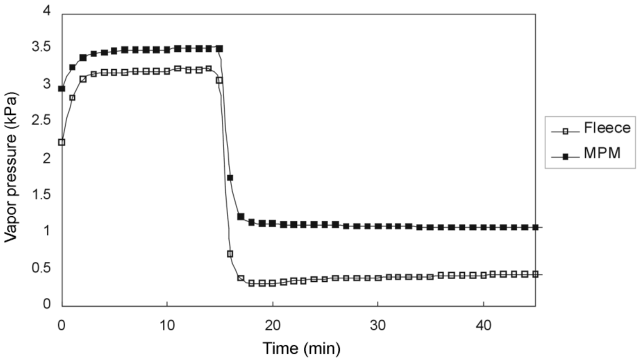

Figure 10. Vapor pressure inside the outer fabrics when applying two different outer fabrics at transient conditions (inner fabric: 150 denier polyester knit, warm condition: 25 ± 0.5 °C, 55 % RH, cold condition: –20 ± 0.5 °C, 15 % RH).

simulator reflect the human subjective assessment of a thermal buffering effect in a real wearing situation. In this study, extreme conditions for a cold environment were selected for the outside temperature to maximize the treatment effects. Based on the results from this experiment, the HCE simulator can be utilized to simulate various wearing situations and predict the performance of thermal adaptive textile materials under dynamic conditions.

Effects of Environmental Conditions

Figures 9 and 10 show the vapor pressure calculated from the temperature and the humidity of the inner layer and the outer layer, respectively. Vapor pressure in the inner layer is measured between the polyester knit and the hot plate and the outer layer measurement is taken between the polyester and the microporous membrane or the wool fleece fabric. In the inner layer, the microclimate within the microporous membrane showed higher vapor pressure than that of the wool fleece fabric under both warm and cold conditions. The difference between the two samples is 0.3~0.4 kPa, which is maintained constant throughout the test in the inner layer. This indicates that the microporous membrane laminated polyester fabric does not transport the moisture from the hot plate as much as the wool fleece fabric. Although an identical polyester knit fabric was used as an inner layer, characteristics of the outer layer affect the innermost microclimate. On the other hand, in the outer layer the difference is much greater in the cold situation (period 2) than for the warm condition (period 1). In the warm condition, the difference is similar to that in the inner layer (0.3~0.4 kPa); however, the difference is doubled to 0.7~0.8 kPa when the samples were connected to the cold environmental chamber (period 2). The larger difference in period 2 likely arises from moisture condensation on the fabric surface under the cold environment. Condensed or even frosted moisture on the surface of the microporous membrane blocked some of the micropores, and thus the moisture transferred from the source cannot escape to the outside of the garment system. Since the wool fleece fabric, however, has much larger pores than the membrane laminated fabric, blocking effects were less severe, although a large amount of condensed moisture was absorbed inside the wool fleece fabric (Table 6). Therefore it can be said that the "breathability" of the microporous membrane laminated fabric can be deteriorated when exposed to non-standard conditions. This result demonstrates that the end use conditions should be considered when the performance of a functional textile material is evaluated.

Conclusions

In this study a Human-Clothing-Environment (HCE) simulator was introduced as a novel instrument to assess the dynamic heat and moisture transfer properties of various fabrics, and its construction is explained. Applications of the HCE are also presented. The HCE simulator consists of two independently controlled environmental chambers, a vertical skin model, and microclimate sensors. It simulates real wearing situations effectively in terms of layering systems and various wearing conditions. Thus heat and moisture transfer properties and the material characteristics can be evaluated under dynamic environmental conditions.

Accuracy and data reproducibility of the HCE simulator were demonstrated from a series of experiments. Using polyethylene glycol treated nonwoven fabrics, the HCE simulator could verify thermal buffering characteristics of temperature adaptive materials under transient conditions. The thermal releasing effects of the PEG 1500 were observed more clearly in the outer layer of the tested system than in the inner layer implying that the amount and the location of the phase changing material is an important factor to be considered for garment applications of these materials. Also, the effects of the end use condition on the performance of the functional textile materials were examined by using a microporous membrane laminated polyester fabric. Under arctic conditions, the breathability of the microporous membrane would be deteriorated due to condensation and/or freezing of moisture on the fabric surface. It is expected that the developed HCE simulator can be utilized to measure heat and moisture transfer properties of textiles by simulating real wearing situations and to predict the comfort properties of garments by giving the weight of each variable when verified by human use trials or sweating manikin tests. The results from the HCE simulator may also be applied for developing and planning materials and provide standards for garment evaluations of textile materials.

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