Objective Evaluation Equation for Comfortability of Water-resistant and Vapour-permeable Clothes

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ABSTRACT

Thermal insulation value, thermal conductivity, q-max and vapour permeability of fabric were regressed with subjective comfortability of the clothes made of the same fabric and following conclusions were obtained. Accurate objective evaluation equation for comfortability of water-resistant and vapour-permeable clothes was obtained with small errors. In the contribution of heat and moisture parameters to the objective evaluation equation, the influence of thermal insulation value by dry contact method and vapour permeability by water method is large.

1. Introduction

Clothes having various functional properties are desired in these days for the purpose of attaining physiological comfortability. Water-resistant and vapour-permeable clothes have been attracted recently for the use of sportswears and outdoor wears. However, in the point of physiological comfortability of such clothes, satisfactory physical indexes have not been developed yet, and the degree of comfortability has been evaluated only subjectively by panels wearing the clothes.

In this paper, physical properties of water-resistant and vapour-permeable fabrics, such as, thermal insulation value, thermal conductivity, air permeability, vapour permeability, are measured and clothes made of those fabrics are evaluated their physiological comfortability by wearing test and the correlation between them is investigated. Further, objective evaluation equation of clothes comfortability is derived from those physical properties.

2. Experimental

2-1. Water-resistant and Vapour-permeable Fabrics

Polyester and nylon weaves are used for water-resistant and vapour-permeable fabrics. Twelve fabrics having different degree of water-resistance and vapour-permeability are collected. Outlines of fabric samples are shown in Table I. Windbreakers of the same size are made from these fabrics.

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Table I Outlines of Fabric Samples

Sample No.	Fiber	Structure	Yarn Density(/m) Warp	Weft	Thickness* (mm)	Weight (g/m^2)	Kind of Treatment	Type of Treatment
A	Polyester	Plain	6000	4400	0.227	96	Azekura-1	Coating
B	Polyester	Plain	6000	4400	0.229	117	Azekura-2	Coating
C	Polyester	Plain	6000	4400	0.233	124	Entrant-G	Coating
D	Polyester	Plain	6000	4400	0.239	120	Entrant-2	Coating
E	Polyester	Plain	6000	4400	0.203	116	Saitos-AQ	Laminate
F	Polyester	Plain	4800	4600	0.285	114	Goretex	Laminate
G	Nylon	Plain	5400	3800	0.121	68	Azekura-1	Coating
H	Nylon	Plain	5400	3800	0.145	79	Azekura-2	Coating
I	Nylon	Plain	5400	3800	0.172	88	Entrant-G	Coating
J	Nylon	Plain	5400	3800	0.162	85	Entrant-2	Coating
K	Nylon	Plain	5400	3800	0.142	91	Azekura-3	Laminate
L	Nylon	Plain	5400	3800	0.144	93	Saitos-AQ	Laminate

* Thickness is measured at the pressure 588 Pa

2-2. Method of Experiment

Thermal properties of fabrics such as thermal insulation value (T. I. V.) , thermal conductivity (k) and q-max (warm/cool feeling evaluation value) are measured by Thermo Labo II [1] . Air permeability of fabrics is measured by KES Permeability Tester [2] . Vapour permeability of fabrics is measured by three methods[3]such as water method, calcium chloride method and potassium acetate method.

Thermal insulation value (T. I. V.) of fabrics is defined as follows:

$$\text{T. I. V.} = ((W_0 - W)/W_0) \times 100\ (\%) \quad (1)$$

W_0 : heat loss without fabric ($J/s/m^2$)

W : heat loss with fabric ($J/s/m^2$)

There are four kinds of measurement for thermal insulation value [4] , that is, dry contact, dry space, wet contact and wet space methods. These conditions are simulated models of human skin. As the heat loss of dry space method is quite small, the data of dry space method are omitted in this paper.

Thermal conductivity (k) of fabrics is defined as follows:

$$k = W \cdot D/A/\Delta T \quad (2)$$

k : apparent thermal conductivity of fabric (J/s/m/K)

W : heat loss to keep a constant temperature of heat plate (J/s)

D : thickness of fabric (m)

A : area of heat plate ($=0.0025m^2$)

ΔT : temperature difference ($=10.0K$)

Pressure at the measurement is 588 Pa.

q-max (warm/cool feeling evaluation value) is measured as the maximum heat flow from a copper plate having 0.41855 $J/K/cm^2$ with 9cm^2 of area and 9.79 g of mass. Pressure at the measurement is 980 Pa.

Air permeability is measured as air resistance of fabric when a constant quantity of air is pushed out and sucked in through a fabric.

$$R = \Delta P / V \qquad (3)$$

R : air resistance (Pa · s/m)

ΔP : pressure difference between face side and back side of fabric (Pa)

V : air flow per unit area (m/s)

Vapour permeability is measured as follows :

Water Method :

A constant water is put into a beaker and the mouth is covered with fabric sample. The beaker is placed in a standard conditions (20±0.3℃, 65±3% relative humidity (RH)) . Water vapour is evaporated and permeated through the fabric sample. The quantum of permeated vapour is evaluated by the weight loss of the beaker. It takes about a month to get reliable results.

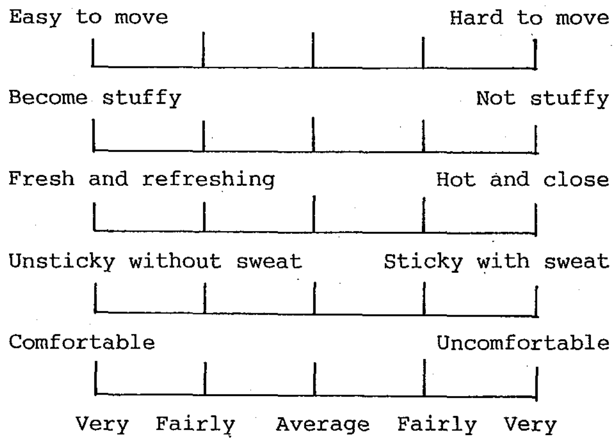

Fig. 1 Items of questionnaires for subjective evaluation of clothing comfortability.

Calcium Chloride Method :

Fabric sample is covered on a beaker with calcium chloride. The beaker is set in a chamber with constant temperature (40±2℃) and RH(90±5%) . Weight increase after 1 hour is measured.

Potassium Acetate Method :

Fabric sample is covered on a beaker with saturated potassium acetate solution. The beaker is put in a vessel with water in upside down. Weight increase after 15 minutes is measured.

2-3. Wearing Test with Windbreakers

Twelve windbreakers are worn by 7 females aged 20 to 23. Panties and jeans are worn for bottom and brassieres and T-shirts for top. Sensors to measure temperature and RH are attached on the center of the chest (Front) and back side (Back). All the test is carried out at

Table II Rerults of Heat and Moisture Parameters of Fabric Samples

Sample No.	Thermal Insulation Value Dry-C (%)	Wet-C (%)	Wet-S (%)	Thermal Conductivity (J/s/m/K)	q-max Resin (J/s/m²)	Vapour Permeability Water (g/m²/h)	Calcium	Potassium	Air Permeability (kPa·s/m)
A	10.9	20.7	65.1	0.053	0.100	11.96	499	1214	27.6
B	5.8	26.9	62.2	0.055	0.117	11.31	516	728	-
C	8.0	30.6	62.9	0.060	0.122	10.92	558	716	-
D	8.0	48.7	68.7	0.055	0.118	9.62	330	219	-
E	13.0	34.3	65.5	0.053	0.123	10.14	224	724	-
F	22.7	51.9	69.6	0.052	0.089	9.36	221	302	-
G	7.8	30.3	61.4	0.047	0.128	11.83	585	1140	22.1
H	9.2	33.7	62.8	0.053	0.125	11.05	519	599	-
I	9.2	35.7	64.9	0.058	0.125	10.53	474	522	-
J	7.1	41.9	66.7	0.057	0.126	10.27	353	306	-
K	7.8	41.1	66.5	0.058	0.145	9.49	194	762	-
L	9.9	37.6	66.5	0.057	0.148	9.62	196	711	-

constant temperature (20±0.3℃) and RH (65±3%). Procedure of the wearing test is as follows:

(1) Wear windbreaker and keep quiet. Measure blood pressure (maximum and minimum) and the pulse rate after 10 minutes.

(2) Answer questionnaires of subjective evaluation of physiological comfortability about the windbreaker. The content of questionnaire is shown in Fig. 1 .

(3) Attach sensors on the center of chest (Front) and back side (Back). About 2 mm height on the skin.

(4) Exercise 5 minutes by bicycle ergometer. Rest 10 minutes after the exercise. Repeat the same cycle more twice. 40 revolutions of pedal per minute are kept using a metronome with 1.5 kg load.

(5) After 3 cycles of exercise, blood pressure and the pulse rate are measured.

(6) Answer questionnaires of subjective evaluation of physiological comfortability about the windbreaker after exercise.

3. Development of Objective Evaluation Equation

Thermal properties and vapour permeability (these properties are called heat and moisture parameters in this paper) are regressed with subjective data of comfortability obtained as mentioned in 2-3. In order to clarify the contribution of heat and moisture parameters on

Table III Changes of Score of Subjective Evaluation of Clothes Before and After SD Method

Sample	A	B	C	D	E	F	G	H	I	J	K	L
Hard to move	0.57	0.57	0.67	0.72	0.46	1.16	0.67	0.56	0.45	0.45	0.50	1.11
Become stuffy	1.86	1.86	1.57	1.71	1.87	2.77	1.00	1.56	1.56	1.55	1.76	2.33
Hot and close	1.57	1.86	1.60	2.06	1.57	2.33	0.88	1.67	1.34	0.89	1.88	1.89
Sticky with sweat	1.13	1.00	1.83	1.34	1.86	2.17	0.78	0.89	1.11	1.22	1.38	1.78
Uncomfortable	1.14	1.06	1.17	1.20	1.28	1.67	0.66	1.44	0.77	1.34	1.25	1.67
Total score	6.27	6.35	6.84	7.03	7.04	10.10	3.99	6.12	5.23	5.45	6.77	8.78

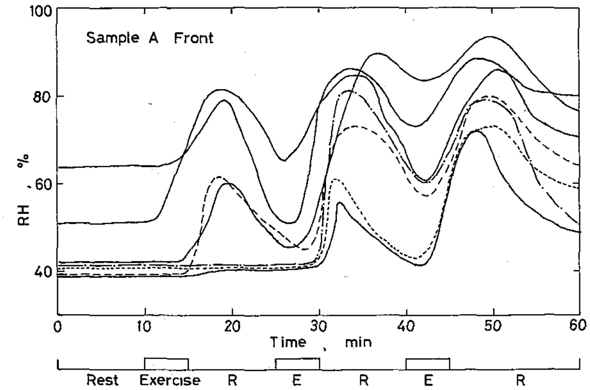

Fig. 2 Changes of RH (%) through three cycles of exercise and rest at front side of sample A.

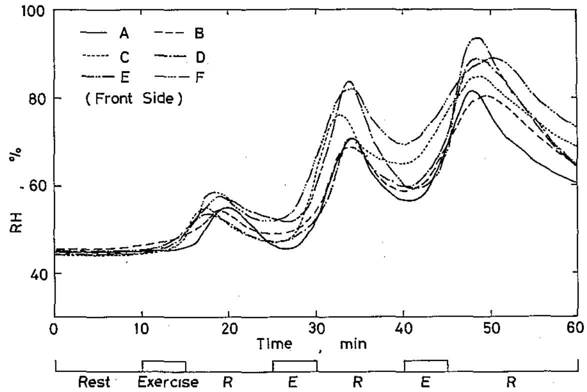

Fig. 3 Averaged changes of RH (%) through three cycles of exercise and rest for six polyester samples.

comfortability and to avoid multi-collinearity [5] , a method of stepwise block regression developed by Kawabata [6] is used for regression. Heat and moisture parameters of fabric are shown inTable II. The method of stepwise block regression is as follows :

1) Multiple regression equations Y between subjective values y and the heat and moisture parameters of each block are obtained. Then, regressed values $\tilde{Y}$ are calculated for all the samples.

$$\tilde{Y}_1 = C_0 + C_1X_1 + C_2X_2 + C_3X_3 \tag{4}$$

$$\tilde{Y}_2 = C_0 + C_4X_4 + C_5X_5 \tag{5}$$

$$\tilde{Y}_3 = C_0 + C_6X_6 + C_7X_7 + C_8X_8 \tag{6}$$

2) The block showing the highest correlation between y and $\tilde{Y}_i$ is decided to be the 1st block. The regression equation is denoted as $Y_{(1)}$.

3) The residue between y and the 1st block ; $y-\tilde{Y}_{(1)}$, is calculated for all the samples. Multiple regressions Y between the residue and the heat and moisture parameters of remaining blocks are obtained. Then, regressed values $\tilde{Y}$ are calculated for all the samples.

4) The 2nd block is decided as having the highest correlation between y and $\tilde{Y}_{(1)} + \tilde{Y}_i$ to be $Y_{(2)}$.

Table IV Relative Humidity Change (%) After Exercise

Sample		A	B	C	D	E	F	G	H	I	J	K	L
1st exercise	Front	0.6	1.8	1.8	2.7	8.4	7.0	0.0	2.8	0.0	0.0	0.9	0.0
(after 25 min)	Back	0.0	0.8	6.5	0.0	4.7	3.3	0.0	5.3	0.0	0.0	4.7	4.5
2nd exercise	Front	12.8	12.0	18.7	15.9	15.9	23.8	3.0	13.6	10.0	8.7	18.1	14.8
(after 40 min)	Back	8.9	7.5	15.0	11.1	12.9	20.8	4.6	14.1	11.3	15.3	26.2	27.8
3rd exercise	Front	21.9	25.4	29.3	29.2	29.6	35.4	6.3	20.6	15.4	12.4	22.9	18.6
(after 55 min)	Back	17.3	22.8	19.5	25.0	27.6	29.8	8.7	17.3	24.6	20.9	32.0	30.2
Total Change		61.5	70.3	90.8	83.9	97.3	120.1	22.6	73.7	61.3	57.3	104.8	95.9

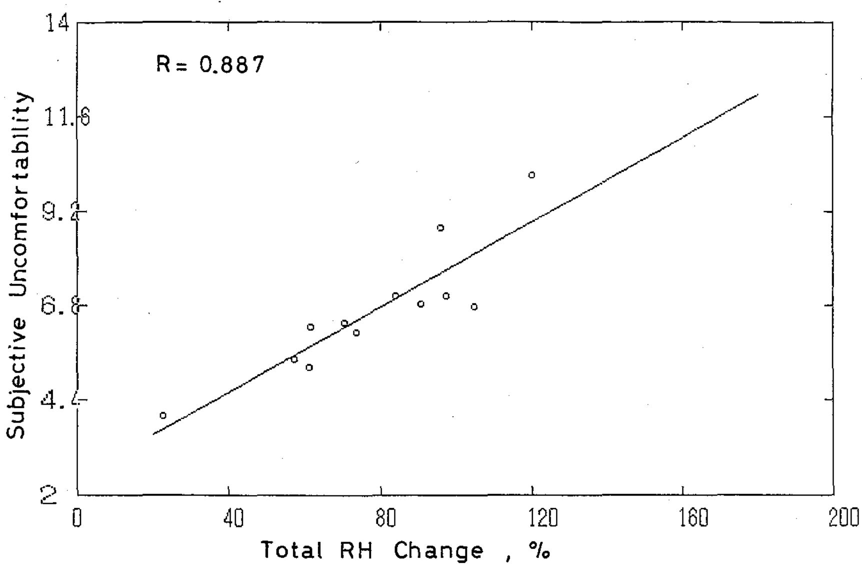

Fig. 4 Relationship between subjective uncomfortability and total RH change.

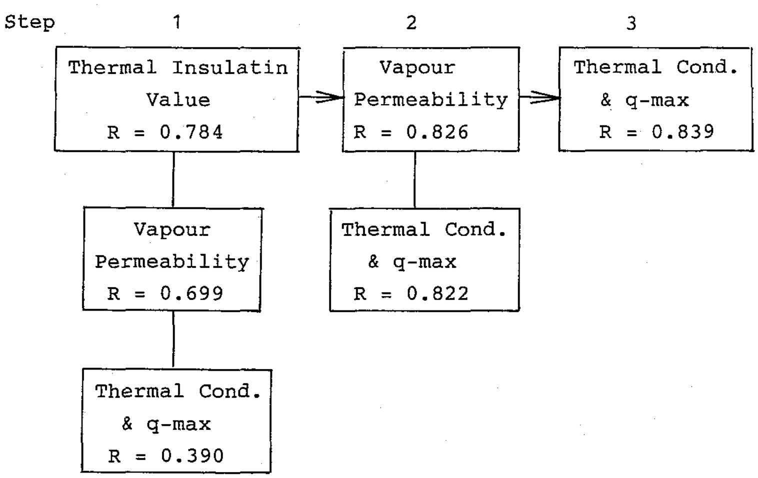

Fig. 5 Regression process of stepwise block regression for development of objective evaluation equation.

Then the total regression equation becomes $Y_{(1)}+Y_{(2)}$.

5) The 3 blocks are decided as the similar manner, getting following equation finally.

$$Y=C_0+\sum_{i=1}^{8} C_i X_i \quad (7)$$

For the heat and moisture parameters, it is convenient to use normalized values by mean and standard deviation.

$$Y=C_0+\sum_{i=1}^{8} C_i \frac{X_i-\bar{X}_i}{\sigma_i} \quad (8)$$

Where, Y ; physiological comfortability of clothes evaluated objectively

C_0, C_i ; constant ($i=1$ to 8)

X_i : i-th heat and moisture parameter

Table V Heat and Moisture Parameters and Coefficients of MU-01 Equation Used for Objective Exercise Obtained by Evaluation of Clothing Comfortability.

Block	i	Parameter	Mean $\bar{X}_i$	S.D.	Uncomfortability i	C_i
	0				0	6.6642
	1	Dry-C	9.950	4.2435	1	0.7430
1	2	Wet-C	36.092	8.5035	2	-0.0708
	3	Wet-S	65.233	2.4479	3	0.6624
2	4	Ther-Co	0.0548	0.00336	6	-1.0701
	5	q-max	0.1222	0.01552	7	0.5227
	6	Water	10.508	0.8702	8	0.4866
3	7	Calcium	389.08	145.73	4	0.3464
	8	Potassium	661.92	293.38	5	0.0874

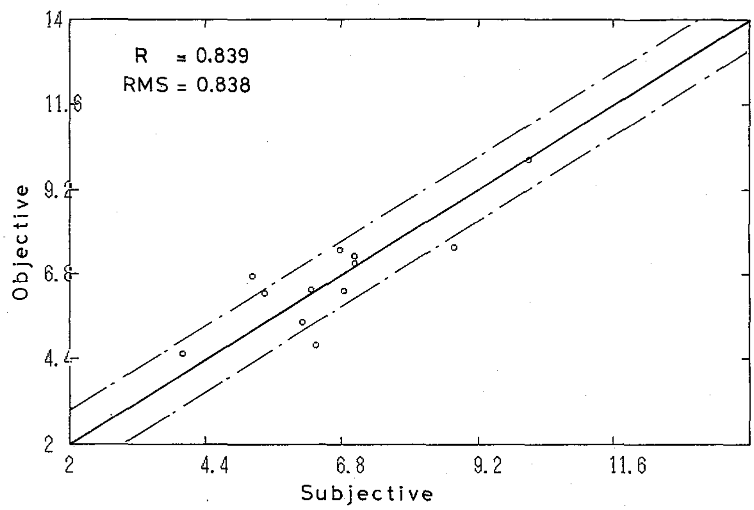

Fig. 6 Relationship between objective uncomfortability obtained by equation MU-01 and subjective uncomfortability.

$\bar{X}_i$: mean value of X_i

σ_i : standard deviation of X_i

4. Results

Results of basic heat and moisture parameters of fabric samples are shown in Table II. These values are averaged results of five samples, respectively. Difference of T. I. V. between each fabric sample was clear in the case of dry contact and wet contact methods. In general, No. F has larger T. I. V and No. B has smaller T. I. V.

In regard to thermal conductivity, the difference between each sample was small.

In regard to q-max, that is warm/cool feeling when man touches the sample, No. K and L have larger value and No. F has smaller value.

There was a little difference between each method of vapour permeability.

Air permeability was measured only for the samples A and G. Therefore, this data cannot be used for development of objective evaluation equation.

Changes of maximum and minimum blood pressures before and after the exercise were little and the difference between each clothes was not recognized. Although the pulse rate increased after the exercise, the difference between each clothes was not distinguished. Therefore, these parameters cannot also be used for development of objective evaluation equation.

Results of subjective evaluation of physiological comfortability about windbreakers are shown in Table III. The score is averaged value of 7 panels. The score was calculated as the similar manner with SD Method. If the score is large, the difference of physiological comfortability before and after the exercise is large. Therefore, the score could be an index of subjective uncomfortability of clothes.

Temperature and RH within clothes were followed during exercise and it was clear that temperature changed little and that RH changed considerably depending on each clothes. Results of RH changes for 7 panels are shown in Fig.2 in the case of front side of sample A. RH increased gradually with the repetition of exercise. These RH change curves are averaged and the result is shown in Fig.3 for 6 samples made of polyester. Results of back side showed the similar tendency with front side. It is easily expected that the clothes having smaller RH change is more comfortable [7, 8]. Here, RH change was calculated after each exercise and the result is shown in Table IV for both front and back sides. Total RH change was also obtained from these data.

Correlation between the total RH change and the score of subjective uncomfortability of clothes is shown in Fig. 4. It is clear that the correlation is very high. Therefore, the score can be used to be an subjective value for development of objective evaluation equation of comfortable clothes.

5. Development of Objective Evaluation Equation

Heat and moisture parameters shown in Table II were regressed with the score of subjective uncomfortability and the step of block regression was shown in Fig. 5. Regression accuracy is shown by the correlation coefficient (R) between subjective and objective values. The correlation increases as the repetition of regression. Comfortability of the water-resistant and vapour-permeable clothes is affected by the order of thermal insulation value (1st block), vapour permeability (2nd block) and thermal conductivity and q-max (3rd block). Coefficients of final equation (8) obtained here (named MU-01) are shown in Table V together with means and standard deviations of heat and moisture parameters.

Correlation between subjective and objective values of the clothes uncomfortability is shown in Fig. 6. RMS (root mean square) is regression error and the value was smaller than that of subjective evaluation (=1.591).

6. Discussion

Objective evaluation equation for comfortability of water-resistant and vapour-permeable clothes was derived from heat and moisture parameters and the equation showed high accuracy with small errors. Contribution of heat and moisture parameters to the objective evaluation equation is discussed here. The most important block was thermal insulation value and the result of dry contact method was most effective to clothing comfortability. That is, clothes made of fabrics having smaller value of thermal insulation value by dry contact method shows more comfortable as shown in Table V. Vapour permeability appeared in the 2 nd block. Coefficient of vapour permeability by water method was the largest and effective to clothing comfortability as shown in Table V. That is, clothes made of fabrics having larger value of vapour permeability by water method shows more comfortable.

Comfortability of two new clothes, of which comfortability was evaluated objectively in fabric state by equation MU-01, was evaluated subjectively by three consumers, and both results agreed very well with each other. The equation developed here is proved to be very effective and powerful. In the future, the authors want to add more samples and try to develop the objective evaluation equation having larger accuracy and smaller errors.

7. Conclusion

Following conclusions were obtained :

(1) Accurate objective evaluation equation for comfortability of water-resistant and vapour-permeable clothes was obtained with small errors.

(2) In the contribution of heat and moisture parameters to the objective evaluation equation, the influence of thermal insulation value by dry contact method and vapour permeability by water method is large.

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