Characteristics of Thermal Comfort in Environment Chamber for Winter

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Key words : Predicted mean vote, Thermal sensation vote, Comfort sensation vote, Standard new effective temperature, Humidity sensation vote

Abstract

The purpose of this study is to analyze and characterize the correlation of the thermal comfort sensation with physiological responses for men in winter indoor environment. A number of experiments were conducted under twenty different environmental conditions with college male students. Clinical information on each participant was reported in terms of electrocardiogram (ECG), electroencephalogram (EEG) and self-centered evaluation.

The comfort zone in winter is found, throughout the study, at Standard New Effective Temperature (SET*) of 25.2 ℃, Predicted Mean Vote (PMV) between 0.27 and 0.62, and Thermal Sensation Vote (TSV) in the range of -0.76 and 0.36. The largest difference in skin temperature is measured at the calf area with respect to air temperature changes. Skin sensitivity to environment temperature is explained as calf, head, chest and abdomen in descending order. Change in heat rate is analyzed to be in parallel with that of SET*.

Nomenclature

clo : Unit of thermal residence of cloth
CSV : Comfort sensation vote
EC : Experimental condition
ECG : Electrocardiogram
EEG : Electroencephalogram
f_{cl} : Area ratio of cloth
HSV : Humidity sensation vote
I_{cl} : Thermal residence of cloth
M : Metabolism [met]
MRT : Mean radiant temperature [℃]
P_a : Partial pressure of watery vapor[kgf/m²]
PMV : Predicted mean vote

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PPD : Predicted percentage of dissatisfied
SET* : Standard new effective temperature[℃]
SD : Standard deviation
SSV : Sweating sensation vote
TSV : Thermal sensation vote
t_{cl} : Surface temperature of cloth[℃]
t_a : Air temperature[℃]
t_{sk} : Skin temperature[℃]
$\overline{t_r}$: Mean radiant temperature[℃]
W : Work[W/m²]
R.V. : Real value
v_a : Air velocity[m/s]
w : Skin wetness[-]

Greek symbol

α : Stable ray(1/10s)
β : Unstable ray(17~30c/s)
δ : Irregular ray
θ : Normal ray(4~8c/s)

Under letter

a : air
cl : cloth
r : radiant
sk : skin

1. Introduction

Sensing the temperature by human body includes complex heat transfer processes, and is studied in terms of correlation of environment with thermal comfort sensation. Most of studies in this area, however, are drawn using either environmental conditions or physiological factors.

The study using the tool of environmental conditions means to identify human thermal comfort sensation by means of thermal factors: air temperature, humidity, air-flow, radiation, clothing, metabolism. The self-centered evaluations from the experiment participants are reported and statistically analyzed. Many researchers have been reported the results in this area, such as Fanger(1), Shiller(2), Gagge(3), Nevins(4), ASHRAE(5), Miura(6), Tanabe(7), Fukai(8), Lee(9), Sohn(10), and Kum(11). The other approach is reviewing the thermal sensation through the windows of physiological reaction and heat transfer model between human body and environment. The factors concerned in this type of study are metabolism, pulsation, blood pressure, rectum temperature, perspiration ratio and skin temperature. This method is used by In-Hout(12), Jones(13), Ogawa(14) and Nishi(15).

It is required an integrated tool to evaluate human thermal sensation, but which is insufficient to be represented as either of the method introduced above. This study, therefore, adopted the both methods by using an environmental chamber: physiological and physiological reactions could be measured in the chamber through subjective evaluation, electrocardiogram and electroencephalogram. Relative humidity in the chamber was precisely controlled throughout the study, which has been recognized as a difficult technical area. Thanks to the precise control, the most comfort condition in winter is found according to temperature and humidity changes in the chamber.

2. Experiment

2.1 Environmental test lab

As shown in Fig.1 the test lab is divided into two regions: one is the environmental chamber and the other is the equipment room. The floor space of the environmental chamber is 20.48 m² (6.3 L x 3.25 W) and the height is 2.2 m. The walls are covered with 50 mm thick gypsum board, and the floor is composed of two layered floor being able to take a role of

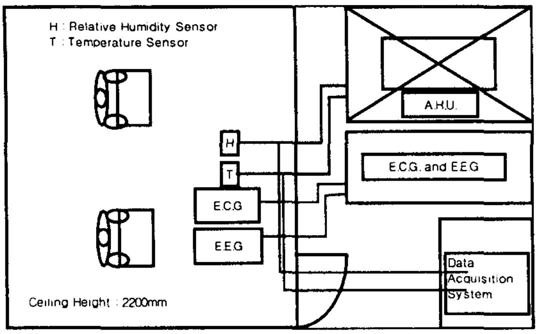


Fig. 1 Schematic diagram for HVAC system in environmental chamber throughout the test.

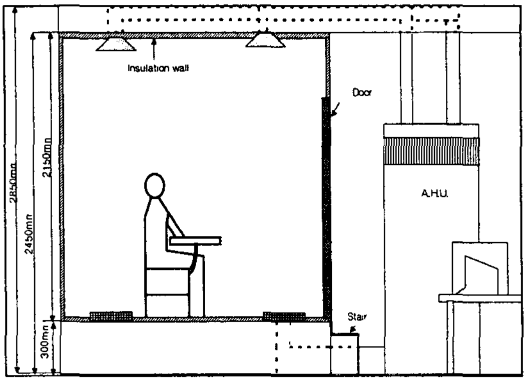


Fig. 2 Cross section of environmental chamber.

intake and/or exhaust of air. Also installed in the chamber are ECG and EEG recorders to measure them from participants. Figure 2 schematically shows a front view of the environmental chamber.

The equipment room has a air handling unit which controls temperature, humidity and airflow in the environmental chamber. Other devices to operate sensors, such as ECG, EEG, thermocouples, etc., are installed in the room. Insulated flexible ducts transport the conditioned air to the chamber through ceiling, and angular diffusers are applied at the end of the ducts for fine air distribution in the chamber[16]. The maximum capacity of the chiller is set to be 3 RT that is 3 times higher than calculated cooling load of the chamber for rapid and fine response in extreme conditions[17]. All the air is recirculated .

Table 1 Cloth property of subjects

Cloth	Weight[g]
socks	50
panties	57
short T-shirt	171
trainning jumper	630
trainning pants	625
Sum	
0.93	1533

clo. value(male)=0.000558×total weight of clothing+0.0688)

2.2 Experimental method

The experiment period for thermal comfort sensation in winter started from January, 1998, and continued until the middle of February, 1998 for 37 days in the environmental test lab at Kyunghee University.

Among those of volunteers 80 participants were selected, whose physiological conditions are normal in terms of temperature, weight, blood pressure and pulse. Characteristics of the cloths that participants should be wearing are

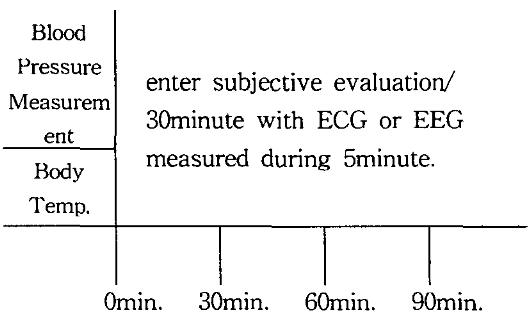


Fig 3 Time schedule of experiment.

listed in Table 1, that demonstrates the total thermal resistance against the cloths to be 0.93 clo[18].

In total 40 tests were conducted by means of two tests per day, once in the morning and the other in the afternoon. A pair of participants for each experiment dwelled in the chamber as indicated in Fig.3. Total time period for each test was 90 minutes. The physiological condition of every participant was measured before each experiment, and subjective evaluation was started after 30 minutes of dwelling in the chamber, and answered for every ten minutes. In order to measure vertical temperature distribution K-type thermocouples were located 30 cm from the bottom to 180 cm for

Table 2 Environmental and distribution condition of the measured data

condition / exp. no.	E.C.		R.V.		PMV	PPD	TSV	SET* (℃)
	t_a ℃	R.H. %	t_a ℃	R.H. %				
01	18	40	18.34	47.32	-1.56	54	-2.5	20.1
02	18	50	18.62	50.1	-1.42	46	-2.15	21.1
03	18	60	18.57	61.8	-1.35	43	-1.8	21.2
04	18	70	19.17	69.83	-1.3	40	-1.35	21.3
05	20	40	20.27	39.9	-1.01	27	-1.4	22.5
06	20	50	20.85	54.1	-0.8	19	-1.35	23.1
07	20	60	20.3	61.6	-0.88	21	-0.75	22.8
08	20	70	20.52	69.4	-0.77	17	-0.4	23.1
09	24	40	24.62	40.5	0.18	6	-0.167	26.2
10	24	50	25.01	49.3	0.11	5	0.15	26.1
11	24	60	24.44	59.1	0.3	7	0	26.8
12	24	70	24.48	69.4	0.38	8	0.45	27.3
13	28	40	27.77	41.2	1.09	30	1.1	28.9
14	28	50	28.7	49.8	1.41	46	1.1	30.1
15	28	60	28.1	55.1	1.36	43	0.95	30.3
16	28	70	28	63.2	1.4	46	2.05	30.9
17	30	40	29.6	41.1	1.61	57	1.4	30.3
18	30	50	30.3	47.3	1.91	72	1.65	31.6
19	30	60	30.1	59.3	1.96	75	2.1	32.3
20	30	70	30.4	64.7	2.17	84	2.37	33.9

every 30 cm. Humidity was measured by Industrial Transmitters Series I-100. Thermocouples (AWG36) were attached on the spots of the participants, such as forehead, chest, forearm and calf, in order to measure skin temperature with respect to environment temperature. Table 2 summarizes environmental chamber conditions and experimental data measured at each condition. Other experimental conditions are listed in Table 3, self-centered subjective evaluation form is shown in Table 4, and Table 5 shows anthropometric statistical data of the participants. The subjectively evaluated data were statistically analyzed with SPSSTM statistics software program.

Table 3 Experimental conditions

Experiment time	90 minute
Cloth	0.93 clo
Activity of subject	1.0 met
Air velocity	0.1 m/s
M.R.T.	Equal to t_a
Subjects	80
Experiment No.	40

Table 4 Scale of subject vote

Thermal sensation vote

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	War m	Hot

Humidity sensation vote

-2	-1	0	1	2
Dry	Slightly dry	Neutral	Slightly wet	Wet

Comfort sensation vote

0	1	2	3
Comfort	Slightly comfort	Discomfort	Very discomfort

Sweating sensation vote

0	1	2
Not sweating	Slightly sweating	Sweating

Table 5 Anthropometric data for the subjects

Quantity	Male(80 persons)	
	Mean±S.D.	Min.~Max.
Age(Years)	25.03 ± 0.74	24~26
Height(cm)	173.2± 2.32	170~177
Weight(kg)	72.7±2.78	68~78
Body surface area(m^2)	1.86±0.039	1.94~1.78

3. Results and considerations

3.1 Predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD)

The relationships of PMV and PPD in winter and in summer are shown in Fig.4. Compared Table 2 with Fig.4, the lower and the higher temperatures are the difference between the theoretical equation and empirical date. And similar trend is noticed in high temperature zone in winter. It is generally known as The limit of PMV-PPD(1). The dissatisfied sensation is sensible to gradual changes in humidity. The comfort sensation range within 80% of satisfaction is found to be $-0.27 < PMV < 0.62$.

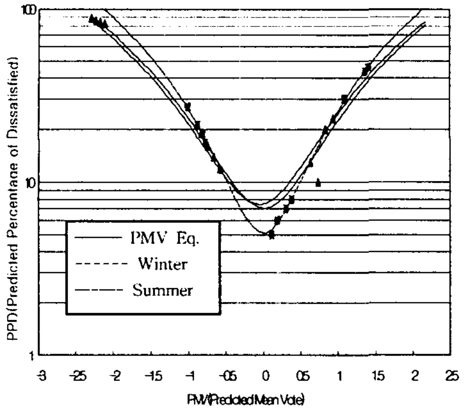


Fig. 4 PMV and PPD relationships for summer and winter.

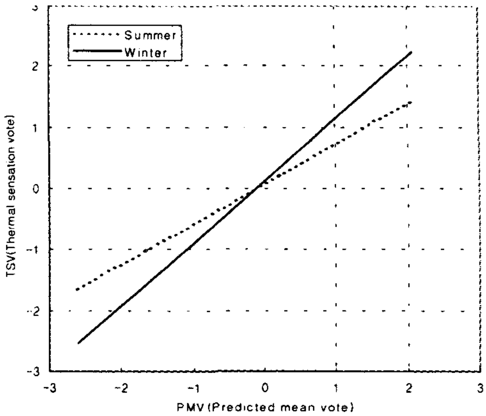


Fig. 5 Relationship between PMV and TSV.

3.2 Predicted mean vote (PMV) and thermal sensation vote (TSV)

The gradient of TSV in winter with respect to PMV is greater than 1.0, that has been observed in summer comfort sensation study[15]. This indicates that the participants responded more sensible in warm environment than in cold one. In other words participants responded more sensible along with severe environmental condition. The result from the experiments shows that the most comfortable indoor condition is to be $-0.27 < PMV < 0.62$ that is somewhat offset the recommendation from ISO 7730 that is $-0.5 < PMV < 0.5$. Within the PMV range yielded from the experiment the range of TSV varies from -0.77 to 0.36 as shown in Fig.5. Especially, at low temperature comfort zone, the range of TSV differs from it. The value of TSV is around -0.02 at the neutral temperature point that is PMV = 0.0, that implies the participant's comfort sensation is identical to calculated one. An analysis with neutral TSV (TSV = 0.0) results in similar conclusion because of the value of PMV at TSV = 0.0 is 0.03.

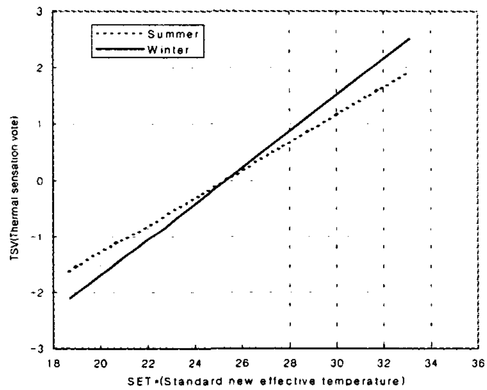


Fig. 6 Relationship between SET* and TSV.

3.3 Standard new effective temperature (SET^*) and thermal sensation vote (TSV)

The results of the sensation vote are analyzed and displayed in Fig.6. The TSV in winter is more sensitive to temperature change than that in summer. A correlation equation between SET^* and TSV in winter is yielded as in Eq. (1) from the sensation vote data.

$$TSV = 0.2375\, SET^* - 5.8678 \tag{1}$$

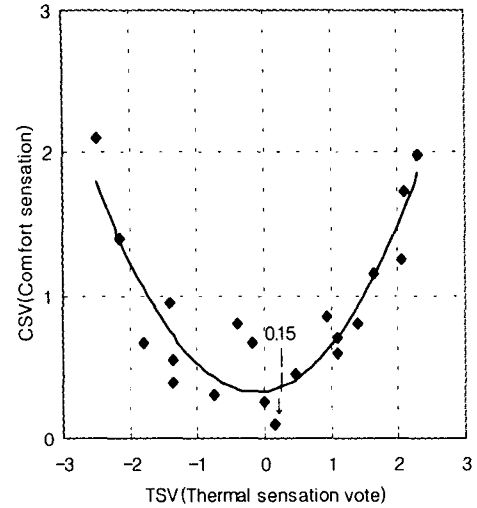


Fig. 7 Relationship between TSV and CSV.

3.4 Thermal sensation vote (TSV) and comfort sensation vote (CSV)

The relationship of TSV with CSV is charted in Fig.7. It shows that the most CSV is located at 0.15 TSV. This result implies that comfort sensation range in winter is to be 0.0 < TSV < 0.2, and consequently indicates a little skewed to warm side of TSV make participants more comfortable in winter than at neutral point.

3.5 Standard new effective temperature (SET*) and predicted percentage of dissatisfied (PPD)

One of the results throughout the study shows that increase in dissatisfied sensation is obvious as SET* goes higher. The least dissatisfied sensation is located in Fig.8 at SET* = 26.1 ± 0.5 ℃. Please notice that this point is located about 1 ℃ higher than that of SET* = 25.2 ℃ which is for neutral TSV. This result is identical to that drawn in section 3.3, that most comfort sensation is located at a litter higher position than neutral TSV.

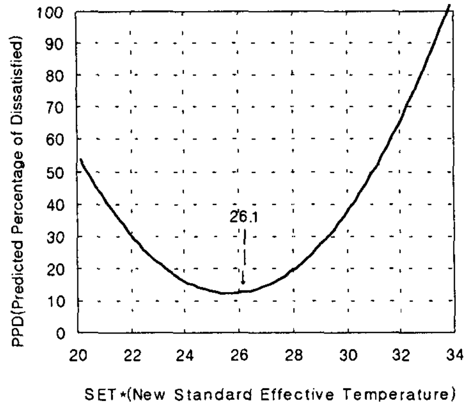


Fig. 8 Relationship between SET* and PPD.

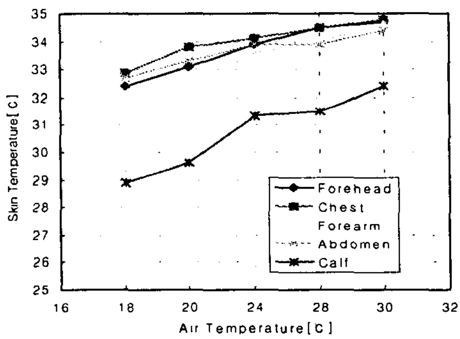


Fig. 9 Skin temperature at different body parts under different ambient air temperature.

3.6 Room temperature, skin temperature and sensibility

Figure 9 shows variations of the skin temperatures with respect to room temperature, and Fig.10 indicates sensibility for different skin area. Chest temperature is being maintained high, whereas, calf temperature is lowest. The area exposed to environment is sensibly reacted to environmental conditions. This result agrees the theory that lower the location in a body, the more developed is temperature sensory organ[19]. According to the result in Fig.10 sensibility of skin can be enumerated in

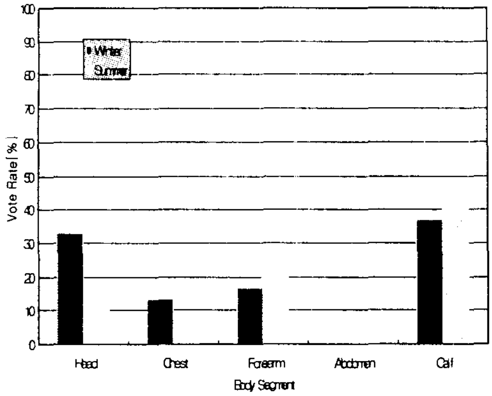


Fig. 10 Vote rate of body parts.

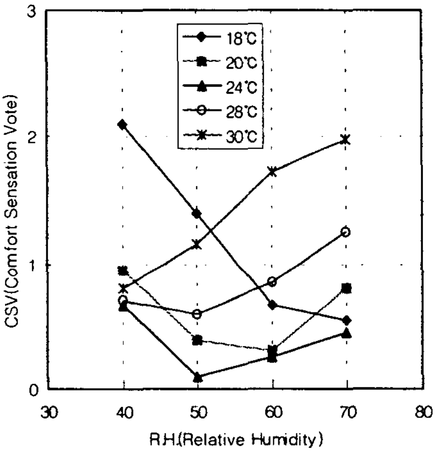


Fig. 11 CSV with respect to relative humidity for value of air temperature.

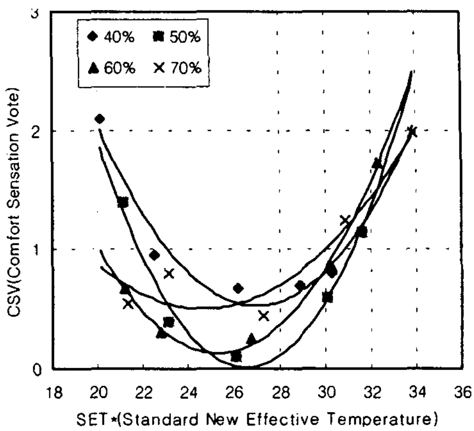


Fig. 12 CSV with respect to relative humidity for value of air temperature.

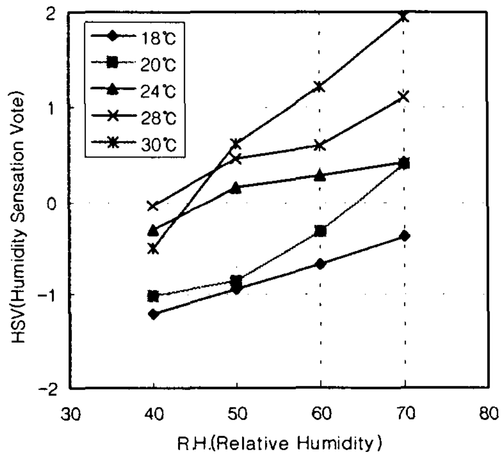


Fig. 13 HSV with respect to relative humidity for value of SET*.

descending order as calf, forearm, forehead. chest and abdomen, respectively.

3.7 Relative humidity (RH), comfort sensation vote and standard hew effective temperature (SET*)

The relationship of RH with CSV is in Fig.11. Higher CSV is measured at high temperature than low one at low RH, and rapid decrease in CSV at high temperature is obvious as RH is growing. This result draws a conclusion that the change in CSV along with temperature changes is remarkable at RH around 40% and 70%. Also the highest CSV value is marked in Fig.11 at SET* around 26 ℃.

3.8 Relative humidity (RH) and humidity sensation vote (HSV)

Figure 13 shows the relationship of RH with HSV. Higher HSV was measured in high tem-

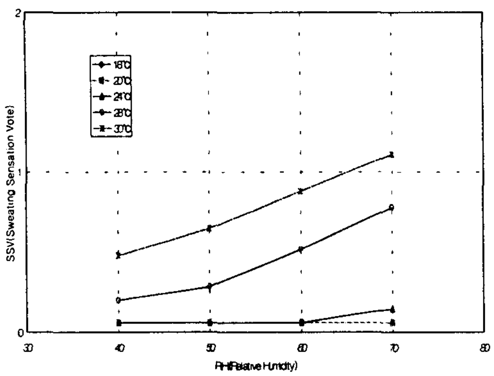


Fig. 14 SSV with respect to relative humidity for value of air temperature.

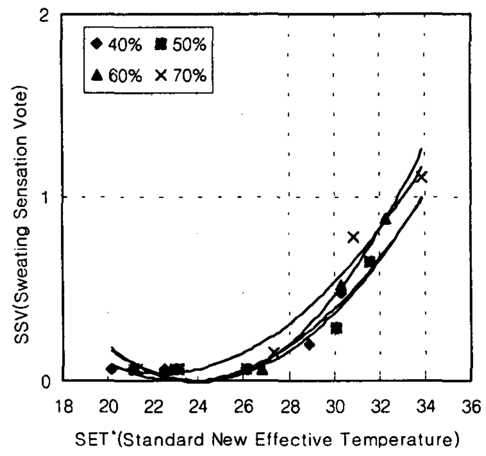


Fig. 15 SSV with respect to SET* for value of relative humidity.

perature region at low RH, that is similar reaction for summer vote. The higher RH, the higher HSV was answered in most of temperature region. It is found that sensational change in humidity is negligible at around 24 ℃. Not a dramatic change in humidity sensation is also measured at 26.1 ℃<SET*<26.8 ℃

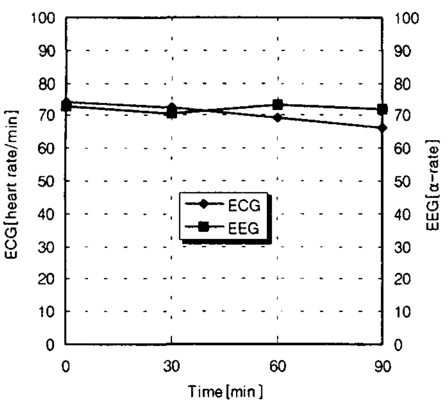
3.9 Relative humidity (RH), sweating sensation vote (SSV) and standard new effective temperature(SET*)

Figure 14 describes the relationship between RH and SSV. The figure shows sweating starts from 28 ℃, that is independent of RH. As shown in Fig.15 sweating rate is increased at SET* higher than 28 ℃ This result verifies the conclusion in summer test which includes the effect of sweating at SET* higher than 28 ℃.

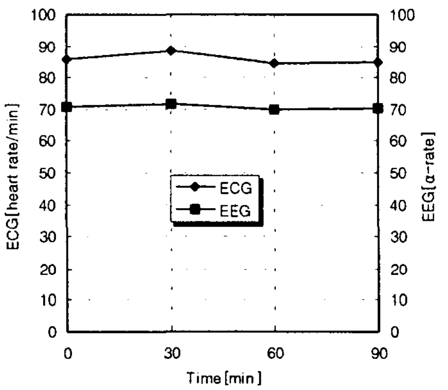
3.10 Standard new effective temperature(SET*), electroencephalogram (EEG) and electrocardiogram (ECG)

It is the change in EEG and ECG with respect to that in SET* in Fig.16 that separately describes the changes at low temperature region (a), medium temperature region (b) and high temperature region (c). Decrease in ECG is obvious in low temperature region (a) as time goes by, because of the physiological reaction to reduce the amount of heat transfer from human body as low as possible. Any remarkable change in ECG at medium temperature region is recorded. In high temperature region (c), however, change in ECG is opposite to that in low temperature region found. This can be explained as such that human body increases heat transfer.

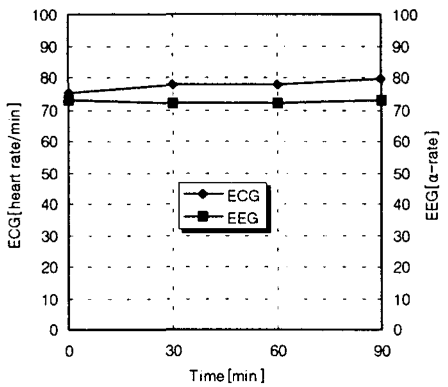
Measurement data in EEG change with respect to environmental temperature changes fairly indicates constant, that was recorded to identify the psychological tranquility. EEG is described in the form of percentage of α, β, γ and θ that are measured while relaxed with closed eyes. Among the different rays α ray is dominant unless a participant is facing a psychological stress or external tension. Due to relatively mild environmental conditions, any dramatic change in EEG was not recorded throughout the experiment



(a) SET* 20.1℃



(b) SET* 26.1℃



(c) SET* 33.9℃

Fig. 16 Result of E.C.G and E.E.G during experiment.

4. Conclusions

A number of conclusions are drawn from the experimental data that consist of participant's subjective evaluation, EEG and ECG records.

(1) The slope of TSV curve is larger than that of PMV in winter. This means that the sensitivity of participant's sensation is greater than that of calculated. Moderate SET* is 25.2 ℃ based on TSV in winter.

(2) The comfort zone is located at higher than the moderate point of TSV, and SET* at low PPD is 26.1 ℃ ± 0.5 ℃. The results with respect to TSV and CSV, respectively, shows identical.

(3) The largest temperature difference in skin is at calf area as air temperature varies. Sensitivity vote of human body is enumerated in descending order as calf, forehead, forearm, chest and abdomen.

(4) The most comfort temperature is found at SET* = 26 ℃. Though the result somewhat differ from the moderate point of SET* = 25.2 ℃, it is within a tolerance up to 2 ℃ , that is already reported[6,7,11] from some references.

(5) CSV is located near comfort zone in low humidity at high temperature. The lowest difference in humidity change is at 26.1 ℃ < SET* < 26.8 ℃.

(6) The trend of ECG follows that of environmental temperature in parallel: the lower the temperature, the slower is ECG. Variation of EEG is negligible within an environment of stress-free and no external tensions. Conclusively comfort zone of SET* corresponds with physiological and psychological comfort zone.

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