Sensors and Materials, Vol. 14, No. 7 (2002) 363–372
MYU Tokyo

S & M 0496

Estimation of Effective Comfort Index in a Domicile Using Gas Sensor Output

Yoshinori Nakamoto, Takashi Oyabu, Yoshihiro Ueda[1] and Haruhiko Kimura[2]

Kanazawa Seiryo University, Kanazawa 920-8620, Japan
[1] Industrial Research Institute of Ishikawa, Kanazawa 920-0223, Japan
[2] Faculty of Engineering, Kanazawa University, Kanazawa 920-8667, Japan

(Received September 28, 2001; accepted July 1, 2002)

Key words: comfort index, gas sensor, thermal index, LBG clustering, membership function

As human beings age, their sensitivity to the thermal index decreases. Therefore, it is necessary to compensate for their lack of sensitivity. Design which creates a comfortable environment is also necessary for a residential space for the aged. Therefore, in this study an attempt was made to estimate the comfort index using a tin oxide gas sensor. Temperature, humidity and gas sensor output in an experimental room were measured for 2 years. The comfort index was evaluated according to a five grade scale by an occupant. The data for temperature and humidity were clustered using the LBG algorithm which is named after its devisers Linde, Buzo and Gray, and the correspondence was investigated between the clustering result and the comfort index. It was clarified that the comfort index in a residential environment is influenced by temperature and humidity. It is known that the sensor output is also significantly influenced by temperature and humidity. Then, the membership function was derived from the data for the comfort index and the sensor output. By applying the membership function, the comfort index can be estimated using the sensor output.

1. Introduction

Japan is rapidly becoming the fastest aging society in the world. The numbers of both aged and aged households have been increasing. Conversely, numbers of people in the younger generations have been decreasing. Support for the aged is lacking in both finance and personnel. Because the senses of human beings become duller as they age, research which takes into account their decreasing sensitivity, is greatly desired. Most aged spend much time in their residential space, and some accidents might be caused by their lack of sensitivity. Therefore, the design of a comfortable environment which compensates for their decreased thermal sense is particularly needed. Various indexes have been designed for estimating the comfort level. A simple and suitable index for human sensitivity is required.

A tin oxide gas sensor is widely used in gas leakage detectors which are installed in a residential environment. The applications of the sensor are not only gas leakage detection. Using gas sensor outputs, the occupants' behavior can be recognized without using a video camera,[1,2] and moreover, the air pollution level can be monitored.[3,4] Thus, several important detections and recognitions can be made on the basis of the sensor outputs. Therefore, we attempt to find a means of using sensor outputs in the creation of a comfortable environment.

The still sensor has a number of defects. One is that the sensor does not have gas selectivity. Another major defect is that the base level of the sensor output (offset level) varies according to the environmental conditions. Thus, it can be understood that a tin oxide gas sensor is influenced by the indoor and outdoor thermal indexes.[5] In particular, there is a strong correlation between the sensor output and temperature, relative humidity and atmospheric pressure.[6] If the comfort index of the residential environment can be derived using temperature and humidity, the comfort index can be obtained using the characteristics of the sensor outputs.

In this study, first the possibility of evaluating the human comfort index based on temperature and humidity was confirmed. The data were clustered using a LBG algorithm, and the correspondence between the clustering result and the comfort index was investigated.[7] Moreover, we attempted to determine a function for the relationship between the comfort index and the sensor output using a membership function of fuzzy sets. The comfort index was derived using this function.[8]

2. Experimental

Various types of tin oxide gas sensors have been developed. The sensor used in this study is a type of combustible gas sensor (CGS: TGS#800). The sensor does not have gas selectivity for a specific gas. The measurement system is composed of a thermometer, a hygrometer and the CGS. The CGS is connected in series with a load resister, and the direct-current power supply of 5 V is applied to the circuit, and its heater voltage is 5 V. The voltage at both ends of this load resistor is obtained as the sensor output. This system was set up in an ordinary wooden house in Kanazawa City in the Hokuriku region of Japan. The outputs were measured at the time of the household's awakening each morning for two years from April 1, 1996 to March 31, 1998. Figure 1 shows the measurement result for CGS output. The sensor output during the daytime fluctuates according to occupants' activities and the characteristics have higher levels during the daytime than at midnight. Output levels gradually decrease after midnight and take a minimum level at awakening. Regarding the results, it is considered that the indoor air quality reaches the cleanest level immediately before awakening. As described later, the valuation of the comfort index by human is influenced by the room temperature and humidity. However, because the gas generated by human activity influences the sensor output in daytime, the valuation of the

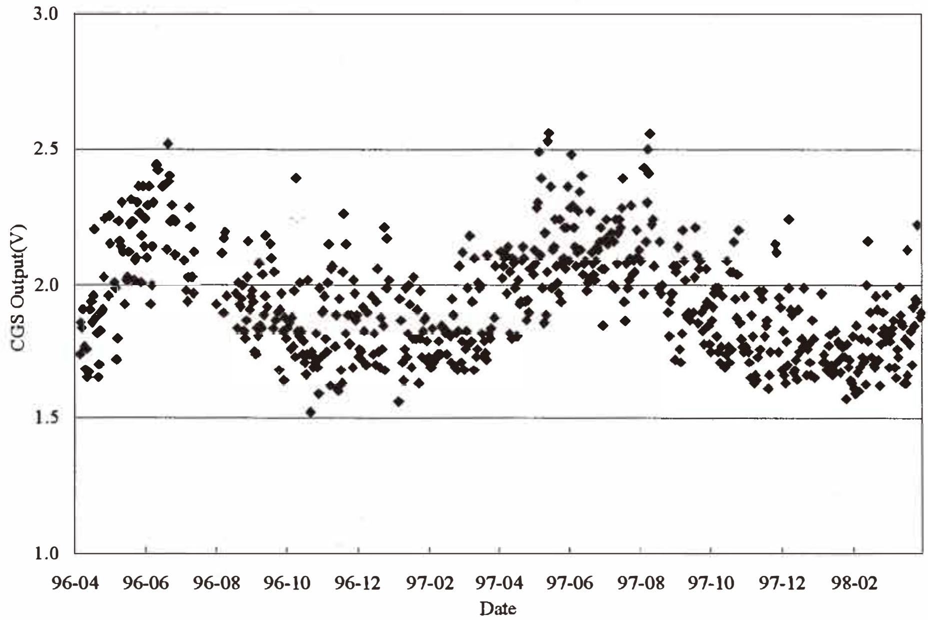


Fig. 1. CGS output measured over a period of 2 years.

comfort index by the sensor output in daytime is difficult. Therefore, we used the sensor output at the time of awakening in this study. The room temperature and relative humidity were also measured at the same time. The comfort index was recorded according to five grades by an occupant.

3. Experimental Results and Discussion

3.1 *Room temperature, relative humidity and comfort index*

Figure 2 shows the measurement results for room temperature and relative humidity. This region has high temperatures and high humidity in summer, and low temperatures and high humidity in winter. Therefore, it is easy to understand the seasonal changes from the temperature characteristics. In this region, the rainy season is long and humidity is high (over 60% RH) throughout the year except for short periods in spring and autumn. However, it is well known that a tin oxide gas sensor is influenced by humidity. The correlation coefficient of the gas sensor output and room temperature was 0.8983 and that of the gas sensor output and humidity was –0.7049, and these data were processed by the moving average method.[6] It was understood that these correlations were considerably high. The factors which effect the thermal environment and control the comfort index in a residential space are room temperature, relative humidity, radiant temperature and air movement. On the other hand, the discomfort index (DI) is the most common index for

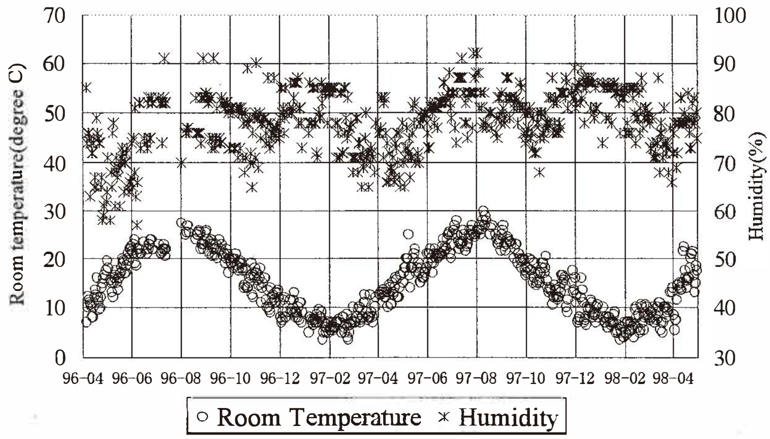


Fig. 2. Room temperature and humidity measured over a period of 2 years.

Table 1
Average, maximum and minimum values of discomfort index for each season.

	Spring (Mar.–May)	Summer (Jun.–Aug.)	Autumn (Sep.–Nov.)	Winter (Dec.–Feb.)
Average	58.3	72.6	64.1	50.6
Maximum	74.1	81.6	77.7	62.9
Minimum	46.7	63.6	52.1	44.9

indicating the degree of discomfort in terms of climate conditions in Japan. As the DI decreases, it becomes more comfortable. Table 1 shows the average value, the maximum value and the minimum value for DI in every season, along with the experiment data. In summer, as there are high temperatures, DI has a high value. This agrees with human perceptions of comfort. Conversely, in winter, as there are low temperatures, DI has a low value. This appears to indicate that winter is the most comfortable season, but this does not agree with human perceptions of comfort. Actually, winter is too cold, so it is not comfortable. Thus, it is thought that DI is not applicable to all seasons.

In addition, there are two other indexes, namely, PMV (Predicted Mean Vote) and SET (Standard Effective Temperature). These indexes are calculated using several factors, for example, room temperature, relative humidity, mean radiant temperature, wind velocity, clothing, metabolism and task intensity. These are controlled to improve the degree of comfort. However, these methods for the estimation of comfort are not simple, and the values of the factors might differ for each occupant, because these indexes are derived from information obtained from individuals. Therefore, it is not easy to estimate a total comfort index. It is more accurate and simple to estimate the degree of comfort.

3.2 *Relationship between room temperature, relative humidity and the comfort index*

The factors which affect the thermal environment and govern the comfort index are temperature, humidity, air flow and radiant temperature in a residential space. The window is, however, almost shut at the time of awakening. Therefore, it is difficult for an occupant to feel air flow. An occupant feels that the radiant temperature is similar to the temperature at the time of awakening. Therefore, it appears that room temperature and humidity have the most significant influence on the comfort index at the time of awakening.

The comfort index was recorded by an occupant using a five-grade scale. On the scale, CI-1 (comfort index 1) indicates uncomfortable, CI-2 indicates slightly uncomfortable, CI-3 indicates normal, CI-4 indicates slightly comfortable and CI-5 indicates comfortable. This classification seems well suited to human sensitivity, though it is difficult to express the sensitivity numerically.

Figure 3 confirms that the valuation of comfort is influenced by temperature and humidity. Figure 3-(1) shows the proportion of each comfort index grade at every room temperature. On one degree of temperature, the proportion of each comfort index grade in the measurement data which was evaluated by the occupant was calculated. After the comfort index grades of all measured temperatures had been calculated, it was clarified that there were many lower comfort index grades in both high temperature and low temperature. For example, the occupant evaluates the comfort index at 20 degrees centigrade, such that CI-1 constitutes 0, CI-2 constitutes 0.03, CI-3 constitutes 0.70, CI-4 constitutes 0.17 and CI-5 constitutes 0.10. CI-3 accounts for about 0.6 from 10 to 20 degrees centigrade. Below 10 degrees centigrade, as room temperature goes down, the proportion of CI-3 decreases and the proportion of CI-2 increases. Above 20 degrees centigrade, as room temperature goes up, the proportion of CI-3 increases and the proportion of CI-2 decreases.

Figure 3-(2) shows the proportion of each comfort index grade at every relative humidity. The comfort index data on humidity were also processed in the same way. The proportions of CI-5 and CI-4 increase as relative humidity becomes lower than about 80%. CI-3 accounts for roughly 0.5. For CI-2 and CI-1, the proportion increases as relative humidity becomes higher than 70%.

It is generally difficult to label Hokuriku region as having a comfortable climate. These

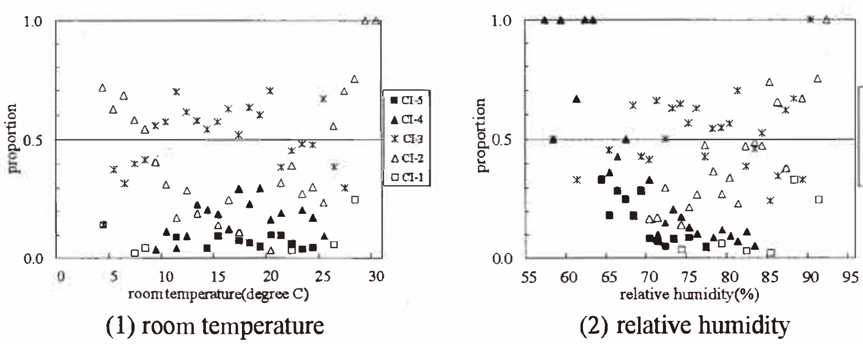


Fig. 3. Proportion of each comfort index grade at each room temperature and relative humidity.

data were measured immediately after awakening, so the human perceptions of comfort may have some uncertainty. However, the above-mentioned results are obtained. Therefore, it can be estimated that the occupant's evaluation of the comfort index is sufficiently accurate.

3.3 *Clustering of room temperature and relative humidity using LBG algorithm*

The comfort index obtained from the experiment was estimated by an occupant based on thermal sensitivities such as room temperature and relative humidity. The measurement data for room temperature and relative humidity were clustered to evaluate the validity of the comfort index. At this time, the clustering method used the LBG algorithm which is named after its devisers Linde, Buzo and Gray. This algorithm is used to obtain the semi-optimal solution. When the number of clusters is previously determined, it is a much easier algorithm.

These data fell into five clusters, and the average and standard deviation were calculated for each cluster. Figure 4 shows the relative position of each cluster. It is apparent that Cluster-1 and Cluster-5 are central, Cluster-3 has a higher position, and Cluster-2 and Cluster-4 have lower positions in terms of room temperature. Also, it is apparent that Cluster-5 is significantly lower, Cluster-4 is the next lowest, and Cluster-2 is the highest in terms of humidity.

3.4 *Relationship between clustering results and comfort index*

The comfort index is estimated according to room temperature and relative humidity in this experiment. In evaluating the clustering results presented above, it is clearly apparent that Cluster-2 is CI-1 and Cluster-5 is CI-5. However, the classification of Cluster-1, Cluster-3 and Cluster-4 is more difficult. Figure 5 shows the proportions of comfort index grade for every cluster. For example, on the data classified into Cluster-3, CI-1 constitutes 1.7%, CI-2 constitutes 35.2%, CI-3 constitutes 50.6%, CI-4 constitutes 11.4% and CI-5 constitutes 1.1%. The proportions of CI-4 and CI-5 account for 48.4% of Cluster-5.

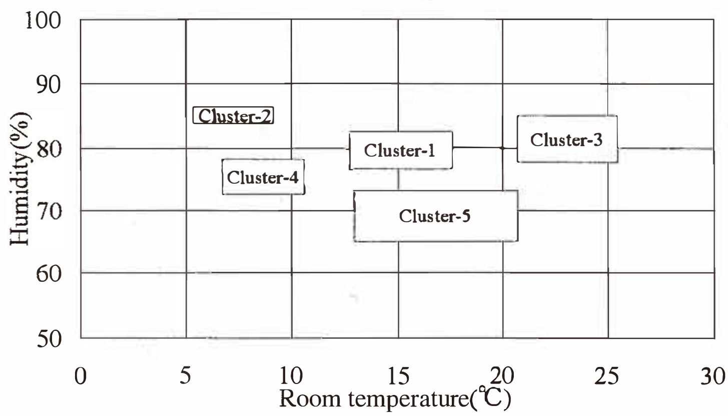


Fig. 4. Clustering results of room temperature and humidity.

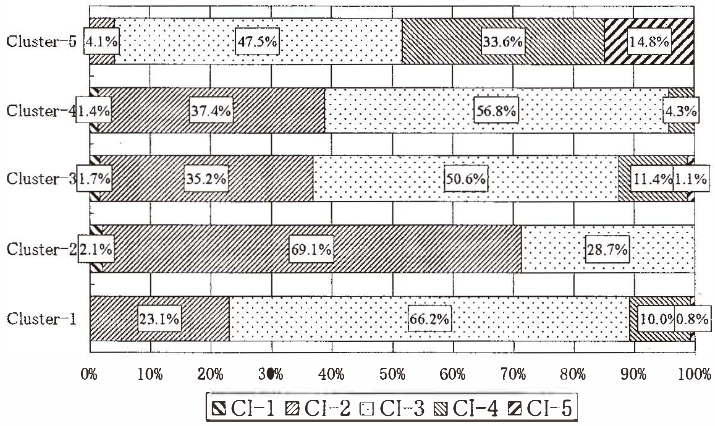


Fig. 5. Proportion of each comfort index in each cluster.

Therefore, this cluster has the highest degree of comfort. Similarly, the proportion of CI-1 and CI-2 account for 90.3% of Cluster-2. Therefore, this cluster has the lowest degree of comfort. For the remaining clusters, Cluster-1, Cluster-3 and Cluster-4, it is difficult to determine how each cluster relates to the indexes, because the proportion of CI-3 accounts for half or more of each cluster. These results are influenced by the significant fact that the proportion of CI-2 and CI-3 accounts for about 80% of the whole. When the occupant estimates the comfort index, some factors may influence human sensitivity. For example, if comfortable conditions continue for a few days in this region, people become accustomed to that condition. The final object of this research is the detection of uncomfortable conditions, and to be able to compensate for the lack of thermal sensitivity of the aged. Therefore, it is important that the clusters expressing discomfort can be classified. Finally, it was understood that the human degrees of comfort correspond to thermal factors, particularly room temperature and relative humidity.

3.5 *Relationship between gas sensor output and comfort index using membership function*

Evaluation of the comfort index is influenced by an individual's physical and mental state. The comfort index is estimated using subjective and ambiguous information, because the sensing of factors such as temperature and humidity is subjective in humans. However, it is considered that a common level of sensitivity exists among individuals with healthy bodies for the evaluation of the comfort index, as in this experiment. If ambiguous information such as sensibility data can be estimated quantitatively, fuzzy theory can be effectively applied to derive the index. The adopted membership function is very simple and is defined by human heuristics.

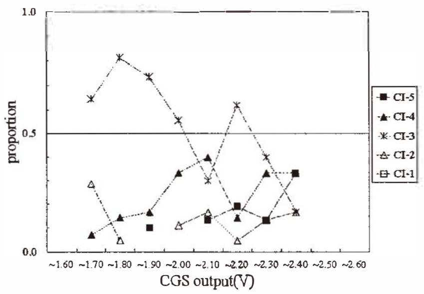
In a residential environment, it is clear that the sensor output is influenced by three main thermal indexes which are temperature, humidity and atmospheric pressure. In paragraph 3.4, the relationships between room temperature and humidity and the comfort index were clarified. It is necessary to clarify the relationship between the sensor output and the comfort index. For this purpose, the data for each season were analyzed.

Figure 6-(1) shows the relationship between the sensor output and the comfort index in the spring. Spring has data in the entire range of the measurement values for the whole year. The percentage of CI-2 is rather high when the gas sensor output is low. When the sensor output is high, the proportion is about 0.1, and as the sensor output increases, the percentage of CI-3 decreases though there is some variance. Conversely, the percentage of CI-4 and CI-5 increase as the sensor output increases. The percentages of CI-3 and CI-4 are large as a whole.

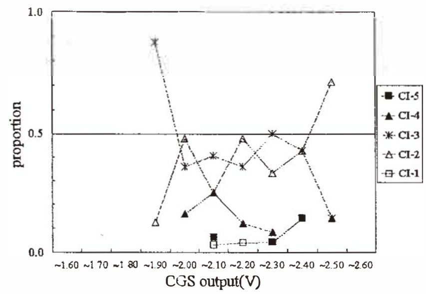
Figure 6-(2) shows the same relationship in the summer. The observed sensor output is higher than 1.8 V. The percentages of CI-1, CI-4 and CI-5 are lower than 0.2. The remaining percentage is divided between CI-2 and CI-3. When the gas sensor output is lower than 1.9 V, the proportion of CI-3 is larger than those of the other grades. However, when the sensor output is higher than 2.4 V, the proportion of CI-2 is larger. That is, a low value for gas sensor output suggests a higher degree of comfort than a high value. These trends are slightly apparent.

Figure 6-(3) shows the same relationship in the autumn. The observed sensor output is lower than 2.4 V. In these data, the proportion of CI-2 is between 0.1 and 0.4, and the proportion of CI-3 is between 0.5 and 0.8, and these proportions become symmetrical around the boundary of 0.5.

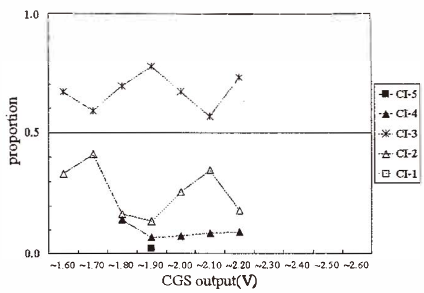
Figure 6-(4) shows the same relationship in the winter. The observed sensor output is



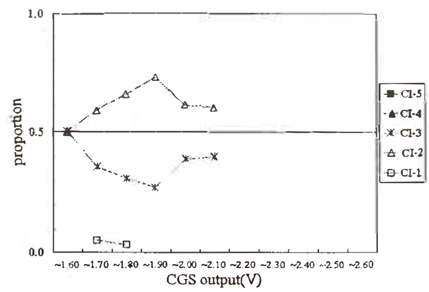
(1) Spring



(2) Summer



(3) Autumn



(4) Winter

Fig. 6. Proportion of each comfort index in relation to CGS output in each season.

lower than 2.1 V. CI-2 and CI-3 share the major proportion, similar to the case of autumn. The proportions of CI-2 and CI-3 become symmetrical around the boundary of 0.5. However, the proportion of CI-2 is larger than the proportion of CI-3, contrary to the results for autumn.

3.6 *Membership function of the comfort index*

The degree to which an element belongs to fuzzy set A is expressed within the range from 0 to 1 in fuzzy theory. In this study, we set such that the degree of comfort from the gas sensor output is expressed by a value from 1 to 5. An approximate function for each comfort index grade was calculated according to the above results. By multiplying each approximate function by each comfort index as weight, the membership functions for the comfort index were derived for each season. Table 2 shows these membership functions, where x is gas sensor output and the coefficient for each season was determined from Fig. 6.

Moreover, we calculate the comfort index by substituting the gas sensor output for the membership function. The results are shown in Fig. 7. Because the membership functions

Table 2
Membership function of comfort index and application level for each season.

Season	Membership function	Range
Spring	$\mu_{cr}(x) = 1.4x + 0.62$	$1.6 < x < 2.4$
Summer	$\mu_{cr}(x) = -0.16x + 3.17$	$1.8 < x < 2.0$
	$\mu_{cr}(x) = -0.05x + 2.89$	$2.0 \leq x < 2.5$
Autumm	$\mu_{cr}(x) = 2.0x - 0.8$	$1.7 < x < 1.9$
	$\mu_{cr}(x) = -1.5x + 5.85$	$1.9 \leq x < 2.1$
	$\mu_{cr}(x) = 2.0x - 1.5$	$2.1 \leq x < 2.2$
Winter	$\mu_{cr}(x) = -1.0x + 4.1$	$1.6 \leq x < 1.9$
	$\mu_{cr}(x) = 1.5x - 0.65$	$1.9 \leq x < 2.2$

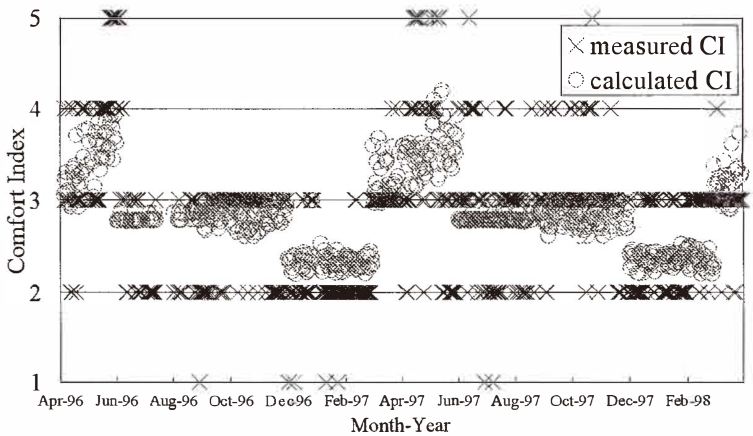


Fig. 7. Comparison between measured comfort index and calculated comfort index.

of each comfort index grade are different for each season, the continuity is broken at the turn of the season. However, the calculated result is well expressed for the climate condition of Hokuriku region. The standard deviation is 0.68.

4. Conclusions

The evaluation of the degree of comfort using the gas sensor output is proposed as an index in the indoor environment. This index is simple, like DI, but it can be used to evaluate the comfort index throughout the year, unlike DI. For this study, the room temperature, relative humidity, gas sensor output, and the comfort index grade at the time of awakening were recorded in the experiment. The data for room temperature and humidity were clustered using the LBG algorithm. Estimated comfort indexes were matched to each cluster. The relationships between the gas sensor output and the room temperature and humidity were clarified. Therefore, using a gas sensor which is widely spread to households is effective without a temperature sensor and a humidity sensor. It was necessary to clarify the relationship between the gas sensor output and the comfort index using a membership function. The derived function can estimate the comfort index grade based on the gas sensor output. The sensor output can be used to derive the comfort index. The index can substitute for the thermal sensitivity of aged, for example, the index indicates attention level, the index gives the alarm or the index operates the air conditioner. We aim to express the comfort index more accurately in the future.

If environmental conditions change significantly, it can feel comfortable or uncomfortable in a residential space. However, regardless of changes it seems that it generally feels normal because a healthy body can adapt easily to changes in the environment. However, it is difficult for the aged to adapt in this way. Therefore, it is important to compare the above results with results of an experiment involving aged individuals. Moreover, we will attempt to predict the comfort index grade and maintain a comfortable environment using gas sensor output.

References

1 T. Oyabu, S. Hirobayashi and H. Kimura: Trans. IEE of Japan, Vol. 117-E, No. 6 (1997) p. 314
2 T. Hayashi, H. Kimura and T. Oyabu: Trans. IEICE, Vol. J83-A, No. 4 (2000) p. 412
3 T. Oyabu, Y. Matsuura and H. Kimura: Sensors and Actuators B **35–36** (1996) 308.
4 T. Oyabu, T. Onodera, S. Hirobayashi and H. Kimura: Trans. IEE of Japan, Vol. 118-E, No. 12 (1998) p. 572
5 Y. Nakamoto, T. Oyabu and H. Nambo: Estimation of Indoor Climate Using Offset Level of Gas Sensor, The 1st Korea-Japan Joint Conference on Industrial Engineering and Management, B-3(4) (Oct. 30–31, 1998, Taejon, Korea)
6 Y. Nakamoto, T. Oyabu and H. Kimura: Trans. IEE of Japan, Vol. 121-E, No. 1 (2001) p. 14
7 Y. Nakamoto, T. Oyabu and H. Kimura: Prediction of Comfortable Index using Membership Function on Gas Sensor Characteristics, The 4th International Conference on Engineering Design and Automation, MP1-A(1) (Jul. 30–Aug. 2, 2000, Orlando, USA)
8 Y. Nakamoto, T. Oyabu, Y. Ueda, S. Furukawa and H. Kimura: Estimation of Effective Comfort Index using Room Temperature and Humidity, The 3rd Asia-Pacific Conference on Industrial Engineering and Management Systems, FC-3, (Dec. 20–22, 2000, Hong Kong)