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Environmental Monitoring Using Comfort Sensing System

Daesuk Na*, Jeongho Kang** and Sekwang Park*

Abstract

This research is about a comfort sensing system for human environmental monitoring using a one-bodied humidity and temperature sensor and an air flow sensor. The thermal comfort that a human being feels in indoor environment has been known to be influenced mostly by six parameters, i.e. air temperature, radiation, air flow, humidity, activity level and clothing thermal resistance. Considering an environmental monitoring, we have designed and fabricated a one-bodied humidity and temperature sensor and an air flow sensor that detect air relative humidity, temperature and air flow in human environment using surface micromachining technologies. Micro-controller calculates a PMV (predicted mean vote) and CSV (comfort sensing vote) with sensing signals and display a PMV on LCD (liquid crystal display) for human comfort on indoor climate. Our work has demonstrated that a comfort sensing system can provide an effective means of measuring and monitoring the indoor comfort sensing index of a human being. Experimental results with simulated environment clearly suggest that our comfort sensing system can be used in many applications such as air conditioning system, feedback controlling in automobile, home and hospital etc..

Key Words : comfort, PMV, thermal environment, environmental monitoring

1. Introduction

The thermal comfort that a human being feels has been known to be influenced mostly by six parameters, i.e. air temperature, radiation, air flow, humidity, activity level and clothing thermal resistance[1][2]. It was not until Fanger empirically established the well-known PMV equation that the formulation of the parameters was successfully made. PMV index basically quantifies the degree of discomfort and is expressed on such psychophysical scale as hot, warm, slightly warm, neutral, slightly cool, cool and cold[2]. The most important requirement for an air conditioning system such as cooling and heating apparatus is to create a comfortable indoor climate with high-energy efficiency. Conventional air conditional system is sensing only air temperature and has limitations of air conditioning for comfort on indoor climate. With the rapid development of microprocessor technologies and control tools such as fuzzy and neural network, there has been growing need for in-situ monitoring of parameters necessary for the optimal control of air conditioning system.

The most important prerequisite for the commercial applications of the PMV scheme is to extract correct values of PMV index at low cost. Considering a thermal comfort, we have designed and fabricated a one-bodied humidity and

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temperature sensor and flow sensor that detects air humidity, temperature and air flow on indoor climate.

The control of humidity, temperature in an ambient atmosphere is imperative for improving quality of life and enhancing industrial processes. Present-day systems are becoming more and more integrated, therefore there is a strong demand for multifunctional, small-sized sensors for detecting several parameters like humidity and temperature[3]. In response to this strong demand, we have been developing one-bodied thin-film sensor for detection of humidity and temperature.

An advantage of performing several measurements using a single sensor structure is that the information certainly comes from the same location in the sample solution. Besides that, the number of contact leads is reduced and the size of the single multi-purpose sensor structure will be smaller than two separate structures[4].

2. Experimental

Simulation of humidity sensor having interdigitated electrode

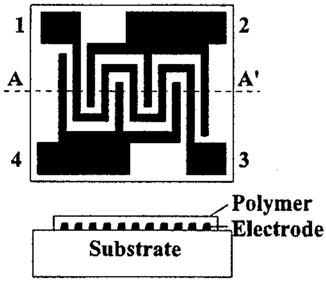
Computer simulation and 3-D modeling of one-bodied humidity and temperature sensor have been carried out to predict the capacitance range and sensitivity to relative humidity. And the influence of geometric parameters like the structural width and height on the basic capacitance was investigated with simulation calculations.

The governing equation of static electric field is a Poisson type equation:

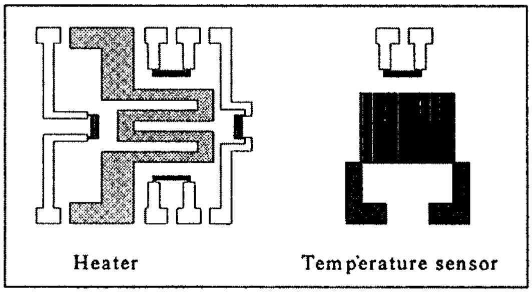
$$\nabla^2 V = -\frac{\rho}{\varepsilon} \qquad \text{-------------------} \quad (1)$$

where V is electric potential, is the electric charge density, is the electric permittivity.

One-bodied humidity and temperature sensor have resistor-electrode pairs as a repeating unit, as shown in figure 1 (a).



(a) One-bodied humidity and temperature sensor.



(b) Flow sensor.

Figure 1. A schematic diagram of the fabricated sensors.

This unit can be divided into inner domain and corner domain. We set up a 3-D FEM model and conducted electrostatic analysis with simulation tool using finite element method and obtained the profile of electric field surrounding the electrodes and resistors. As shown in figure 2.

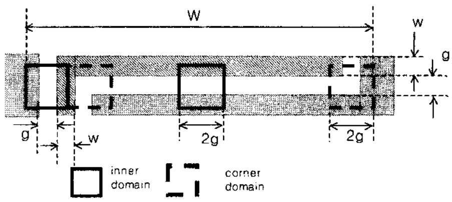


Figure 2. Resistor-electrode pair and modeling of the one-bodied humidity and temperature sensor.

Electric energy stored between resistor and electrode can be calculated from the profile of the electric field[5]. Thus we can calculate the capacitance of electrode-resistor pairs through equation (2).

$$C = 2W / (V_1 - V_0)^2 \quad (2)$$

Assuming that the ratio of electrode width (w) to electrode spacing (g) is 1:1, the total capacitance of the one-bodied humidity and temperature sensor consisting of N electrode-resistor pairs is

$$C_{total} = [\frac{C_{inner}}{2g}(W - 4g) + C_{corner}] \times N\ [pF].$$

Where C_{inner}, C_{corner} are capacitances of inner and corner domains and each area of domain is g × g.

The sensitivity (S) of sensor is

$$S = (C_{wet} - C_{dry}) / 100\ [pF\%R.H.].$$

Where C_{dry} and C_{wet} are the capacitances of the sensor at 0 %, R.H., and 100 %R.H.. The relative permittivity of polyimides varies with relative humidity between 3.2(dry-0%R.H.) and 4.0 (moist-100%R.H.), and the variation is linear for most of the range of R.H. (10-90%)[6] We used these values to determine the dielectric constant of polyimides and obtain C_{dry}, C_{wet}.

The influence of geometric parameters like structural width and thickness on the basic capacitance was investigated with simulation calculation using the inner domain. Figure 3 shows the capacitance per area and the sensitivity as a function of the electrode distance and thickness. Also, figure 4 shows the capacitance per area and the sensitivity as a function of electrode distance and polyimide thickness and the sufficient polyimide thickness was found to be twice the electrode distance.

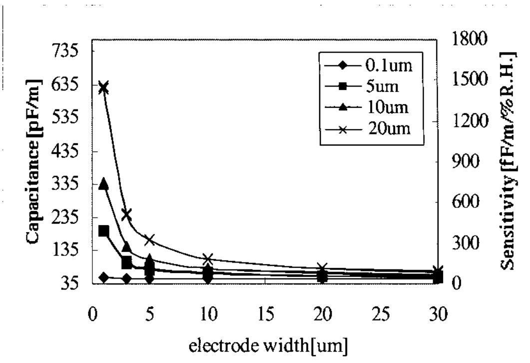
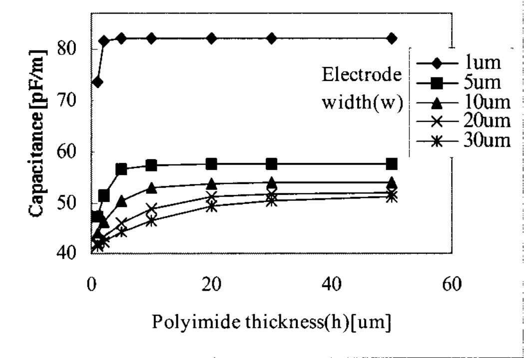
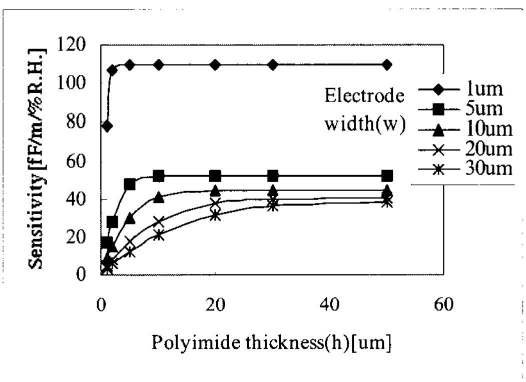


Figure 3. Assuming that the polyimide thickness is enough high, the capacitance and the sensitivity as a function of electrode width.



(a)



(b)

Figure 4. The capacitance(a) and the sensitivity(b) as a function of polyimide thickness and electrode width.

Multi sensor design

The design of sensors is based on a thermal comfort. The controlling mechanism as a kind of heat exchanger helps the body core to maintain relatively constant temperature in given thermal environment. Heat is generated inside a human body and dissipates through various channels for the heat exchange between the body and thermal environment [2]. To get values of PMV index in indoor environment, it is necessary to know air temperature, relative humidity and air flow.
Therefore, each sensor for their values are designed by FEM and fabricated by lithography and micromachining technology[7].

In one-bodied humidity and temperature sensor, as shown in figure 1 (a), the used structure consists only of shaped electrode on a substrate. The structure consists of a resistor passing through interdigitated electrodes that is a common design for conductivity sensor [6][8]. We have made the distance of fingers wider to create a resistive path for temperature measurements and placed the resistive electrode between interdigitatated electrodes. interdigitated electrodes and resistive electrode can be used for evaluating relative humidity by measuring capacitance variance to RH.. Resistive electrode between interdigitated electrodes can be used for temperature measurement.

Flow sensor is made of Pt on ceramic plate. Pt is sputtered on ceramic plate. We design Pt patterns of 100Ω and 1kΩ. 100 Ω is used for heater and 1 kΩ is used for detecting temperature of air flow. By constructing Wheatstone bridge with heater (Rh), temperature sensor (Rf) and other resistors, unbalanced output will be generated by air flow with temperature compensation. A closed-loop configuration, in which the temperature is kept constant and the required power is measured, potentially offers higher response speeds[9]. The design for the driving circuit of the flow sensor with temperature compensation is shown in figure 5. The flow sensor consists of heater and temperature sensor, which is made of Pt on ceramic. The schematic diagram of the fabricated air flow sensor is given in figure 1 (b).

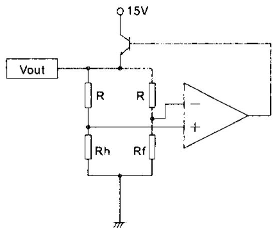


Figure 5. Driving circuits of fabricated flow sensor.

Fabrication of one-bodied humidity and temperature sensor

The sensor area is 4 mm × 4 mm which leads to measurable capacitances of 20~30 pF. The fabrication of the electrodes and resistors has been accomplished on the substrate using photolithography technology. Soda-lime glasses with a thickness of 1mm were first thoroughly cleaned employing ultrasonic and chemical means. Next, Aluminum layer 2 um in thickness was thermally evaporated onto the glass substrate. The aluminum film was subsequently patterned using photolithography process. Polyimide layer of 8 um thickness has been deposited by spin coating and patterned using a photolithographic step. In the last step, the polyimide film was cured in a nitrogen atmosphere. After curing, the thickness of polyimide film was determined to be 5 um.

The temperature and humidity responses of the fabricated sensor were measured in a temperature and humidity chamber (STH-702). The temperature was varied from -40 °C to 150 °C and the resistance of the resistor was measured to obtain its temperature response. The capacitance variances to relative humidity were measured by applying 5 V to interdigitated electrodes and 0 V to the resistor with the capacitance measuring circuit. The relative humidity varied from 3 %R.H. to 98 %R.H.

Comfort sensing system design and construction

These fabricated sensors are packaged in probe with driving and amplifier circuit to detect temperature, relative humidity and air flow in indoor climate. Microcontroller is used for measuring of output voltage of each sensor and calculates PMV and CSV index and displays the calculated results on LCD.

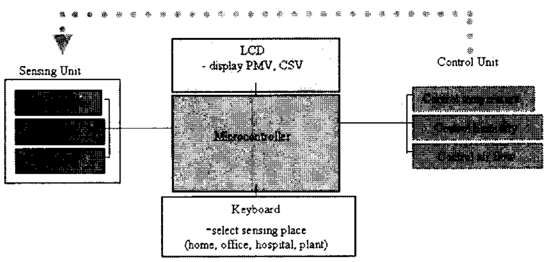


Figure 6. A block diagram of the comfort sensing system.

Figure 6 shows a block diagram of the comfort sensing system constructed using a one-bodied humidity and temper ature sensor and a flow sensor. The system consists of: 1) a sensing unit with signal processing, 2) MPU (80C31 microcontroller) which calculates PMV and CSV index and controls the control unit, 3) a display part using LCD, and 4) keyboard. A system has been fabricated using these sensors and MPU with PMV equation (1) in ISO7730[2], and experimental results with environment clearly suggest that our system can be used in many applications such as an air conditioning system,feedback-controlling in automobile, home and hospital etc..

$$\begin{aligned} PMV = \; & (0.303 \cdot e^{-0.36M} + 0.028)\{(M-W) \\ & -3.05\times10^{-3}[5773-6.99(M-W)-P_a] \\ & -0.42[(M-W)-58.15] \\ & -1.7\times10^{-5}\cdot M\cdot(5867-P_a) \\ & -0.0014\cdot M(34-t_a)-3.96\times10^{-8}\cdot f_{cl}\cdot \\ & [(t_{cl}+273)^4-(\bar{t}_r+273)^4] \\ & -f_{cl}\cdot h_c\cdot(t_{cl}-t_a)\} \end{aligned} \quad \text{------------------- (3)}$$

where

$$\begin{aligned} t_{cl} = \; & 35.7-0.028(M-W) \\ & -I_{cl}\cdot\{3.96\times10^{-8}\cdot f_{cl}[(t_{cl}+273)^4 \\ & -(\bar{t}_r+273)^4]+f_{cl}\cdot h_c(t_{cl}-t_a)\} \end{aligned}$$

$$h_c = \begin{cases} 2.38\,(t_{cl}-t_a)^{0.25} & \text{for } 2.38\,(t_{cl}-t_a)^{0.25} \geq 12.1\sqrt{V_{ar}} \\ 12.1\sqrt{V_{ar}} & \text{for } 2.38\,(t_{cl}-t_a)^{0.25} \leq 12.1\sqrt{V_{ar}} \end{cases},$$

$$f_{cl} = \begin{cases} 1.00+1.29\cdot I_{cl} & \text{for } I_{cl} \leq 0.078\cdot m^2\cdot ℃/W \\ 1.05+0.645\cdot I_{cl} & \text{for } I_{cl} \leq 0.078\cdot m^2\cdot ℃/W \end{cases}$$

M :metabolic rate [met]=[58.2 W/m^2]
W : external work [met]
I_{cl} : thermal resistance of clothing [clo]=[0.155 m^2 ℃/W]
f_{cl} : ratio of man's surface area while clothed, to man's surface area while nude.
t_a : air temperature[℃]
t_r : mean radiant temperature [℃]
V_{ar} : relative air velocity [m/s]
P_a : partial water vapor pressure [Pa]
h_c : convective heat transfer coefficient [W/m^2 ℃]
t_{cl} : surface temperature of clothing [℃]

Comfort sensing system calculates PMV and CSV index using PMV equation (3) and displays the calculated results on LCD. Figure 7 shows a flow chart of comfort sensing system on indoor climate.

It consists of: 1) detection of temperature, humidity and air flow in indoor climate, 2) input parameters of metabolic, external work and clothing using keyboard, 3) calculation of PMV and CSV 4) display on LCD. Initial step prepares internal user setting in special function register, internal RAM and other devices. According to key input, branch to modify of initial variable using key input and set default mode (home, office, hospital and plant).

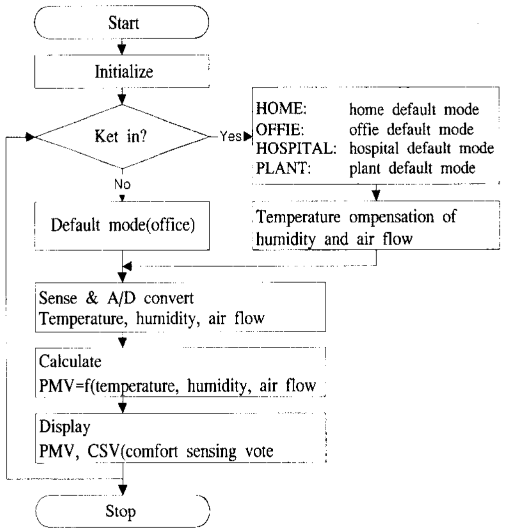


Figure 7. A flow chart of comfort sensing system.

Values of default mode are based on mean values of each place. After mode selection, temperature, relative humidity and air flow in indoor climate are detected from sensors. Temperature compensation of detected values is completed in software and calculated to PMV and CSV and displayed on LCD. Execution is returned to key input routine and repeats those routines.

3. Results and discussion

In order to construct a comfort sensing system using fabricated sensors, it was necessary to investigate the characteristics of these sensors in response to temperature, humidity and air flow among other things. Driving circuits of fabricated air flow sensor is shown in figure 6. Humidity and temperature sensor output the frequency variation of each detection on indoor climate. For measurement of air flow, driving circuit is consists of feedback system as shown in figure 6. According to heat losses that are caused by air flow in heater (Rh) output voltage of OP-AMP is increased and come to steady state, and air flow is measured by output voltage at that time. Figure 8, 9, 10 is the characteristics of each sensor. Each fabricated sensor has good characteristics and is useful in comfort sensing system on indoor climate.

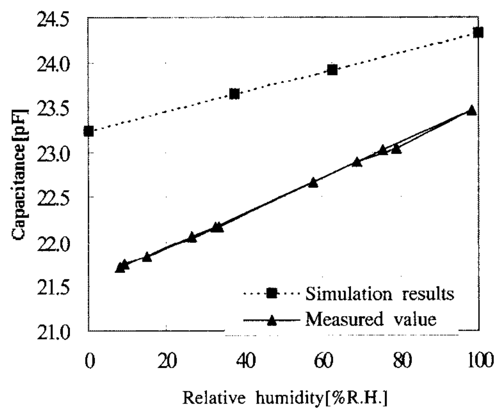


Figure 8. The capacitance variance and simulation results.

We have performed the 3-D accurate simulation of one-bodied humidity and temperature sensor using finite-element methods and developed the fabrication process of the sensor. Then one-bodied humidity and temperature sensor have been fabricated using semiconductor process and the experimental results were made a comparison with capacitance calculated by FEM simulation tool. Figure 8 shows the capacitance variance to relative humidity change and the capacitance calculated by simulation tool. The capacitance of the fabricated sensor varied linearly over most range of R.H. with linearity (below 2 %FS) and low hysteresis, and showed good agreement with values calculated by simulation tool.

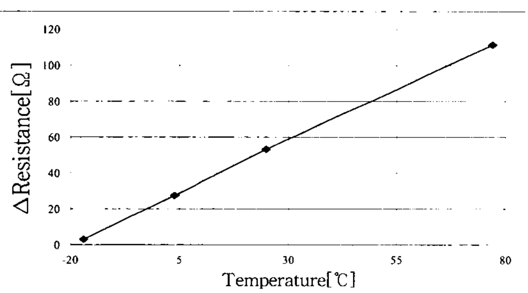


Figure 9. The temperature characteristics of the fabricated one-bodied humidity and temperature sensor.

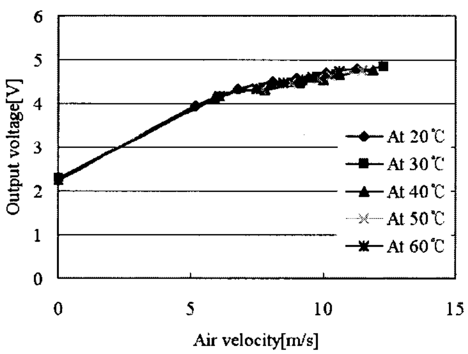


Figure 10. Characteristics of an air flow sensor.

Experimental results are 2 % lower than values calculated, which is due to the accuracy of measurement circuits and stray capacitance from, for example, the leads and contact pads. And the fabricated sensor had the response time of 40 seconds in absorption, 70 seconds in desorption. As shown in figure 9, the temperature coefficient of resistors used as temperature sensor was about 1 Ω/°C. Figure 10 shows characteristics of an air flow sensor.

More than 50 sensors are fabricated and tested to measure their characteristics. In humidity sensing part, thickness of sensing layer is about 10 um, distance of electrode is about 16 um, sensitivity is 17 fF/%R.H., and offset is about 24 pF. Response time of absorption is about 40 seconds over the range from 10 %R.H. to 50 %R.H., that of desorption is about 70 seconds over the range from 90 %R.H. to 50 %R.H. Nonlinearity is 2 %FS over the range from 8 %R.H. to 97 %R.H. and hysteresis is below 2 %FS. In temperature sensing part, TCR (temperature coefficient of resistance) is about 1 Ω/°C, offset is about 290 Ω.

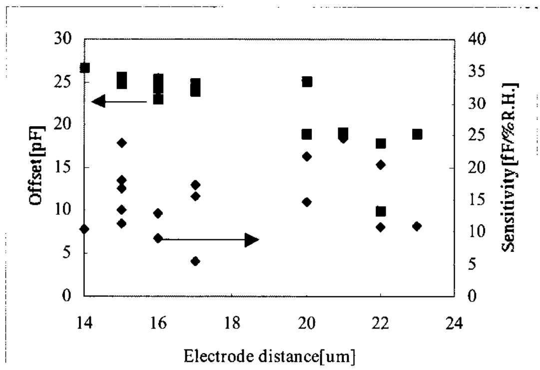


Figure 11. Typical graph of offset and sensitivity of humidity as a function of electrode distance.

Figure 11 shows typical graph of offset and sensitivity of humidity as a function of electrode distance. Characteristics of one-bodied humidity and temperature sensor are shown in table 1.

Increasing the capacitance and sensitivity of sensor needs to increase the thickness of electrodes or humidity-sensitive films, or decrease the electrode width or interval. New fabrication process needs to be developed to increase the thickness of electrodes or humidity-sensitive films. Decreasing the electrode width or interval is considered good method for improving the characteristics of sensor. The simulation results shows that sensor having polyimide thickness, 5 um, have greatest sensitivity at electrode width, 2.5 um.

Table 1. Characteristics of fabricated humidity and temperature sensor.

Sensing part	Characteristics	Value
Humidity	Thickness of sensing layer	10 um ± 1 um
	Electrode distance	16 um ± 1 um
	Sensitivity	About 17fF/%R.H.
	Offset	About 24 pF
	Operating range	8%R.H.~97%R.H.
	Nonlinearity (at 8 %R.H.~97 %R.H.)	Below 2 %FS
	Hysteresis	Below 2 %FS
	Rising time (from 10 %R.H. to 50 %R.H.)	About 40 seconds
	Falling time (from 90 %R.H. to 50 %R.H.)	About 70 seconds
	Temperature coefficient	About 4 fF/°C
Temperature	TCR of temperature	About 1 [Ù/°C]
	Offset of temperature	About 290 Ù

Table 2. The average of the details of participants in moderated thermal environmental.

NO	1		2	3		4
Date[mm/dd]	5/21		6/4	9/11		9/11
Area	Lab.		Hospital	Lab.		Hospital
Sex	M	F	M	M	F	M
Participant	25	6	7	34	7	17
Height[cm]	174	162	175	175	166	173
Weight[kg]	66	49	73	63	54	66
Age	19	19	32	20	19	27
Clothing [clo]	.62	.53	.49	.53	.49	.52
Metabolic rate	1.1	1.1	0.87	1	1	1

Table 2 is the average of the details of participants in moderated thermal environment. The participants vote about comfort of each moderated thermal environment during the test of measurement.

We designed and made a comfort sensing system using above fabricated sensors. Figure 12 describes the CSV index changing aspects of physical factors such as indoor temperature range of 19 to 32 under constant humidity of about 65 %R.H. and flow of 0.1 m/s. Healthy eight men exposed to moderate thermal environment and CSV of the fabricated comfort sensing system and CSV of a human being were recorded at the same time according to the variation of temperature.

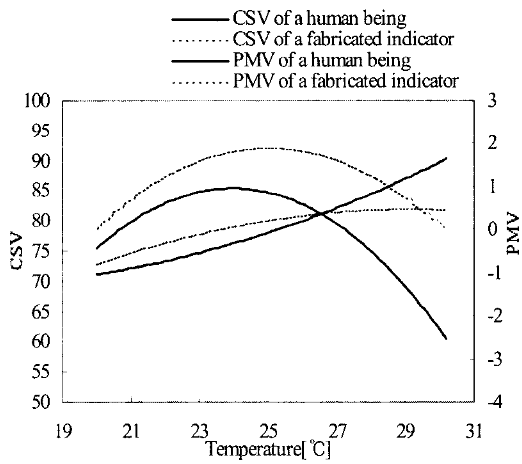


Figure 12. A CSV index as changing room temperature.

It is clear from the figure 12 that the output values from comfort sensing system are in a good agreement with CSV of a human being. Operator in general controls a temperature to make a comfort climate. But this kind of control method requires more energy than that of the fabricated comfort sensing system due to operating heater or air conditioner. For instance, CSV is about 70 % at 31 of room temperature and to increase CSV up to 80 % there are two methods. One is to decrease a room temperature with air conditioner, but it requires high energy consumption. The other is to increase air flow instead of decreasing a room temperature. The later is more effective in energy saving point of view. In fact if the air flow is controlled from 0.1 m/s to 0.5 m/s at 70 % of CSV, after one minute CSV represents about 80 %. Fabricated system in figure 6 can be utilized in controlling a comfort environment with much more effective energy saving. Experimental results clearly suggest that our sensing system can be applied in air conditioning system as a practical means of monitoring PMV and CSV indices and feedback-controlling for comfort environment.

4. Conclusion

Our work has demonstrated that a comfort sensing system on indoor climate can provide an effective means of measuring and monitoring the comfort sensing of a human being. In order to construct comfort sensing system on indoor climate, we have designed and fabricated 1) one-bodied humidity and temperature sensor, 2) air flow sensor. Fabricated sensors have good characteristics and are useful in comfort sensing system. Comfort sensing system can provide an effective means of measuring the comfort sensing of a human being. Experimental results in simulated environment clearly suggest that our sensing system can be utilized in air conditioning system as a practical means of monitoring PMV and CSV indices and feedback-controlling in automobile, home and hospital etc..

Acknowledgement

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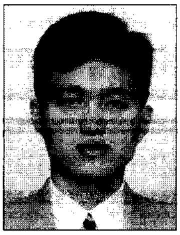

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