A Cost-Effective Stand-Alone Thermal Comfort Calculation System for Healthy Air Evaluation in Academic Classrooms through PMV and PPD Indications

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ABSTRACT

There are many academic buildings in Thailand that consumed annual electricity per usage area approximately 37 kWh/m^2.yr, in which contribution of air-conditioned area is approximately 27%. Thereafter, energy reduction is ultimately necessary, especially this paper concern the application of Thermal Comfort based on the ASHRAE thermal sensation scale standard exploiting Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) as standard indicators. Not only PMV equation in ASHRAE, but PMV can also be calculated by classical artificial (feed forward) neural networks (ANN) or the time-series NARX feedback neural networks. Consequently, to ease on-site measurement, the wireless sensor networks were developed to monitor uncontrolled air-conditioned academic classroom. The real-time sensor collected temperature and relative humidity values, and simultaneously transfers data to be analysed in a main computer station. Finally, the portable PMV and PPD calculator device was designed and tested. This device is cost-effective and easy-to-use with a touch screen Graphic User Interface (GUI), and possibly connected to the distributed sensors networks, while integrating the ANN model into the Raspberry Pi.

Keywords: Thermal Comfort, Academic classrooms, Buildings Energy Management, Microcontroller

1. INTRODUCTION

In Thailand, there were more than 160 universities, colleges, institutes of undergraduate and graduate levels in Thailand, which most of large portion of academic buildings were constructed before 2000. However, the air-conditioning system of academic buildings typically consumed electricity about 63 – 165 kWh/yr per square meter or air-conditioned area, and averaged to 76.2 $kWh/m^2.yr$. The contribution of energy usage for air-conditioning was 53%. Therefore, there is room of energy savings potential using appropriated building energy management measures.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) defined the Thermal comfort, which is a state of human mind, indicating the level of comfort. The average thermal sensation response using the ASHRAE thermal sensation scale is called the predicted mean vote (PMV)[1]. To achieve thermal comfort maintenance and energy consumption minimization in most conditions are conflicted so that optimization method are required to find appropriate solutions over time. The investigation of thermal comfort in classrooms has attracted much interested since the classrooms occupy most area and power consumption in university through dynamic loads, i.e. the number of students and room arrangements. Thermal comfort in university classrooms through objective approach and subjective preference based on the questionnaires has recently been investigated in [2]. The average energy consumption of a precision inverter air conditioning (A/C) system in comparison with a conventional A/C system was investigated by T. Sookchaiya et al.[3], which they found that the system could provide people in Thailand the human thermal comfort and health.

Considering the building control tool, an Artificial Neural Network was considerably competitive to the other multi – agent control systems. It was confirmed by [4] that ANN was applicable to a better control of the building's heating system, in order to control the indoor temperature of a solar building. In the first part of this paper the author presented the prediction of the thermal comfort level using ANN.

1.1 Artificial Neural Networks

The original artificial neural networks (ANN) structure is depicted in Fig.1, comprising of two parts; an input layer and general neurons in the hidden and output layers. The output a is a function of weights W, input P and bias b. The adaptive learning ability of the ANN was applied to solve the complex problem in estimating PMV values of the air-conditioned space in an academic building.

PMV model by Fanger [6] is a function of six variables given by Equation (1) depending on 6 factors: clothing insulation, air temperature and humidity, air velocity, the metabolic rate, and the mean radiant temperature, was used in predicting the average vote

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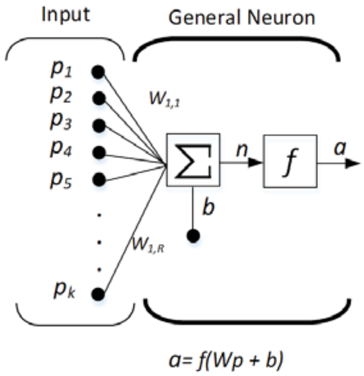


Fig.1:: Original artificial neural network structure [5]

of group of occupants on the thermal sensation scale. PMV can be estimated,

$$PMV = f(M, W, Pa, f_{cl}, T_{cl}, \bar{T}_r) \tag{1}$$

$$\begin{aligned} PMV = \quad & (a_0 e^{-a_1 M} + a_2)[(M - W) \\ & -a_3 \{a_4 - a_5(M - W) - Pa\} \\ & -a_6 \{(M - W) - a_7\} - a_8 M(a_9 - Pa) \\ & -a_{10}(a_{11} - T_{ai}) - a_{11} f_{cl}\{(T_{cl} + 273)^4 \\ & -(\bar{T}_r + 273)^4\} - f_{cl} h_c (T_{cl} - T_{ai})] \end{aligned} \tag{2}$$

where,

Coefficients a_0 to a_{11} are, 0.303, 0.036, 0.028, 3.05e-3, 5733, 6.99, 0.42, 58.15, 1.7e-5, 5867, 0.0014, 34, 3.96e-8, respectively.

M(W/m^2)is the metabolic rate and (W/m^2)is an external work,

P_a(Pascal) is the partial water vapor pressure,

$T_{ai}(^\circ C)$ and $\bar{T}_r(^\circ C)$ are the air temperature and mean radiant temperature.

$T_{cl}$is the surface temperature of clothing, as a function of 9 parameters as given by (3) and (4)

$$PMV = f(M, W, Pa, I_{cl}, f_{cl}, T_{cl}, \bar{T}_r, h_c, T_{ai}) \tag{3}$$

$$\begin{aligned} T_{cl} = \quad & 35.7 - 0.028(M - W) - I_{cl}[3.96e \\ & -8 f_{cl}[(T_{cl} + 273)^4 - (\bar{T}_r + 273)^4] \\ & +f_{cl} h_c (T_{cl} - T_{ai})] \end{aligned} \tag{4}$$

h_c is the convective heat transfer coefficient, as a function of given by (5) and (6).

and

$$h_c = \begin{cases} h_c^* & \text{if } h_c^* > 12.1\sqrt{V_a} \\ 12.1\sqrt{V_a} & \text{if } h_c^* < 12.1\sqrt{V_a} \end{cases} \tag{5}$$

where

$$h_c^* = 2.38(T_{cl} - T_{ai})^{1/4} \tag{6}$$

V_a (m/s) is the air velocity

I_{cl} ($m^{2\circ}$C/W) is the clothing thermal resistance

f_{cl} is the ratio of body surface area covered by clothes to the naked surface area, is defined by Equation (7)

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & \text{if } I_{cl} \leq 0.078 \\ 1.05 + 0.645 I_{cl} & \text{if } I_{cl} > 0.078 \end{cases} \tag{7}$$

In this paper the mean radiant temperature, $\bar{T}_r$ is not directly measured, however, calculated as function of indoor temperature based on our database.

There are two approaches of ANN modeling and prediction; typical (or classical) ANN model and NARX model. The optimum topology of ANN and NARX models were 1 x 7 x 4 x 1, and 1 x 10 x 1, respectively.

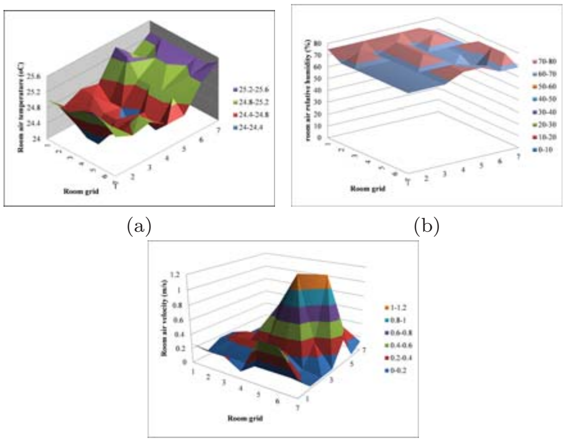
To predict PMV_{ANN}, the typical ANN model needs 3 inputs; air temperature, relative humidity and air velocity (T_{ai}, H_{ai}, V_a) and 1 output; the PMV determined by gathered indoor air conditions data from field measurements in an actual classroom during its normal operation called PMV_m. Several training patterns were trial until the simple and appropriated one, the TRAINLM training function with Levenberg-Marquardt back propagation type was satisfied. The ANN should result in the smallest discrepancy between the Fanger's and calculated PMVs, so that various configurations for the ANN were used. By many attempt of trial and error, the number of neurons in the two hidden layers of classical ANN model was finally 7 and 4.

The NARX-type model is a recurrent dynamic network commonly used in time-series nonlinear modeling of the dynamic system [7]. The NARX model was used for modeling the PMV behavior of the classroom rather varying upon the transient room air conditions and inside activities.

In case of the NARX model, the Fanger's PMV values were employed as inputs of the model for the prediction of the next time-series ahead of PMV. Therefore, the NARX model needs only 1 input (PMV_m) to predict PMV_{NARX} in the time-series accordingly. The NARX network was efficiently trained by using a series-parallel architecture. Therefore, the real PMV output can be further used as input instead of feeding back the estimated output, so that the input to the network is better accurate. When the series-parallel NARX network (open loop) training process is successfully done, the feedback loop is closed.

The measured data from real classroom shown by surface plots of air temperature, relative humidity, and air velocity in Figure 2 referring to the room 7 x 7 grids. The questionnaires were used for surveying information on temperature, humid and air movement sensation from the seated persons in the classroom to get PMV_q values.

The experiment was conducted with 60 seated persons during 9:30 – 12:30 hr. All three FCUs of split type air-conditioner were always turned on. The indoor air temperatures are in the range of 24 - 25.6 °C relative humidity 50% to 80%, and air velocity about 0.03 to 1.2 m/s

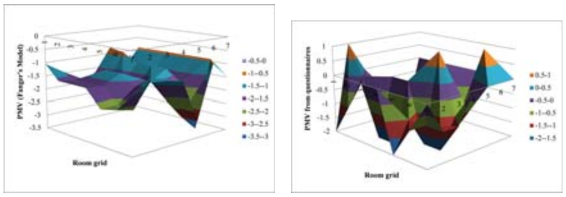


(a) (b)

(c)

Fig.2:: Measured room air conditions (a) Temperature, (b) Relative humidity, and (c) Air velocity [8]

The PMVs values calculated by Fanger's equations and those analyzed from the occupants questionnaires are illustrated and compared in Figure 3.



(a) (b)

Fig.3:: PMV distribution within the experimental classroom (a) calculated by Fanger's Equation, (b) based on Questionnaires [8]

In comparison of 62 data sets, between the PMVs calculated by Eq. (2) and the PMVs from the questionnaires, there was about one-half (35 data sets) having acceptable discrepancy ($PMV_q - PMV_m \leq \pm 1$ point), implying the effect of individual thermal comfort sensation on the PMV. There were 15 sets from the verification data having thermal/humid/air movement as PMV value about -1 (slightly cool, slightly dry and too still) and 0 (neural and just right). The ANN and NARX networks were verified after training process that the relationship between the outputs of the network and the targets were plotted by regression. The network outputs and the targets would be exactly equal if the training were successfully done. All weights and biases reported from the classical ANN PMV model, and the time-series NARX PMV model shall be used further used in predicting the PMV of the academic classroom. Afterward, by testing the other sets of PMV data, the R^2 resulted from the feed-forward neural network type TRAINLM and NARX model were about 0.9736 and 1, respectively that were in acceptable level. These showed that the predicted values of the PMV by NARX agreed well with the PMV values from Fanger's model and from the questionnaires.

1.2 Distributed Sensors Network

The investigation of thermal comfort in classrooms has been much interested since the classrooms occupy most area and power consumption in university through dynamic loads, i.e. the number of students and room arrangements. Thermal comfort in university classrooms through objective approach and subjective preference based on the questionnaires has recently been investigated in [9], and the results reveal that each location in classroom has different level of thermal comfort. However, the real-time measurement of thermal conditions through hardware-based technique to be compared with results obtained from questionnaires has found in [10]. Since, measurement of indoor air parameters for PMV calculation was crucial so that the real-time sensor collects temperature and relative humidity values, and simultaneously transfers data to be analyzed in a main computer station was developed. Consequently, the experiment was conducted at Thai-Nichi Institute of Technology (TNI), located in Suanluang District (Latitude 13.7° North and Longitude 100.63° East), Bangkok, Thailand. The sensor networks consist of temperature and relative humidity sensors developed by the Intelligent Electronics System (IES)'s techniques to simplify the measurement. Table 1 summarizes the room architecture and air-conditioner features. Figure 1 shows the detailed floor plan of the classroom that installed the distributed sensor network. The external wall of the experimental room faces South with single pane glassed windows along the wall. During the experiment, remote control was not allowed to control the indoor air-conditioning system. There were 12 monitoring sensor stations installed on the desk among students at the coldest and warmest area to evaluate the thermal uniformity of environment as illustrated in Figure 4. Measured results of temperature, relative humidity (RH), and air velocity were analyzed in order to determine student thermal comfort and consequently compared with the questionnaires results. The conditions of air measurement were performed at 1-min intervals during the lesson for 3 hours.

The sensor sets were microcontroller-based system employing SHT-15, which is a cost-effective sensor. This temperature and humidity sensor could provide a calibrated digital signal output compatible with 14-bit microcontroller. The measuring temperature range is between -40°C to 100°C while the measuring RH range is 0-100%. The temperature accuracy is +/- 0.3°C at a room temperature of 25°C and the absolute RH accuracy is +/- 2% RH. The power supply was set to 5V yielding a low power consumption, i.e. typically at 30 μW.

The individual temperature sensor set senses the room temperature as well as the RH, and sends the data to the microcontroller as an interface unit to the

Table 1:: Architecture and air-conditioned features of the experimental classroom

Specifications	Value
No. of seats	No. of seats 56 (occupied by 47 students)
Floor area (m^2)	100 (8.2 m x 12.2 m)
Height (m)	2.8 (floor to ceiling) and 1-m spandrel height
Volume (m^3)	280
A_{window}/A_{floor}	0.20
Windows exposition	South (single pane glass windows)
No. of Fan Coil Unit (FCU)	Three ceiling hanged (one of the split type have 2 RT air-conditioners w/o remote control)
Ventilation	Operated

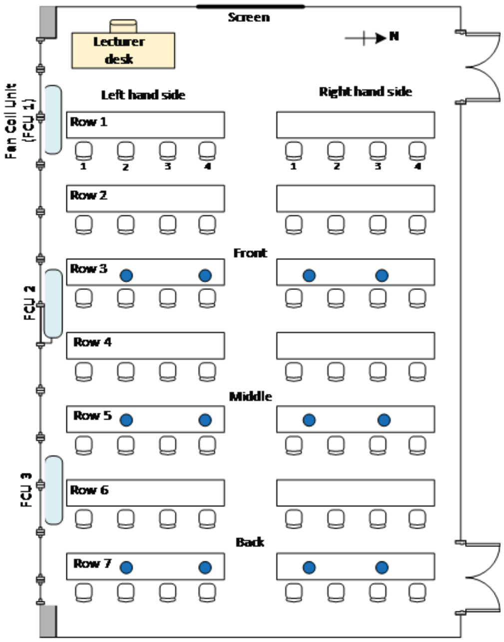


Fig.4:: The floor plan of the experimental room [11].

transceiver prior to the wireless data transmission to the base station. As shown in figure 4, the sensors were installed in the front of the room at row 3, in the middle of the room at row 5, and in the back of the room and row 7.

The transmitter and receiver, combined into a single ship operating at 2.4GHz ISM band, were implemented by the RF transceiver model NRF24L01, and the data rate is relatively high up to 2Mbps. The photo of the implemented temperature and humidity sensor SHT-15 and RF module NRF24L01 is depicted in Figure 5. The sensor was operated by a 9-V battery.

In the measurement process, the room air temperature abbreviated as T_a and the RH were measured by the sensor in 1-min time intervals at 12 points of the left and right hand sides of the class room. From overall 3 hours measurement, the measured temperatures

Fig.5:: Photo of the implemented temperature and humidity sensor SHT-15 and RF module NRF24L01 [11].

and relative humidity were nearly constant. The average temperature for 30-min of front, middle and back row were measured at 23.6 - 25.1 °C, 23.4 - 26.5 °C, and 23.3 - 27.4 °C, respectively. The measured temperature results were consistent to those obtained by digital temperature probe.

While the measurement were conducted, the air velocity measured in 7 row × 9 column grids, including the middle passage, were measured by the rotating vane digital anemometer, and the results are depicted in Figure 6. The questionnaires, divided into four parts, were distributed to the classroom occupants after one hour from the beginning of the lesson. Part 1 collects general information, involving gender and age. Most student ages are between 15-20 years. Percentages of engineering male and female students are 94% and 6%, respectively. Part 2 measures individual thermal sensation by rating on thermal, moisture, air movement preferences, environment satisfaction, perspiration preference, and thermal acceptability. Therefore, the thermal preferences are rated to 7-points scale according to [1], providing the occupant Actual Mean Vote (AMV). Part 3 collected individual clothing data by checklist of cloth types to determine the thermal insulation of the occupants. Most of the occupants wear the engineering student's uniform consisting of T-shirt, trousers and short-sleeves jacket. Part 4 is thermal comfort perception of occupants rated by occupants to recheck the score of the preceding parts, i.e. the preferences and acceptability of air conditions.

Almost occupants were students who wearing trousers, short-sleeved shirt plus suit jacket (I_{clo} = 0.96) [12], resting seat and quiet corresponding with the metabolic rate 1.0 met. While, it was assumed that the metabolic heat generation was approximately 58.1 W/m^2. It was found that most of occupants reported their thermal preference from cold the rather cold, while rather desired humidity and air movement of environment were preferred.

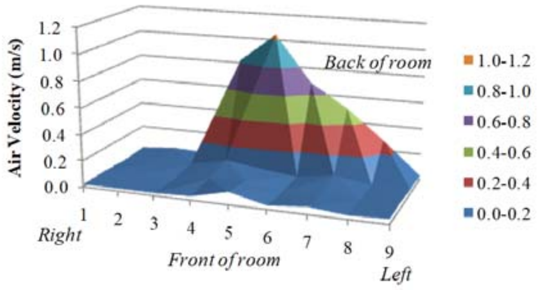


Fig.6:: Air velocity distribution of the experimental room [11].

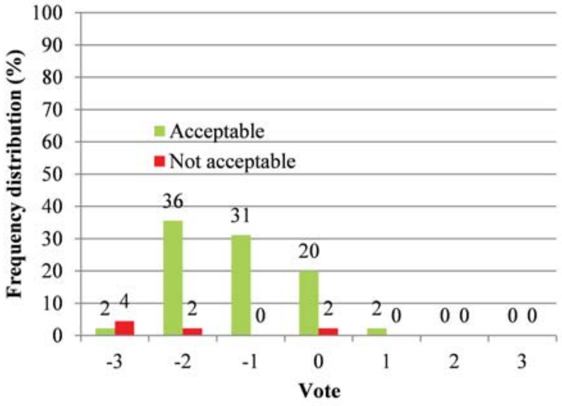


Fig.7:: Plots of thermal acceptability [11].

The occupants' votes were compared to the thermal preference where three particular indices were considered, including the thermal preference index, moisture preference, and air movement preference. Figure 7 shows the correlation between the thermal vote and the thermal acceptability. Most occupants of 87% accepted thermal condition and expressed their vote range from -2 to 0 (rather cold). Therefore, the Actual Percentage of Dissatisfied (APD) was only 9%, indicating the occupants who felt that the environment was unacceptable. In addition, most occupants of 98% did not have perspiration, suggesting that they feel comfortable. In questionnaires part 4, the occupants were asked for their decision on thermal comfort that voted into 7-scale, ranged from -3 unsatisfied to 3 very satisfied, summarized as contour plot in Figure 8. According to the ASHRAE handbook, A Predictive Percentage Dissatisfied (PPD) of 10% corresponds to the PMV range of ±0.5. Although PMV equal to 0, about 5% of the people would be dissatisfied [1].

The PMV values was compared against those AMV values given by an actual group of occupants Therefore, the real-time monitoring from the distributed sensors network can guide the occupants' thermal perception and sensation. The comparison between the PMV-PPD based on measurement and the actual mean vote (7-point scale) are summarized in Table 2. It has found that the AMV values were corresponding to those provided by Fanger Model in most of the locations.

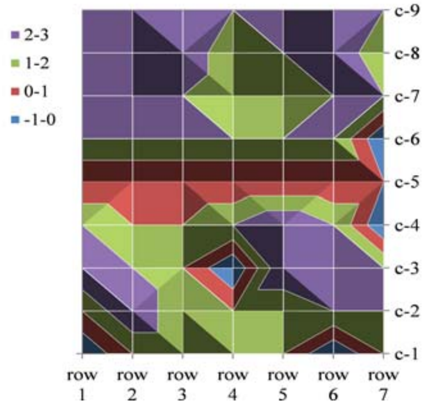


Fig.8:: Contour Plot of the thermal comfort perception. (actual mean vote) of the occupants based on 7-point scale (-1 rather unsatisfied to 3 very satisfied) [11].

Table 2:: Comparison of AMV and PMV at each location of the experimental classroom [11]

Row	Location	LHS1 (c-2)			LHS2 (c-4)		
		AMV	PMV	PPD	AMV	PMV	PPD
3	Front	1	0.0	5.1	1	0.1	5.1
5	Middle	1	-0.9	20.5	3	0.5	11.2
7	Back	2	0.1	5.5	-1	-0.7	16.4
Row	Location	RHS1 (c-6)			RHS2 (c-8)		
		AMV	PMV	PPD	AMV	PMV	PPD
3	Front	2	0.1	5.3	3	0.0	5.3
5	Middle	2	0.2	5.5	2	0.1	5.2
7	Back	-1	-0.8	18.6	1	-0.3	8.1

Note: LHS=Left Hand Side, RHS=Right Hand Side, the numbers 0, 2, 4, 6, 8 are column of 2, 4, 6, 8 of seats.

1.3 Portable Thermal Comfort Measurement

The research results on PMV modeling and distributed sensors network successfully conducted as summarized in part 1.1 and 1.2 lead to the development of the portable thermal comfort measuring device. The portable PMV calculator could indicate the thermal comfort scale through the use of Raspberry Pi Microcontroller equipped with humid and temperature sensors. The proposed device depicts a real-time PMV values in which the operator could conduct distribute thermal comfort monitoring in the target building. The developed device is cost-effective with easy-to-use through a touch screen Graphic User Interface (GUI). The block diagram of proposed system is shown in Figure 9. There are five inputs, including temperature, humidity, clothing insulation, radiant temperature, and air velocity.

The microcontroller is a Raspberry PI as major factors are considered as follows; (i) Temperature, (ii)

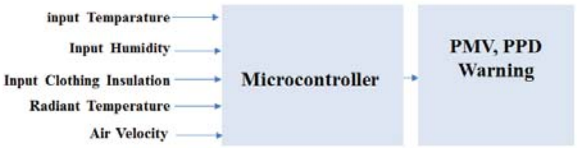


Fig.9:: Block diagram of the portable thermal comfort measuring device [13].

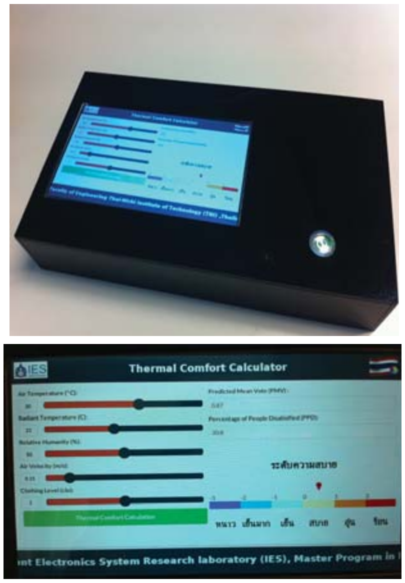


Fig.10:: The complete design of the stand-alone PMV calculation device [13].

Humidity, (iii) Mean radiant temperature, (iv) Air movement, and (v) Clothing. The PMV Equation is given by Equation (2). The specification of Raspberry PI are as follows; Broadcom BCM2837 chipset running at 1.2 GHz, 64-bit quad-core ARM Cortex-A53, A 1.2GHz 64-bit quad-core ARMv8 CPU, Dual core Video core IV®Multimedia co-processor, 802.11 b/g/n Wireless LAN, Bluetooth 4.1, Bluetooth Low Energy (BLE), 4 USB ports, 40 GPIO pins, Full HDMI port, Ethernet port, Combined 3.5mm audio jack and composite video, Camera interface (CSI), Display interface (DSI), Micro SD card slot (now push-pull rather than push-push), and VideoCore IV 3D graphics core. Figure 10 shows the complete design of the stand-alone PMV calculation device. The screen shows PMV and PPD values based on the input 5 parameters as mentioned beforehand.

The resulting PMV and PPD calculated by this portable thermal comfort calculator are comparable to those of a web-based PMV calculation system [14]. The benefit of this semi-computer equipment is its practically, durability, easily touch screen, only one on/off button, and could be distributed in the space. It is expected to connect this equipment to the adaptive control system of the air-conditioning system.

1.4 Conclusion

The academic buildings in big cities or urban areas normally required air-conditioning system which consumed much portion of electricity. Therefore, this paper propose tool for assisting energy reduction by adjusting indoor air condition; temperature and air movement in consideration of Thermal Comfort based on index suggested by the ASHRAE thermal sensation scale standard. The portable PMV and PPD calculator using microcontroller is a Raspberry PI could be connected to distributed sensors network. In addition, the ANN and NARX model would be easily programmed into the Raspberry PI and sense feedback control signal to electronic control unit of air-conditioner to adjust temperature and air movement according to the thermal comfort of occupants automatically.

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