A Computer-Aided Modeling and Measurement System for Environmental Thermal Comfort Sensing

Qingyuan Zhu, Jian Yi, Shiyue Sheng, Chenglu Wen, Member, IEEE, and Huosheng Hu, Senior Member, IEEE

Abstract—Predicted mean vote (PMV) is a well-known thermal comfort index with four environmental variables (air temperature, relative humidity, air velocity, and average radiation temperature) and two human factors (metabolic rate and clothing thermal resistance). This paper presents a novel computer-aided thermal comfort measurement system with PMV, which combined the advanced sensors with the virtual instrument technology. The system software is developed using the LabVIEW platform. The measured data can be transmitted to the server-computer in a data center and displayed on a web page through the Internet. The impact of the measurement error of each environmental variable on PMV is analyzed via MATLAB. The system tests were conducted under the certain environmental conditions and Monte Carlo method is deployed to analyze the PMV measurement uncertainty. The experimental results show the feasibility and effectiveness of the proposed system, and confirm that the measurement uncertainty of PMV is not a constant, and varies with the environment changes.

Index Terms—Computer-aided measurement system, Monte Carlo method (MCM), predicted mean vote (PMV), thermal comfort, uncertainty.

I. INTRODUCTION

THERMAL comfort is a subjective evaluation that expresses satisfaction with the thermal environment. At present, thermal comfort is usually calculated according to different standards, including ANSI/ASHRAE Standard 55 [1], EN 1525 [2], and ISO 7730 standard [3]. Different standards use different thermal comfort indexes. For example, ISO 7730 standard employs predicted mean vote (PMV) and predicted percentage dissatisfaction. In contrast, ANSI/ASHRAE Standard 55 employs thermal sensation scale. Among these indicators, the PMV index is a well-known and widely used example, and it has been applied for almost 40 years throughout different building types. It includes all the major variables influencing thermal sensation and gives more objective evaluations. It can quantitatively evaluate the thermal sensation, and adopt a range of sensation levels, numbered from −3 (cold) to 3 (hot) for quantization [4]–[8].


Currently, many smart sensing and wireless sensor networks have been widely deployed in environmental monitoring systems [12]. Wai and Wai [13], [14] used a distributed sensor network to conduct real-time PMV measurements in an office environment. Wang et al. [15] established an environmental monitoring system based on virtual instrument technology and proposed a forecasting control method for the regulation and control of a greenhouse environment. Tse et al. [16] developed a real-time measurement system for thermal comfort using an open networking technology. Through an embedded subsystem within an existing thermal comfort detection system, data is collected and calculated, resulting in limited data storage. When a large amount of data is collected, data loss is likely to occur. Most measuring instruments have only data acquisition and display functions; the capacity to analyze data is weak.

Although the calculation of the PMV model is widely conducted for analyzing its influencing factors, it is still not widely used in thermal comfort measurement applications. This paper aims to analyze the features of the PMV model and propose an integrated measurement system for indoor environmental thermal comfort assessment based on virtual instrument technology. To extract historical data for further analysis and predict the future state of the environment, a database management subsystem is established to effectively manage data inspection. A subsystem of remote data transmission and accession is designed to view the measured data remotely through the Internet. Then, the measuring error of each environment variable affects the PMV system accuracy, which is analyzed under typical conditions. With the use of the Monte Carlo method (MCM), the PMV measurement uncertainty is analyzed. It was found that the measurement uncertainty of PMV is not a constant and varies with the environment changes.
The rest of this paper is organized as follows. Section II introduces the calculation theory of PMV. Section III describes the system design, including system framework, hardware configuration, and the modular software design that offers flexibility and good scalability during the system operation. Experimental results and a discussion are given in Section IV to show the performance of the proposed system, including the analysis of measurement uncertainty. Finally, a brief conclusion and future work are given in Section V.

II. CALCULATION THEORY OF PMV

The PMV index is a prediction index that can be used to predict thermal comfort by a PMV-based thermal comfort model. The index integrates four environmental variables [air temperature, relative humidity (RH), air velocity, and average radiation temperature] and two human factors (metabolic rate and clothing thermal resistance). Its mathematical expression is expressed by the following equation [3], [9], [17]:

\[
PMV = [0.303e^{-0.036M} + 0.0275] \\
\times [M - W - 3.05(5.733 - 0.007(M - W) - P_a)] \\
- 0.42(M - W - 58.15) - 1.73 \times 10^{-2}M \\
\times (5.867 - P_a) - 0.0014M \\
\times [34 - t_a - 3.96 \times 10^{-8} \times f_{cl}[(t_{cl} + 273)^4] \\
- (t_r + 273)^4 | - f_{cl}h_c(t_{cl} - t_a)] \tag{1}
\]

where \( M \) is the metabolic rate (W/m²), \( W \) is the effective mechanical power (W/m²), \( P_a \) is water vapor partial pressure (KPa), \( f_{cl} \) is the clothing surface area factor, \( t_{cl} \) is the clothing surface temperature (°C), \( t_r \) is the mean radiant temperature (°C), \( I_c \) is the clothing insulation (m² K/W), \( t_a \) is the air temperature (°C), and \( h_c \) is the convective heat transfer coefficient [W/(m² K)].

In (1), the water vapor partial pressure, \( P_a \), and the effective mechanical power, \( W \), are calculated by

\[
P_a = RH \times \exp[16.6536 - 4030.183/(t_a + 235)] \tag{2}
\]

\[
W = \eta M \tag{3}
\]

where RH is measured in % and \( \eta \) is the effective utilization coefficient of the mechanical work. The clothing surface area factor, \( f_{cl} \), is determined as follows:

\[
f_{cl} = \begin{cases} 
1.00 + 1.290I_c, & \text{if } I_c \leq 0.078 \text{ m}^2 \cdot \text{K/W} \\
1.05 + 0.645I_c, & \text{if } I_c > 0.078 \text{ m}^2 \cdot \text{K/W}. \end{cases} \tag{4}
\]

The clothing surface temperature, \( t_{cl} \), is calculated by

\[
t_{cl} = 35.7 - 0.028(M - W) - I_c[3.96 \times 10^8 f_{cl}] \\
\times [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl}h_c(t_{cl} - t_a). \tag{5}
\]

The convective heat transfer coefficient, \( h_c \), is determined as follows:

\[
h_c = \begin{cases} 
2.38(t_{cl} - t_a)^{0.25}, & \text{if } 2.38(t_{cl} - t_a)^{0.25} > 12.1v_a^{0.5} \\
12.1v_a^{0.5}, & \text{if } 2.38(t_{cl} - t_a)^{0.25} < 12.1v_a^{0.5}. \end{cases} \tag{6}
\]

where \( v_a \) is the air velocity (m/s).

The environment variables, \( t_a, t_r, v_a, \) and RH, are obtained by the proposed measurement system. The parameters, \( M, I_c, \) and \( \eta \), are constants obtained from [3, Tables B.1 and C.1]. Then, PMV is calculated in an iterative process. The PMV index establishes a quantitative expression about the rate of body heat storage and the thermal sensation. The quantitative expression represents the sensation of the majority of the population under a same environment.

III. SYSTEM DESIGN

A. System Framework

Fig. 1 shows the whole system, which consists of the PMV portable mobile measurement, remote data transmission, and accessing subsystems. First, the measurements of air temperature, RH, air velocity, and black globe temperature are converted into a standard voltage or current signal through signal conditioning and then sent into the integrated acquisition instrument. The integrated acquisition instrument wirelessly transmits the analog signal to the computer-aided PMV measurement system software for data acquisition, PMV calculation, and further analysis.

Moreover, the data transmission subsystem transmits the measured data to the server-computer from a monitoring computer through the Internet. Then, a web page sited in a server-computer is developed using PHP in order to display the measured data. Client computers can visit the web page and access data remotely over the Internet.

B. Hardware Configuration

The thermal comfort measurement system hardware mainly consists of an acquisition instrument and a computer. The acquisition instrument is divided into two layers: 1) the upper layer consisting of the sensors and signal conditioning modules and 2) the lower layer consisting of the data acquisition modules and power supply. The computer functions as the monitoring terminal. This configuration can reduce the temperature change caused by the heating of electronics and the data acquisition module. Fig. 2 shows the physical hardware configuration of our system.

To measure the indoor air temperature and RH, the temperature and humidity sensor is deployed, whose sensitivity is 12 °C/V and 20%/V, respectively. Its power supply is 24 V dc and its output signal is in the range of 0–5 V. Similarly, an air velocity sensor module is used to measure the indoor air velocity, which has a 24 V dc voltage supply, an output voltage signal of 0–10 V, and the sensitivity of 0.5 (m/s)/V.

Radiant temperature is related to the amount of radiant heat transferred from a surface. It depends on the material’s ability to absorb or emit heat, namely emissivity. The mean radiant temperature experienced by a person in a room with sunlight streaming in is based on how much of his or her body is under the sunlight. Thus, the mean radiant temperature can be replaced with the black globe temperature [17]. The black ball temperature sensor consists of a black ball and an integrated temperature transmitter, and the sensor probe is located in the center of the black ball. The sensitivity of the black ball is 15 °C/V with a 24 V dc voltage supply and a module output voltage signal of 1–5 V.
Fig. 1. System framework of the proposed system. The architecture consists of three main parts such as PMV portable mobile measurement, remote data transmission, and accessing system.

Fig. 2. Hardware configuration of the PMV portable mobile measurement subsystem. A wireless measurement suite with 32 analog input channels is used to transmit the collected data to the computer via Wi-Fi. The input analog signals are enhanced by a shared programmable instrumentation amplifier and then fed into an A/D converter. The whole system shares a common-mode voltage and a common-mode noise rejection capability so that the quality of the measurement can be effectively improved.

Table I presents the details of the sensors and data acquisition device discussed above.

C. Software Design

The computer-aided PMV measurement system software is developed using LabVIEW, which has a parameter setting
module, a thermal comfort module, an air quality module, a residential properties module, an emergency stopping module, a historical data querying module, and a system setting module. Fig. 3 shows its main program flowchart.

By means of a parameter setting module, the user can input: 1) the test location, construction parameters (e.g., area, number of windows/doors, occupancy, and so forth), and measurement starting and ending times and 2) the PMV parameter selection and setting.

In the thermal comfort module, the following curves are shown in the measurement interface in real time: 1) air temperature; 2) RH; 3) indoor air velocity; 4) black ball temperature; and 5) PMV. The highest, average, and lowest values of each curve in the interface are updated at a fixed interval. If the testing data exceeds the upper or lower limits set by the user, the system will give an alarm.

If an emergency occurs, the emergency stopping module will halt the measurement and return to the main interface. In addition, this program measures not only PMV, but also the air quality and residential properties as demanded.

D. Remote Data Transmission

In this system, data transmission between the monitoring terminal and the server-computer is realized based on the Internet. The network communication is realized via the Socket interface, as well as the application programming interface (API) and the Internet protocol suite (TCP/IP protocol suite). In our system, a LabVIEW function based on PHP language calls the API of Windows Sockets to achieve network communication. The underlying network protocol and operating system function is used by Windows Sockets for actual communications.

On the server-side, we developed the web page for data receiving using PHP language. The measured data is received through the socket communication interface. The mobile terminal or other client-computers can remotely view and monitor the field measured PMV data by accessing the system web page.

Fig. 4 shows the program flowchart for remote data transmission. The data acquiring program on the server-side is the web application developed using PHP language. This program binds the IP address and the port number through a bind function and then monitors the port if there is a connection request by activating the listen function. The LabVIEW-based measurement system software simplifies the communication with the Internet via the optimization and management of TCP/IP. The field measurement data can be broadcasted to the remote terminal through the computer network without complex underlying TCP programming. In this paper, a TCP node module is used to establish a connection to the Socket interface on the server-side and send data packets by an IP address and server port number.

IV. EXPERIMENTS AND DISCUSSION

A. PMV Calculation Process Verification

To verify the correctness of the PMV values calculated by (1) in our system, we chose six groups of input variables
from [3, Table D.1] to calculate the PMV values by our system. The differences between the example output from [3, Table D.1] and the outputs from our system are shown in Table II. It is clear that the difference in the PMV values is small, i.e., varying between 0 and 0.01 for all six groups of data. The results verify the effectiveness of the PMV calculation in our system.

### TABLE II
**RESULTS FOR THE SIX SETS OF TESTING INPUTS TO THE NEW SENSING SYSTEM**

<table>
<thead>
<tr>
<th>Set no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>22.0</td>
<td>27.0</td>
<td>27.0</td>
<td>23.5</td>
<td>23.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Black globe temperature (°C)</td>
<td>22.0</td>
<td>27.0</td>
<td>27.0</td>
<td>25.5</td>
<td>21.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>0.10</td>
<td>0.10</td>
<td>0.30</td>
<td>0.10</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Metabolic rate (net)</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Clothing thermal resistance</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Outputs of our system</td>
<td>-0.76</td>
<td>0.76</td>
<td>0.43</td>
<td>-0.02</td>
<td>0.05</td>
<td>-0.17</td>
</tr>
<tr>
<td>Example outputs of ISO 7730 standard</td>
<td>-0.75</td>
<td>0.77</td>
<td>0.44</td>
<td>-0.01</td>
<td>0.05</td>
<td>-0.16</td>
</tr>
<tr>
<td>Difference</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

2) The change of \( t_a \) in rows 3, 5, 6, and 7, as well as the change of \( v_a \) in rows 3, 11, 12, and 13 results in the change of the values of \( \partial \text{PMV}/\partial t_a \), \( \partial \text{PMV}/\partial t_r \), and \( \partial \text{PMV}/\partial v_a \).

3) The changes of RH in rows 8, 9, and 10 affect the calculation of \( \partial \text{PMV}/\partial t_a \).

The measurement error of the four environmental variables primarily comes from the sensor error and the quantization error of the A/D signal conversion. As shown in (8), \( \Delta T \) is the measurement error of the environmental variable; \( \Delta T_1 \) is the sensor error; \( n \) is the conversion resolution of A/D [18]. In our system, \( n = 16 \), resulting in \( \Delta T \approx \Delta T_1 \). Thus, the quantization error of the A/D signal conversion is ignored in the following analysis:

\[
\Delta T = (1 + \Delta T_1)(1 + 1/2^{(n+1)}) - 1. \quad (8)
\]

The errors for each of the four variables in our system \((t_a, t_r, \text{RH}, v_a)\) are \( \Delta t_a = \pm 0.3 \, ^\circ\text{C}, \Delta t_r = \pm 0.12 \, ^\circ\text{C}, \Delta \text{RH} = \pm 3\% \), and \( \Delta v_a = \pm 0.04 \, \text{m/s} \), respectively. As shown in Fig. 5, \( \text{PMV} \) decreased linearly from 0.235 to 0.135 as air temperature \((t_a)\) increased from 19 °C to 32 °C, respectively. As shown in Fig. 6, \( \text{PMV} \) increased linearly from 0.184 to 0.202 as the RH increased from 0% to 100%, respectively.

Fig. 7 shows that \( \Delta \text{PMV} \) remains at \( \sim 0.1 \) as the air velocity increases from zero to \(< 0.08 \, \text{m/s} \). At an air velocity equal to 0.08 m/s, \( \Delta \text{PMV} \) dramatically increases to 0.208.

As the air velocity increases from 0.08 to 0.4 m/s, \( \Delta \text{PMV} \) decreases and asymptotically approaches 0.15. It is clear that \( \Delta \text{PMV} \) is affected by the air velocity in the range from 0.08 to 0.4 m/s.

2) **Measurement Errors Influence \( \Delta \text{PMV} \)**: Different values of \( \Delta \text{PMV} \) with different measurement errors in the environmental variables are shown in Table IV.

In the first row of Table IV, the measurement errors in the environment variables are the required errors as listed in [17, Table 2], and a \( \Delta \text{PMV} \) of 0.15 is calculated. In the second row, the measurement errors of the environment variables are about the sensors used in our system. \( \Delta \text{PMV} \) in these two rows are close.

In each of the next four rows, three of the four measurement errors are set to zero, and the other measurement error is calculated under the condition that \( \Delta \text{PMV} = 0.15 \). Because the measurement error is always greater than zero, these four rows of data indicate the minimum requirement of the measurement errors for the four environmental sensors when \( \Delta \text{PMV} \) asymptotically approaches 0.15. Following the principle of equal precision, the last row of data indicates the requirement for the measurement errors of the four environmental sensors when \( \Delta \text{PMV} \) asymptotically approaches 0.15.

### C. System Test in an Indoor Environment

Before starting a measurement, a static calibration for each sensor was carried out so that the displayed value of each sensor is matched to the value measured by the precise instrument under the same condition. Then, the proposed

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TABLE III
RESULTS OF PARTIAL DERIVATIVE OF PMV TO EACH ENVIRONMENTAL VARIABLE FOR 13 TYPICAL GROUPS OF ENVIRONMENTAL VARIABLE VALUES IN THE CONDITION OF $M = 58.15 \text{ W/m}^2$ AND $I_{cl} = 1 \text{ clo}$

<table>
<thead>
<tr>
<th>Row no.</th>
<th>$t_a$(°C)</th>
<th>$t_r$(°C)</th>
<th>RH(%)</th>
<th>$v_a$(m/s)</th>
<th>$\frac{\partial \text{PMV}}{\partial t_a}$</th>
<th>$\frac{\partial \text{PMV}}{\partial t_r}$</th>
<th>$\frac{\partial \text{PMV}}{\partial \text{RH}}$</th>
<th>$\frac{\partial \text{PMV}}{\partial v_a}$</th>
<th>PMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>24</td>
<td>50</td>
<td>0.10</td>
<td>0.162</td>
<td>0.138</td>
<td>0.615</td>
<td>0</td>
<td>-0.39</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>24</td>
<td>50</td>
<td>0.10</td>
<td>0.143</td>
<td>0.126</td>
<td>0.700</td>
<td>-3.249</td>
<td>-0.10</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>24</td>
<td>50</td>
<td>0.10</td>
<td>0.145</td>
<td>0.126</td>
<td>0.785</td>
<td>-2.404</td>
<td>0.19</td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>24</td>
<td>50</td>
<td>0.10</td>
<td>0.147</td>
<td>0.126</td>
<td>0.785</td>
<td>-1.561</td>
<td>0.48</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>20</td>
<td>50</td>
<td>0.10</td>
<td>0.146</td>
<td>0.122</td>
<td>0.785</td>
<td>-1.721</td>
<td>-0.31</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>22</td>
<td>50</td>
<td>0.10</td>
<td>0.145</td>
<td>0.124</td>
<td>0.785</td>
<td>-2.060</td>
<td>-0.06</td>
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<tr>
<td>7</td>
<td>24</td>
<td>26</td>
<td>50</td>
<td>0.10</td>
<td>0.145</td>
<td>0.128</td>
<td>0.785</td>
<td>-2.752</td>
<td>0.44</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>24</td>
<td>45</td>
<td>0.10</td>
<td>0.143</td>
<td>0.126</td>
<td>0.785</td>
<td>-2.404</td>
<td>0.15</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>24</td>
<td>55</td>
<td>0.10</td>
<td>0.148</td>
<td>0.126</td>
<td>0.785</td>
<td>-2.404</td>
<td>0.23</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>24</td>
<td>60</td>
<td>0.10</td>
<td>0.150</td>
<td>0.126</td>
<td>0.785</td>
<td>-2.404</td>
<td>0.27</td>
</tr>
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<td>11</td>
<td>24</td>
<td>24</td>
<td>50</td>
<td>0.05</td>
<td>0.155</td>
<td>0.141</td>
<td>0.785</td>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>12</td>
<td>24</td>
<td>24</td>
<td>50</td>
<td>0.15</td>
<td>0.163</td>
<td>0.119</td>
<td>0.785</td>
<td>-1.740</td>
<td>0.09</td>
</tr>
<tr>
<td>13</td>
<td>24</td>
<td>24</td>
<td>50</td>
<td>0.20</td>
<td>0.177</td>
<td>0.113</td>
<td>0.785</td>
<td>-1.368</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig. 5. Curve of the relationship between system error of PMV and air temperature in the condition of $t_r = t_a$, RH = 50%, $v_a = 0.1 \text{ m/s}$, $M = 58.15 \text{ W/m}^2$, and $I_{cl} = 1 \text{ clo}$.

Fig. 6. Curve of the relationship between system error of PMV and RH in the condition of $t_r = t_a = 24$ °C, $v_a = 0.1 \text{ m/s}$, $M = 58.15 \text{ W/m}^2$, and $I_{cl} = 1 \text{ clo}$.

Fig. 7. Curve of the relationship between system error of PMV and air velocity in the condition of $t_r = t_a = 24$ °C, RH = 50%, $M = 58.15 \text{ W/m}^2$, and $I_{cl} = 1 \text{ clo}$.

The PMV-related measurement parameters were:
1) The PMV sampling rate of one point per second;
2) the activity of sit in and typical indoor clothing.
3) The clothing insulation is $I_{cl} = 1 \text{ clo}$.
4) The clothing surface area factor is $f_{cl} = 1.15$ by calculation.

Under the above conditions, 72 points of data were obtained. The four environmental variables, the calculated PMV, and their distribution histograms are shown in Fig. 8.

D. Measurement Uncertainty Analyzing of PMV Using MCM

Guide to the expression of Uncertainty in Measurement uncertainty framework is a common method used to evaluate the measurement uncertainty in linear systems. It requires approximation at each processing stage when the model is accurate enough.
TABLE IV
RESULTS OF SYSTEM ERROR OF PMV WITH DIFFERENT MEASUREMENT ERROR OF EACH ENVIRONMENT VARIABLE IN THE
CONDITION OF $t_a = 24$ °C, $t_r = 24$ °C, RH = 50%, $v_a = 0.1$ m/s, $M = 58.15$ W/m², AND $I_{cl} = 1$ CLO

<table>
<thead>
<tr>
<th>Row no.</th>
<th>$\Delta t_a$(°C)</th>
<th>$\Delta t_r$(°C)</th>
<th>$\Delta$RH(%)</th>
<th>$\Delta v_a$(m/s)</th>
<th>$\Delta \frac{PMV}{t_a}$</th>
<th>$\Delta \frac{PMV}{t_r}$</th>
<th>$\Delta \frac{PMV}{\Delta$RH$}$</th>
<th>$\Delta \frac{PMV}{\Delta v_a}$</th>
<th>$\Delta$PMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>±0.3</td>
<td>±0.3</td>
<td>±3</td>
<td>±0.02</td>
<td>±0.04</td>
<td>±0.04</td>
<td>±0.02</td>
<td>±0.05</td>
<td>±0.15</td>
</tr>
<tr>
<td>2</td>
<td>±0.3</td>
<td>±0.12</td>
<td>±3</td>
<td>±0.04</td>
<td>±0.06</td>
<td>±0.02</td>
<td>±0.02</td>
<td>±0.1</td>
<td>±0.19</td>
</tr>
<tr>
<td>3</td>
<td>±1.03</td>
<td>0</td>
<td>0</td>
<td>±0.15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>±0.15</td>
<td>±0.15</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>±1.19</td>
<td>0</td>
<td>0</td>
<td>±0.15</td>
<td>0</td>
<td>0</td>
<td>±0.15</td>
<td>±0.15</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>±19.11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>±0.15</td>
<td>0</td>
<td>±0.15</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>±0.06</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>±0.15</td>
<td>±0.15</td>
</tr>
<tr>
<td>7</td>
<td>±0.2575</td>
<td>±0.2975</td>
<td>±4.7775</td>
<td>±0.015</td>
<td>±0.0375</td>
<td>±0.0375</td>
<td>±0.0375</td>
<td>±0.0375</td>
<td>±0.15</td>
</tr>
</tbody>
</table>

Fig. 8. Four environmental variables obtained from an indoor test and the values of PMV calculated by our system. (a) Air temperature. (b) RH. (c) Air velocity. (d) Black globe temperature. (e) PMV.

nonlinear. As a result, the validity of the results may be unreliable. However, in this situation, MCM can generally be expected to give valid results, since it does not make approximation assumptions [19]. Thus, MCM is deployed in this paper to calculate the uncertainty of PMV that has a nonlinear model. Fig. 9 shows its detailed calculation process.

MCM is a numerical method used to assess the measurement uncertainty, which can simulate the spread of uncertainty by repeated sampling [20]. Its application needs to establish probability models as inputs, and then requires the simulating calculation to determine a discrete expression of the output.

\[
\Delta_i = x_i - \bar{x} 
\]
\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \Delta_i^2} 
\]

Finally, the characteristics of the output are estimated by analyzing the discrete expression.

According to the shape of the distribution histograms in Fig. 8, we assumed that the four PMV inputs are the normal distribution and their standard deviations equal their combined standard uncertainties, respectively. To simplify the uncertainty model, the combined standard uncertainty only includes the uncertainties caused by measurement repeatability and the sensor inaccuracy.

The uncertainty caused by the measurement repeatability ($u_1$) belongs to type A uncertainty, which is obtained by

\[
\Delta_i = x_i - \bar{x} 
\]
\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \Delta_i^2} 
\]

\[
u_1 = \frac{\sigma}{\sqrt{n}}. 
\]

Fig. 9. Detailed calculation process of MCM.
In the precision measurement, the width of the confidence interval is usually set at $3\sigma$. Thus, the uncertainties caused by the measurement accuracy of sensors ($u_2$) belong to type B uncertainty, which equals one third of the accuracy values given by their specifications, respectively.

Both of the uncertainty components are independent; therefore, the combined standard uncertainty is obtained by the following equation [21]:

$$u_c = \sqrt{u_1^2 + u_2^2}. \tag{12}$$

Table V presents the three kinds of uncertainties and the assumed distributions for the four environment variables. As can be seen, four groups of random numbers were generated to function as the measurement errors of the four environmental variables.

MCM requires a large number of sample data to estimate the characteristics of the output. As long as the sample sizes are large enough, the estimated result is accurate enough. In order to choose a reasonable sample size, the PMV measurement uncertainty is calculated with the same input when $M = 1000, 2000$, and $5000$, respectively. Here, the input denotes the average values of the four environmental variables, expressed as $\bar{t}_a, \bar{R}_H, \bar{v}_a, \bar{t}_r$, respectively.

Table VI shows the results that are calculated when the input equals the average values ($\bar{t}_a = 27.55^\circ C, \bar{R}_H = 63.3\%, \bar{v}_a = 0.057 \text{ m/s}, \text{ and } \bar{t}_r = 29.84^\circ C$) of the 72 points shown in Fig. 8; then, $M \geq 2000$, and the PMV measurement uncertainty is almost invariable. Therefore, to save computation time, the sample size is set at 2000 in subsequent calculations.

Fig. 10 shows the distribution histogram of the output of MCM under the conditions that $\bar{t}_a = 27.55^\circ C, \bar{R}_H = 63.3\%, \bar{v}_a = 0.057 \text{ m/s}, \text{ and } \bar{t}_r = 29.84^\circ C$. MCM is used to computer the PMV values and the average value of PMV is $1.536$ under these conditions. When the coverage probability $P$ is 95%, the coverage factor $k_p$ is 1.96. Hence, the expanded uncertainty is $u_c = k_p * u = 0.035$, and the PMV measuring result is $1.536 \pm 0.035$. Moreover, the PMV values in Fig. 10(a) fall within this range.

Similar to the above process, the PMV measurement uncertainties are calculated under three different environmental conditions and the results shown in Table VII. The PMV measurement uncertainty is not a constant; it changes with the change of environment values.

V. C ONCLUSION

This paper presents a new computer-aided thermal comfort measurement system with PMV, which consists of five modules, namely multiparameter data acquisition, transmission, calculation, display, and data management. The system was tested under specific environmental conditions, and MCM was used to analyze the PMV measurement uncertainty. How the measurement error of each environmental variable affects the PMV values was analyzed by MATLAB, which provides a theoretical basis for selecting the measurement accuracy of sensors. The PMV values calculated by our system are compared with the PMV values obtained from the ISO 7730 standard [3]. The result shows the correctness of our computer programs for PMV calculation. Moreover, the PMV measured...
data can be transmitted to the server-side in a data center, and can be remotely viewed through the Internet.

The main contribution of this paper is in proposing an integrated measurement system for indoor environmental thermal comfort assessment based on virtual instrument technology. The system has two key features: 1) powerful mathematical analysis function for the complex calculation of PMV and 2) the modular software design that offers flexibility and good scalability in system operation. Our future work will focus on the evaluation of the system in the assessment of thermal comfort.

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REFERENCES


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