Findings of Field Survey for Thermal Comfort and Ventilation in US Office Buildings

Liangcai Tan ¹, Samir Moujaes ²,

HDR Inc. University of Nevada Las Vegas

SUMMARY

This paper presents the measured data and field survey results per a new protocol approach proposed in a sister paper to evaluate the thermal comfort and ventilation conditions in office buildings. For the buildings surveyed, the air temperature was found to be very close to the operative temperature, and the variation of air temperature and operative temperature was less than 3°C. The predicted thermal perception values calculated from ASHRAE Standard 55 are normally higher than the thermal perception values obtained from the perception questionnaire while the predicted percentage of dissatisfied per ASHRAE Standard 55 is lower than that obtained from the occupant questionnaire. This indicates that the calculation equation used in ASHRAE Standard 55 may not be applicable to the real office buildings. The same is true for air velocity. Although the mean value of air velocity in all the buildings was found to be less than 0.2 m/s, the calculated draft rates from ASHRAE Standard 55-2004 were surprisingly higher than 20% in spite that the occupant questionnaire survey shows the draft rate less than 15%. No doubt that discrepancy exists between ASHRAE Standard 55 and real office survey results. The ASHRAE Standard 55 is derived from laboratory studies but this research is conducted in actual office buildings. It is likely that the occupants in real office buildings are more tolerant to air movement and participants in a controlled laboratory are more sensitive to air movement. In addition the variations in humidity in all the buildings was found to be substantial with the relative humidity varying from 10% to 60%. The vertical air temperature differences were normally less than 1°C in all the buildings and the vertical temperature between the heights of 0.1 m and 1.1 m above the floor were very small. Therefore it is possible to eliminate two sensors at each thermal comfort station.

Introduction

Building performance characteristics influence energy usage and environmental conditions in indoor environments. Building owners and managers, architects, industry, and regulatory agencies are focusing on design, construction, maintenance, and remediation solutions for buildings and building systems to alleviate indoor environmental quality (IEQ) and other indoor environmental concerns. However, substantial gaps in knowledge remain and there have been scientific/engineering limitations to resolving these issues and concerns. The efficient operation of buildings and occupant satisfaction/productivity are important considerations and the lack of integrated building protocols and normative baseline data to assess the relationships of building performance and energy consumption contributes to problems in solving IEQ and other indoor environmental concerns. Therefore, this research aims to develop protocols for the measurement and verification of integrated building performance and measure selected environmental parameters in selected buildings throughout the United States. Protocols were developed for the measurement in occupied workplace environments of thermal comfort and ventilation, lighting, indoor air quality and sound. Nine office buildings were monitored. Questionnaire evaluations of occupant perception with their indoor workplace environment were developed and conducted in each building and the results correlated with building design and construction characteristics to assist in establishing guidance for building technology and energy issues. This paper only reported the thermal and ventilation part of the research. This is a sister paper to “New Protocol of Field Survey for Thermal
Comfort and Ventilation in Office Buildings” published in RoomVent 2007 Conference (Moujaes et. al., 2007), in which the protocol was described. This paper reports the findings from the measurements and conclusions from statistical analyses.

Results from Measurements and Questionnaire

Table 1 is a listing of parameter names for Table 2. Descriptive statistics of the average thermal comfort and ventilation data for the nine buildings monitored (Building 1 to 9) are listed in Table 2. The distribution of the state points in the psychrometric chart for all the nine buildings is shown in Figure 1. The operative temperature is the most important parameter of thermal comfort. It represents the combination of air temperature and mean radiant temperature. The box plots for operative temperature measurements for the nine buildings are presented Figure 2. These compare all the nine buildings using a five-number summary, the median, the 25th and 75th percentiles, and the minimum and maximum observed values that are not statistical outliers. The heavy black line inside each box marks the 50th percentile (median) of that distribution. The lower and upper hinges (box boundaries) mark the 25th and 75th percentiles of each distribution, respectively. Whiskers appearing above and below the hinges are vertical lines ending horizontally at the largest and smallest observed values that are not statistical outliers. The outliers are identified with an “O” and the label next to “O” refers to the location ID where that observation was found. Extreme values are marked with an asterisk (*). Some groups may have no extreme values in the data.

Table 1. Parameter Names in Statistical Plots, their Meaning, and their Unit Values

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Meaning</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Dry bulb air temperature at 0.6 m above the floor</td>
<td>°C</td>
</tr>
<tr>
<td>Operative Temperature (OpTemp)</td>
<td>Operative Temperature measured at 0.6 m above the floor</td>
<td>°C</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Relative Humidity measured at 0.6 m above the floor</td>
<td>%</td>
</tr>
<tr>
<td>Humidity Ratio</td>
<td>Calculated Humidity Ratio based on temperature and relative humidity</td>
<td>kg water/ kg dry air</td>
</tr>
<tr>
<td>Velocity</td>
<td>Air velocity at 0.6 m above the floor</td>
<td>m/s</td>
</tr>
<tr>
<td>Draft Rate (DR)</td>
<td>Maximum draft rate among the draft rates in three heights, i.e. 0.1 m, 0.6 m and 1.1 m above the floor.</td>
<td>%</td>
</tr>
<tr>
<td>PMV</td>
<td>Predicted Mean Vote</td>
<td></td>
</tr>
<tr>
<td>PPD</td>
<td>Predicted Percentage of Dissatisfied</td>
<td>%</td>
</tr>
<tr>
<td>Vertical Air Temperature Difference</td>
<td>Vertical Air Temperature Difference between the air temperatures at 1.1 m and 0.1 m above the floor.</td>
<td>°C</td>
</tr>
<tr>
<td>Indoor to Outdoor CO₂ Differential Concentration</td>
<td>Indoor to Outdoor CO₂ Differential Concentration</td>
<td>ppm</td>
</tr>
</tbody>
</table>

Table 2. Descriptive Statistics for Thermal Comfort and Ventilation Field Measurements for All Nine Buildings.
<table>
<thead>
<tr>
<th>Comfort Range</th>
<th>Mean</th>
<th>95% Confidence Interval for Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Set Point</th>
<th>Perception Questionnaire Results (N = 302)</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-28 for cool weather, 24-28 for warm weather</td>
<td>22.7</td>
<td>22.7-22.8</td>
<td>22.6</td>
<td>0.84</td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
<tr>
<td>&lt;60</td>
<td>0.0067</td>
<td>0.0066-0.0068</td>
<td>0.0071</td>
<td>0.0222</td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
<tr>
<td>&lt;0.25</td>
<td>0.09</td>
<td>0.08-0.09</td>
<td>0.08</td>
<td>0.05</td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
<tr>
<td>&lt;20</td>
<td>24.1</td>
<td>23.1-25.2</td>
<td>21.0</td>
<td>22.0</td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
<tr>
<td>&lt;0.5</td>
<td>-0.10</td>
<td>-0.11-0.09</td>
<td>-0.10</td>
<td>-0.22</td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
<tr>
<td>&lt;10</td>
<td>6.3</td>
<td>6.2-6.4</td>
<td>5.8</td>
<td>1.8</td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
<tr>
<td>&lt;3 (PD&lt;5%)</td>
<td>0.32</td>
<td>0.30-0.34</td>
<td>0.21</td>
<td>0.33</td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
<tr>
<td>&lt;700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td>Comfort (PD = 3.3)</td>
<td>ppm</td>
</tr>
</tbody>
</table>

Note:

1. Draft rate (DR) is a function of local air temperature, mean air speed and turbulence intensity. It represents the predicted percentage of people dissatisfied due to annoyance from drafts. The model used to calculate DR (DR-ASHRAE), based on a known air temperature, mean air speed and turbulence intensity is presented in ASHRAE Standard 55-2004 (ASHRAE, 2004). Based on the occupant perception questionnaire results, the percentage of people dissatisfied due to draft (DR-Survey, either very drafty or very stagnant) can be calculated and compared to the DR-ASHRAE calculated from the model in ASHRAE 2004. The DR-ASHRAE may or may not agree with the DR-Survey because the DR-ASHRAE model was developed from laboratory tests and survey results, but the DR-Survey is derived from field measurements.

2. PMV (Predicted Mean Vote) is an index that predicts the mean value of the votes of a large group of persons on the seven point thermal sensation scale (ASHRAE, 2004). It can be calculated from the known air temperature, mean radiant temperature, humidity, mean air speed, metabolic rate, and clothing insulation based on the ASHRAE model (ASHRAE, 2004). The mean vote (MV) represents the mean value of the votes of the questionnaire participants on the seven point thermal sensation scale. PMV is then compared to MV.

The ASHRAE seven point thermal sensation scale is defined as follows:

- +3 hot
- +2 warm
- +1 slightly warm

N/A
In the perception questionnaire, a five point thermal sensation scale is defined as follows:

1 very cool
2 somewhat or slightly cool
3 neither cool nor warm
4 somewhat or slightly warm
5 very warm

To calculate MV, the five point scale is converted to a seven point scale by using the following equation:
\[ MV = \frac{3X - 9}{2} \]

Where, \( X \) = the mean value of votes based on the five point thermal sensation scale.

3. The predicted percentage of dissatisfied (PPD) occupants is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV (ASHRAE, 2004). The following equation is used to calculate PPD:

\[
PPD = 100 - 95 \exp(-0.03353PMV^4 - 0.2179PMV^2)
\]

The percent dissatisfied (PD) represents percentage of occupants that are dissatisfied due to discomfort, including vertical air temperature difference (either cool in feet or warm on head or face), humid or dry air (either very humid or very dry), and stuffy environment (never or occasionally feel fresh). To verify the correctness of the PPD value, the PD is calculated by the following equation:

\[
PD = 100 - 95 \exp(-0.03353MV^4 - 0.2179MV^2)
\]

Figure 2. The Box Plot of Operative Temperature.

Findings and Conclusions
From the results of measurements and questionnaire, the following conclusions can be made:

1. For all the nine buildings, the air temperature was very close to the operative temperature, which indicates that the mean radiant temperature was close to the air temperature. The variation of air and operative temperatures across all the buildings was less than 3°C (the values are between 21 to 24°C). These values fell within the comfort zone with clothing insulation of 1.0 clo, which is typical of the clothing-worn level when the outdoor environment is cool. Therefore, if the actual clothing-worn level is 0.5 clo, which is typical of clothing-worn level when the outdoor environment is warm, then the occupants will feel cool. The occupants participating in the perception questionnaire in five of the nine buildings felt comfortable while the rest of them reported feeling slightly cool. The general average percentage of dissatisfied (PD) occupants was 17%, which is within the 20% limit defined by ASHRAE 2004. The PD values are higher than 20% in three buildings, and the highest PD value is 26%. Among the people who reported feeling dissatisfied, 80% of them felt very cool. Based on ASHRAE 2004, if the operative temperature is less than 24°C in warm weather or summer, occupants will feel cool. The field measurements and questionnaire results support this statement. In general, the space temperature may be increased to achieve a more comfortable environment in the monitored buildings.

2. The PMV values are normally higher than the MV values obtained from the perception questionnaire except in two buildings (BLDG 3 and BLDG 4). This exception may be caused by the small number of questionnaire participants in those buildings (only 7 and 14 participants, respectively). The lower MV values are interpreted as the occupants tended to feel cool if the design temperature was determined based on the PMV value.

3. The PPD values are all lower than the PD values obtained from the occupant questionnaire. This is interpreted as the ASHRAE thermal comfort standard 55-2004 underestimating the percentage of those dissatisfied.

4. The calculated PD values are normally lower than the PD values obtained from the occupant questionnaire. Therefore, the above equation used in ASHRAE Standard 55-2004 may not be applicable to the occupant questionnaire.

5. The variations in humidity in all the buildings was substantial. The relative humidity varied from 10% to 60%. The occupants in seven out of nine buildings felt comfortable while the occupants in the other two buildings felt slightly dry. In one building (BLDG 2), the average relative humidity was less than 20% and the occupants felt slightly dry. The PD was 13%. However, in another building (BLDG 3), the average relative humidity was 40%, but the subjects who took the occupant questionnaire still felt slightly dry and the PD was 21%, which is very high. This may be caused by the small percentage of occupants in that building who participated in the questionnaire. Only seven people participated, which is the least number of participants in all the buildings tested. It is estimated that more than 200 people work in that building. Otherwise, the occupants were satisfied with the humidity, and the PD values were less than 10% (ranging from 0 to 7%).

6. The mean value of air velocity in all the buildings was less than 0.2 m/s. However the calculated draft rates (DR-ASHRAE values) were all higher than 20%, except in two buildings (BLDG 4 and BLDG 9). This may be due to the high turbulence intensity. The high limit defined by ASHRAE 2004 is 20%. If it is higher than 20%, people will feel a draft. The calculated DR-Survey values are all less than 15%, except in one building (BLDG 1). Therefore, there are discrepancies between DR-ASHRAE and DR-Survey. The DR-ASHRAE values are derived from laboratory studies and the DR-Survey values are collected in actual office buildings. Therefore, it is likely that the occupants in real office buildings are more tolerant to air movement and participants in a controlled laboratory are more sensitive to air movement. DR-Survey values include both the participants who feel the air is very drafty and those who feel the
air is very stagnant. If only the participants who feel the air is very drafty are considered the DR-
Survey will be all less than 10% except that in one building (BLDG 1), further supporting the
statements above.

7. The vertical air temperature differences are normally less than 1°C in all the buildings. Most of
them are actually less than 0.5 °C. Based on ASHRAE Standard 55-2004, the occupants should
feel comfortable if the vertical air temperature difference is less than 3°C and less than 5% of the
occupants will feel discomfort. However the actual PD values due to vertical air temperature
differences were approx. 10%, with the highest value of 19%. Obviously, there is a discrepancy
between ASHRAE Standard 55-2004 and the occupant perception questionnaire PD results due
to vertical air temperature differences. More research is needed to explain this discrepancy.

8. The vertical temperature between the heights of 0.1 m and 1.1 m above the floor were very
small. Therefore, the measurement for the vertical air temperature difference may not be needed.
The sensors used to measure the temperature at 0.1 m and 1.1 m above the floor can also
measure velocity. However as mentioned above, the occupants in real office environments may
not be sensitive to the air movement, especially drafts, so the velocity measurement at these two
heights may also not be necessary. Therefore, it is possible to eliminate two sensors at each
thermal comfort station.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of this work by the U.S. Department of Energy
through the National Center of Energy Management and Building Technologies.

REFERENCES


American Society of Air-Conditioning, Heating and Refrigerating Engineers, Inc.


Olson, C. L. 1974. Comparative Robustness of Six Tests in Multivariate Analysis of Variance. Journal of

SPSS Inc. 2003. SPSS Advanced Models 12.0.


GAO-HEHS-95-61.