Performance Evaluation in Built Environment

Project Report

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ABSTRACT

Environmental conditions within educational spaces significantly impact students' comfort, health, and learning efficiency. This study investigates thermal comfort in educational environments, specifically focusing on Fulbright University Vietnam's (FUV) campus. The research addresses challenges arising from centralized air conditioning systems and the lack of data for benchmarking and analysis, prompting the development of a sensory toolkit by the research team. This toolkit is designed to monitor key factors contributing to thermal comfort, including mean radiant temperature, air temperature, relative humidity, and air velocity, utilizing various sensors and microcontroller units for automated data collection and analysis. Results from monitoring four meeting rooms demonstrate fluctuations in thermal conditions throughout the day, influenced by factors such as room size and air velocity. Integration with survey findings reveals discrepancies between predicted mean vote (PMV) values and occupants' adaptive mean vote (AMV), emphasizing the significance of field measurements over simulation results. Additionally, comparative analysis with ASHRAE standards exposes room-specific thermal comfort levels. However, limitations exist, including the subjectivity of the experimental setup and challenges in data validation. In short, this research provides insights into thermal comfort within FUV's meeting rooms, offering a dataset that could potentially initiate an open dialogue with campus building management to revise the operation of the cooling system. Furthermore, recommendations are made for expanded sensor placement, enhanced data collection methods, and longer-term room inspections for future research, aiming to contribute towards the optimization of thermal comfort in educational environments.

I. INTRODUCTION

Students spend a significant amount of time in educational buildings, schools, or classrooms, making the environmental conditions of these spaces crucial. These conditions not only impact comfort and health but also affect the efficiency of students' learning and work (Azmi, Tharim, & Yusof, 2021). Thermal comfort is a major concern, particularly in humid tropical climates (Al-Horr et al., 2016). While there is a growing body of research on thermal comfort for students from primary schools to universities in warm regions like Southeast Asia, there are still gaps in understanding.

In many primary, secondary, and high schools, students have control over the air conditioning in their classrooms. However, this is not the case for college students, as many universities use centralized air conditioning (CAC) systems. This can lead to issues like sick building syndrome, including symptoms such as a runny nose, dry skin, and flu-like symptoms, particularly in university laboratories (Amin, Akasah, & Razzaly, 2015).

To address these challenges, there is a need for standardized platforms and tools to benchmark and analyze the Heating, Ventilation, and Air Conditioning (HVAC) systems in schools. Such tools would enable students to engage in open dialogues with building managers and owners, easing improvements in thermal comfort.

ASHRAE Standard 55 plays a crucial role in defining thermal environmental conditions for human occupancy. It considers factors such as air temperature, radiant temperature, air speed, and humidity, as well as personal factors like clothing insulation and metabolic rate. Based on the work of P.O. Fanger, the standard uses the Predicted Mean Vote (PMV) model to predict the thermal sensation of occupants. The PMV model calculates a numerical value representing thermal sensation, with positive values indicating warmth and negative values indicating coldness.

Fanger also introduced the Predicted Percentage of Dissatisfied (PPD), which estimates the percentage of occupants likely to be dissatisfied with the thermal environment. ASHRAE 55 uses the PMV model and PPD to establish the thermal comfort zone, ensuring that the majority of occupants are thermally comfortable. Following these guidelines allows designers and engineers to create indoor environments that promote comfort and well-being.

In Vietnam, where this research is based, the Vietnamese thermal sensation scale from the Standard "TCVN 7438:2004 - Ergonomics - Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for the comfort" is used to determine thermal comfort conditions.

The campus of Fulbright University Vietnam (FUV) is located in a rental area of the Crescent Plaza building. Since the university's inception, there have been consistent verbal and official complaints from Fulbright students regarding thermal discomfort in their studying rooms, particularly in small-sized rooms like meeting rooms and self-study rooms such as the computer lab. This has led to an unwritten rule among students to always wear a jacket to school to avoid feeling frozen in the middle of the day.

Two main problems have hindered improvements over the past 5 years. Firstly, the building's CAC system cannot be adjusted for specific rooms within the FUV campus, despite differences in room size. Secondly, there has been no collected dataset for benchmarking and analysis of student's thermal comfort, preventing an open dialogue with the building's managers to modify the HVAC system and protect student's health.

To investigate thermal comfort in FUV's learning environments, the research team developed a sensory toolkit to assess thermal comfort in student learning areas. This toolkit aims to automatically monitor four key factors contributing to thermal comfort within closed rooms: mean radiant temperature, air temperature, relative humidity, and air velocity. Analysis of the collected data will be juxtaposed against simulation results, standards, and user satisfaction to provide a comprehensive overview of the HVAC system's impact on room thermal comfort, potentially generating ideas for improvement if necessary.

II. METHODOLOGY

1. Components

- BME680 Sensor: to measure Relative Humidity, Air Temperature, and Air Pressure.

- Tenmars TM-288 Heat Stress WBGT Meter: to measure Average radiation Temperature, with updates provided periodically every 20 seconds.

- UNI-T UT363BT Digital Anemometer: measure Air Velocity, with a measuring resolution of 0.4m/s.

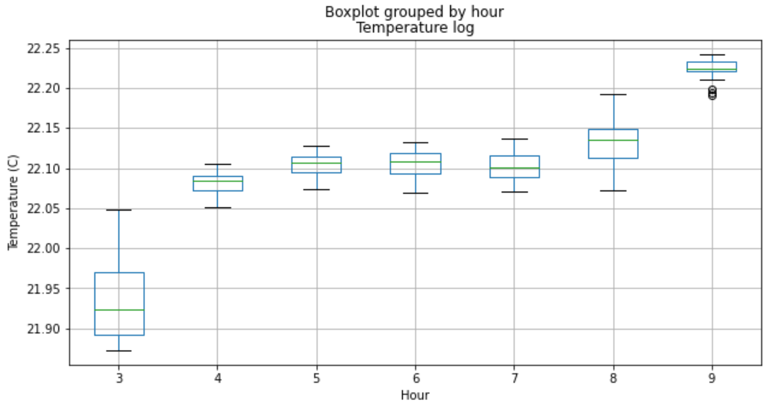
- ESP32: Microcontroller Unit (MCU).

- Raspberry Pi 4 Model B: Data Storage and Analysis purposes.

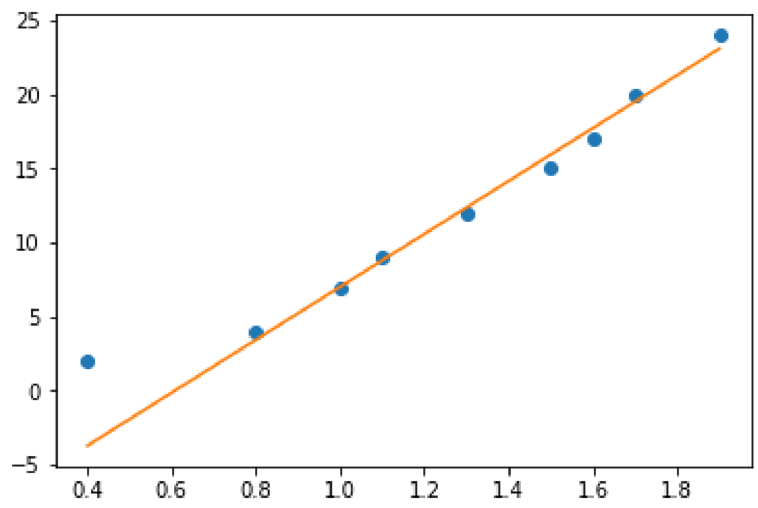
2. Equipment Modifications and Calibration

To enable automated data collection, modifications are made to access the sensors within the WBGT meter and digital anemometer for direct data logging into the MCU.

- WGBT Meter: Raw analog data from GPIO pins of the sensors is calibrated following reference data displayed on the monitor. A linear regression is then applied to establish the correlation between raw data and standard data. Additionally, the data uncertainty is assessed, and an algorithm is developed to automatically remove noise from the data in real-time.



1.a. Uncertainty analysis of WBGT



1.b. Linear function of WBGT

Figure 1. Uncertainty analysis of the calibration for WGBT meter's sensor

- Digital Anemometer: The device is designed to power off after 5 minutes of reading new data. Modifications are made using the MCU to trigger the anemometer when it detects that the device is powered off.

3. Hardware Setup

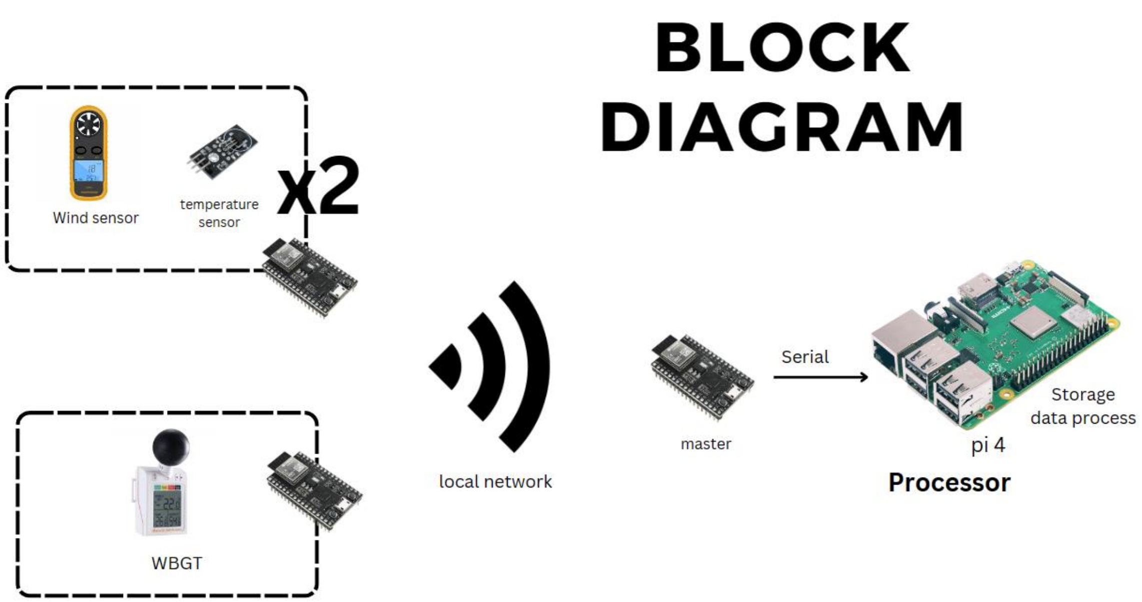


Figure 2. Block diagram of the hardware components

Two pairs of sensors, each consisting of a BME680 sensor and a digital anemometer, are employed; each pair is configured to be read by an ESP32. Additionally, another ESP32 is dedicated to reading data from the WBGT meter. The recorded data is transmitted to a master ESP via local internet and subsequently written to a hard drive on the Raspberry Pi for storage and analysis.

Figure 3. Hardware Setup Overview, featuring Raspberry Pi, ESP32 with WBGT Meter, and Two Sets of ESP32 with BME680 Sensor and Digital Anemometer (from left to right).

4. Power Planning

- WBGT meter and digital anemometer: batteries of the devices.
- ESP32 (Slaves): 5V adapter.
- Raspberry Pi: 5V adapter.
- ESP32 (Master): 5V power from the Raspberry Pi.

5. Data Communication

Following the above setup, data flow in the system is illustrated in the below figure:

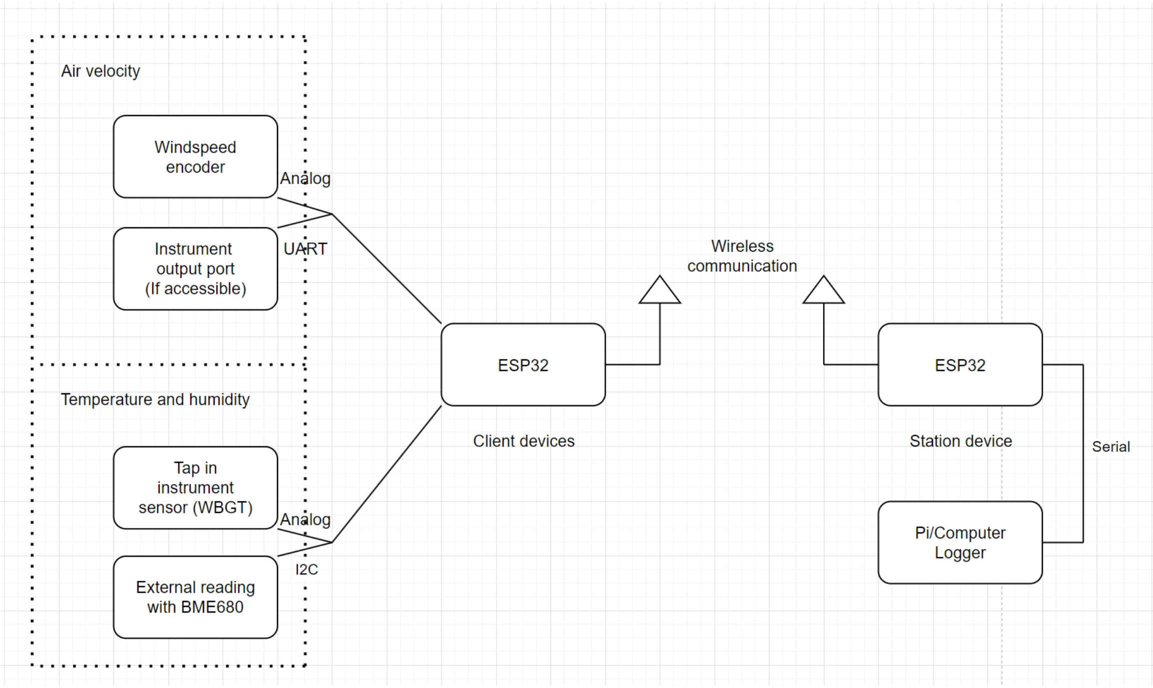


Figure 4. Data communication between hardware components

Each slave ESP32 module will read data from its assigned sensors through wiring connections. Meanshile, one master ESP32 module is responsible for receiving data packets from all slave modules through wireless communication. The master module is also responsible for parsing the received packets to the computer (Raspberry Pi) via direct USB port so that the computer can log the data to CSV files with proper timestamps for later data analysis.

The packet read from master indicates these values: UID of sent ESP + <param name> + <value> + <next param name> +<next value> + …

(e.g.: ”?uid=temp0&tempNTC=21.23&temp=28.46&hum=49.07&pres=1011.20&gas=86.35&”)

```
            type = parse_data(data)
            # print(type)
            if type == 1:
                uid, tempNTC, temp, hum, pres, gas = parse_data_temp(data)
                print(f'{time.strftime("%H:%M:%S")}, {uid}, {tempNTC}, {temp}, {hum}, {pres}
        except KeyboardInterrupt:
            break
        except Exception as e:
            print(e)
            pass
```

```
stripped data:  ?uid=temp0&tempNTC=-218.88&temp=28.46&hum=49.07&pres=1011.20&gas=86.35&
17:53:13, temp0, -218.88, 28.46, 49.07, 1011.2, 86.35
stripped data:  ?uid=temp0&tempNTC=-218.88&temp=28.46&hum=49.08&pres=1011.20&gas=86.08&
17:53:14, temp0, -218.88, 28.46, 49.08, 1011.2, 86.08
stripped data:  ?uid=temp0&tempNTC=-218.88&temp=28.47&hum=49.07&pres=1011.20&ga
17:53:15, temp0, -218.88, 28.47, 49.07, 1011.2, 0
stripped data:  ?uid=temp0&tempNTC=-218.88&temp=28.
17:53:16, temp0, -218.88, 28.0, 0, 0, 0
stripped data:  ?uid=temp0&tempNTC=-218.88&temp=28.47&hum=49.08
17:53:18, temp0, -218.88, 28.47, 49.08, 0, 0
stripped data:  ?uid=temp0&tempNTC=-218.88&temp=28.47&hum=49.08&pres=1011.20&gas=86.17&
17:53:19, temp0, -218.88, 28.47, 49.08, 1011.2, 86.17
stripped data:  ?uid=temp0&tempNTC=-218.88&temp=28.46&hum=49.10
```

Figure 5.Examples of data packets read from ESP32 modules

When Raspberry Pi read the data, it will extract the value from the packet, then store to log file the time record, source ESP ID and sensors value with respect to parameters at the columns.

Data log file fills data in the following order: Timestamp, UID, Average radiationTemp, AirTemp, Humidity, AirPressure.

```
2024-03-30 21:34:38,wind0,23.28,0.0,29.09,65.1,1014.11,75.28
2024-03-30 21:34:39,temp0,23.32,0.0,29.09,65.1,1014.11,75.28
2024-03-30 21:34:39,wind1,23.32,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:39,temp0,23.32,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:40,temp0,23.0,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:40,temp0,22.97,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:41,temp0,22.97,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:41,wind0,0,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:42,wind1,0,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:42,temp0,22.96,0.0,29.01,63.4,1014.27,61.56
2024-03-30 21:34:42,wind0,22.96,0.0,29.09,65.09,1014.11,75.28
2024-03-30 21:34:43,temp0,22.97,0.0,29.09,65.09,1014.11,75.28
2024-03-30 21:34:43,wind1,22.97,0.0,29.01,63.41,1014.26,61.84
2024-03-30 21:34:43,temp0,22.96,0.0,29.01,63.41,1014.26,61.84
2024-03-30 21:34:44,temp0,22.96,0.0,29.01,63.41,1014.26,61.84
2024-03-30 21:34:44,temp0,22.96,0.0,29.01,63.41,1014.26,61.84
```

Figure 6. Part of a log file record

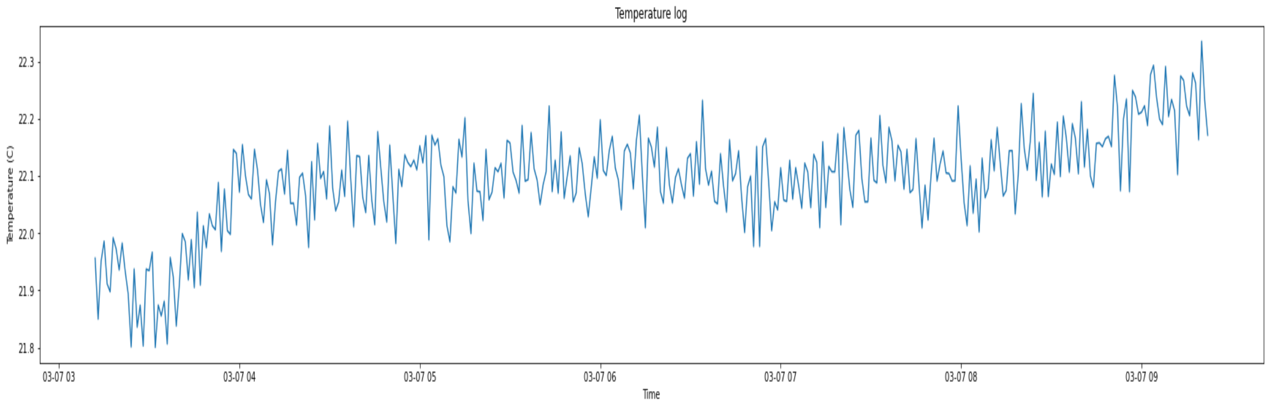


Figure 7. An illustration of average radiation temperature data in six hours.

6. On-site setup locations

- The WGBT meter with one slave ESP32 is positioned in the middle of the room, at a height of 1.2 – 1.5 meters from the floor, to measure the average radiant temperature.
- Indoor air temperature, indoor air humidity, and indoor air velocity are measured at two different points in the room. One set of ESP32 with BME680 Sensor and Digital Anemometer is suspended at the output of the air conditioner, while the other set is placed at a common seating spot in the room.

Thermal comfort is assessed using the Predicted Mean Vote (PMV) index. PMV indicators are calculated using the CBE Thermal Comfort Tool from the University of California, Berkeley.

III. RESULT AND DISCUSSION

This section aims to provide and analyze the following results:

1) A 24-hour dataset comprising four thermal comfort factors recorded in four selected meeting rooms (MRs) at Fulbright. These factors include air temperature, relative humidity, air velocity, and mean radiant temperature.

2) Utilizing survey findings from the observation team, which include clothing level (Clo), metabolic rate (Met), and adaptive mean vote (AMV) of individuals utilizing the rooms, our team integrates this data with our dataset to compute the predicted mean vote (PMV) for each occupant. We then compare these results with the recorded AMV and produce a PMV chart estimated for each room throughout the day. In addition, with the PMV calculated from CFD simulations of the simulation team, including air temperature, our team can compare their simulated data with our experimental dataset.

3) Conduct a comparative analysis between our calculated PMV values and ASHRAE Standard 55-2023 (computed using CBE Thermal Comfort Tool).

1. 24-Hour Dataset Recorded in Four Meeting Rooms

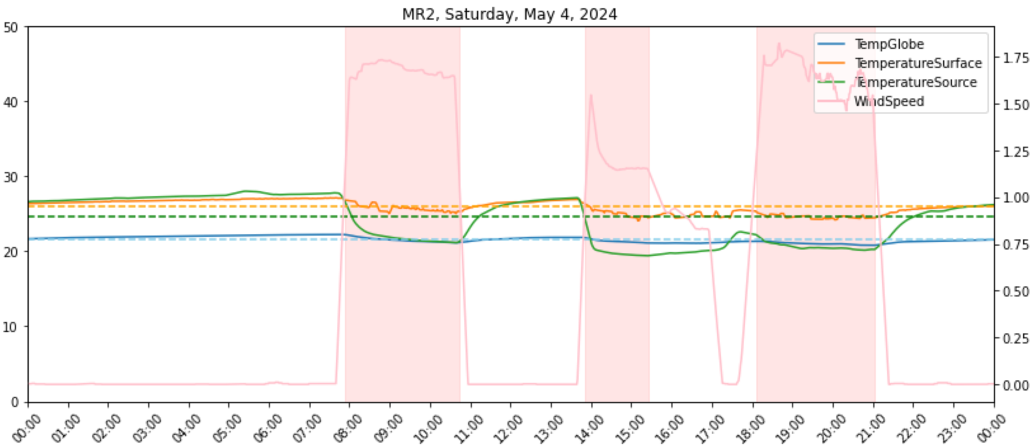
Graph Reading Guidelines: To streamline the interpretation and manage the data complexity depicted in the graphs, we have segmented the recorded dataset for each room into two distinct graphs.

- The first graph for each room showcases four key data elements:
    - Mean radiant temperature (TempGlobe)
    - Air temperature at the supply air vent output (TemperatureSource)
    - Air temperature in the middle of the room, measured at a height of 1.2 – 1.5 meters from the floor (TemperatureSurface)
    - Air velocity at the supply air vent output (WindSpeed)

  - The left y-axis represents temperature in degrees Celsius, while the right y-axis represents air velocity in meters per second (m/s).

- The second graph for each room exhibits three data elements:
  - Relative humidity at the supply air vent output (HumiditySource)
  - Relative humidity in the middle of the room, measured at a height of 1.2 – 1.5 meters from the floor (HumiditySurface)
  - Air velocity at the supply air vent output (WindSpeed)
  - The left y-axis indicates relative humidity in percentage (%), while the right y-axis denotes air velocity in meters per second (m/s).
- Both graphs' x-axis displaying the time of day.
- The pink-shaded area on both graphs indicates the duration during which the supply air vent is actively cooling the room.
- Dotted lines across each graph represent the average values of the respective data elements (i.e., distinguished by color).

i. Meeting room 2



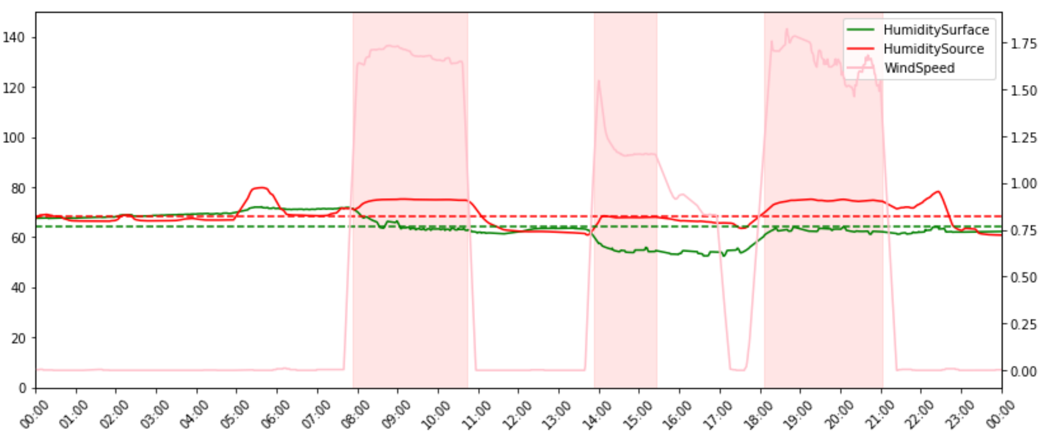


Figure 8. Data measurements of MR2

- Room size (recorded by the CFD simulation team):
    - Floor area: 21.4 (m^2)
    - Height: 2.7 (m)
    - Volume: 57.8 (m^3)
- Recorded date: May 4th, 2024.
- Active range of air velocity: 1.1 m/s to 1.8 m/s.
- Supply air velocity: Inactive at noon, from 11:00 to 14:00.
- Range of air temperature during day time: 24°C to 26°C.

ii. Meeting room 3

Figure 9. Data measurements of MR3

- Room size (recorded by the CFD simulation team):
  - Height: 2.7 (m).
  - Floor area: 4.8 (m^2
  - Volume: 13 (m^3)
- Recorded date: April 23rd, 2024.
- Active range of air velocity: 1.7 m/s to 3.0 m/s.
- Supply air velocity: Active throughout the campus's operating hours.
- Range of air temperature during day time: 20°C to 22°C.

iii. Meeting room 4

Figure 10. Data measurements of MR4

- Room size (recorded by the CFD simulation team):
    - Height: 2.7 (m)
    - Floor area: 5.2 (m^2)
    - Volume: 14 (m^3)
- Recorded date: April 16th, 2024.
- Active range of air velocity: 1.0 m/s to 1.4 m/s.
- Supply air velocity: Active throughout the campus's operating hours.
- Range of air temperature during day time: 22°C to 24°C.

iv. Meeting room 5

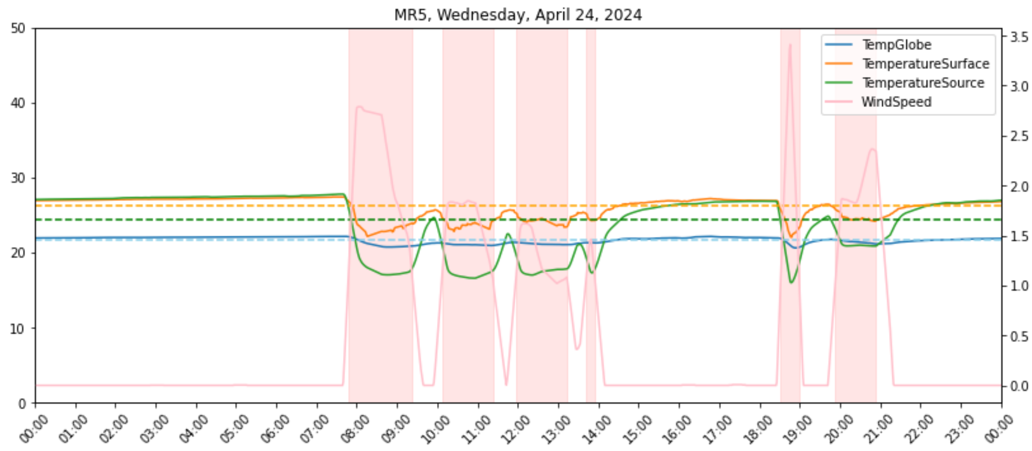


Figure 11. Data measurements of MR5

- Room size (recorded by the CFD simulation team):
  - Height: 2.7 (m)
  - Floor area: 9.4 (m^2)
  - Volume: 25.4 (m^3)
- Recorded date: April 24th, 2024.
- Active range of air velocity: 1.5 m/s to 2.9 m/s.
- Supply air velocity: Active inconsistently, and inactive throughout the afternoon from 14:00 to 18:30.
- Range of air temperature during day time: 23°C to 27°C.

2. Integration with Survey Findings

We utilize five data elements collected from 31 respondents by the observation team:

- Clothing level (Clo)
- Metabolic rate (Met)
- Meeting room number
- Recorded time of response
- Adaptive mean vote (AMV) on a scale of 3: -3 (cold) to +3 (hot)

(Retrieved from Thermal Comfort Survey of the observation team)

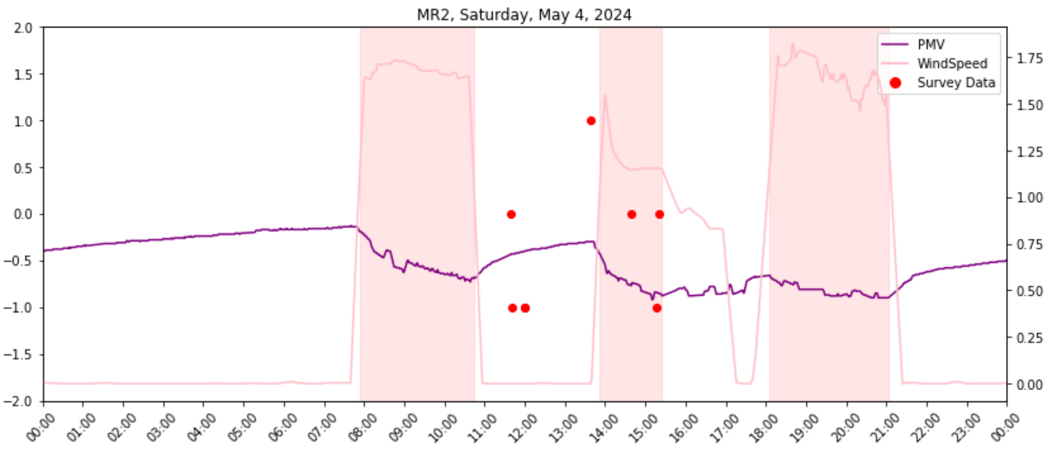
Graph Reading Guidelines: The results for each meeting room are presented in three graphs.

- The first chart displays three data elements (including air velocity, as in section 1):
  - The predicted mean vote (PMV) of the room occupants at specific points of responsing to the survey (Survey Data).
  - The PMV estimation of the room throughout the day (PMV). This estimation is derived by averaging the clothing level and metabolic rate from the survey respondents, with outliers excluded (i.e., Clo = 0.57; Met = 1.05).
  - The left y-axis represents the PMV value range, while the right y-axis represents air velocity (m/s).
- The second chart represents six data elements, which can be interpreted similarly to section 1. It should be noted that:

- The left y-axis has two units, representing both air temperature (°C) and relative humidity (%).
- The right y-axis still represents air velocity (m/s).

- The third graph is a bar chart specifically designed to emphasize the disparities between respondents' AMV and the calculated PMV. When the absolute difference between PMV and AMV exceeds 1 (if the two values on the opposite sides of the Fanger scale), and exceeds 2 (if the two values are on the same side of the Fanger scale), it signifies a contradiction between them.
- The PMV calculations are conducted utilizing a Python library known as pythermalcomfort.

i. Meeting room 2



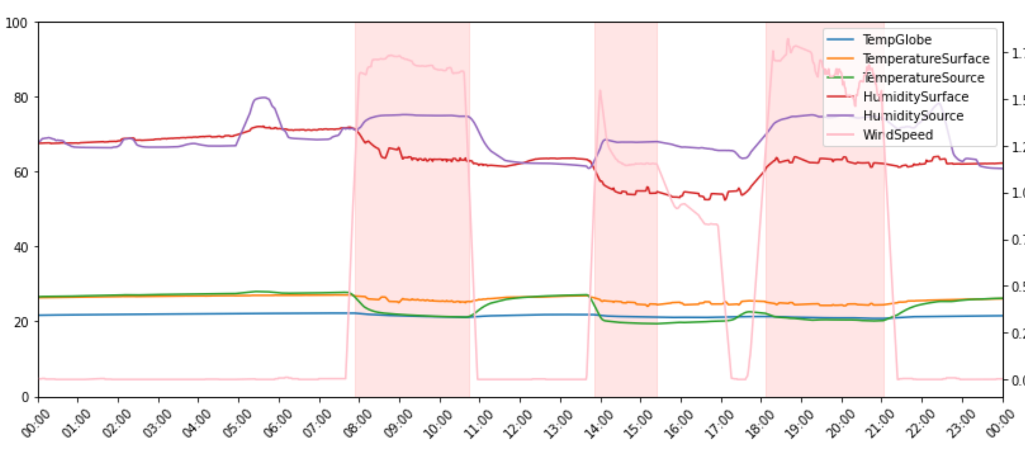


Figure 12. PMV calculations and estimation of MR2

- Number of occupants: 8

- The majority of PMV results from the Survey Data indicate that the thermal comfort in MR2 ranges from slightly cool to neutral. The single occupant who might feel warm likely had a higher-than-average clothing level.
- The estimated PMV trendline demonstrates that the active supply air velocity contributed to maintaining a slightly cool environment in the room.

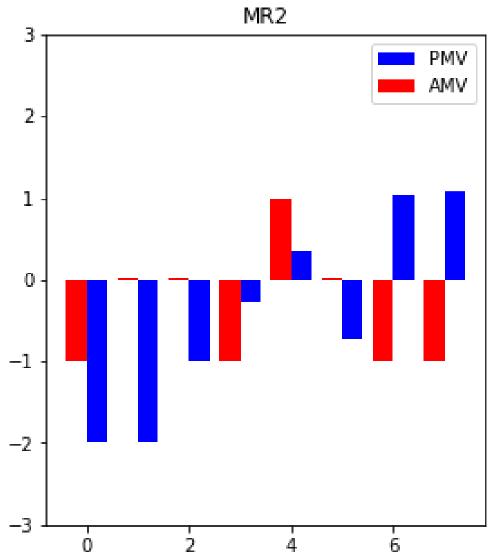
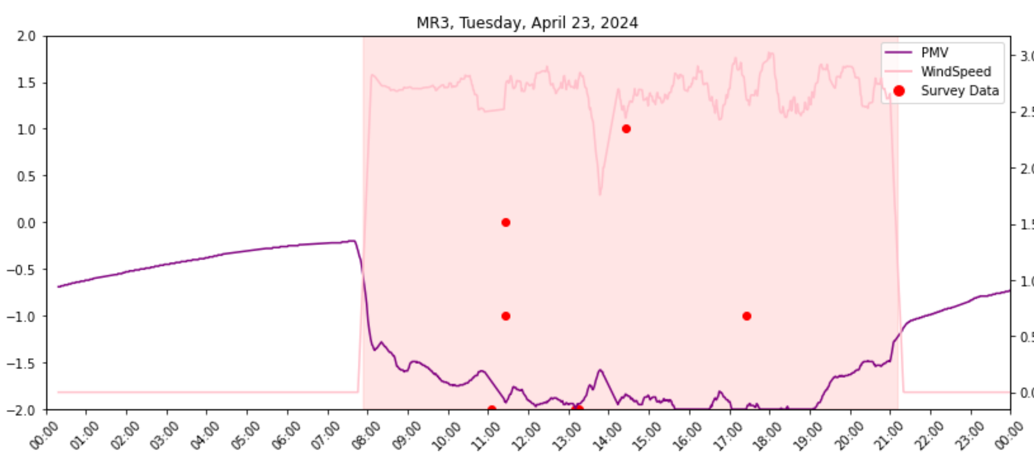


Figure 13. Comparison between AMV and PMV in MR2

- The AMV data indicates that the room's thermal condition ranges from slightly cool to neutral, aligning with the PMV trendline.
- However, there are three AMV data points that contradict the calculated PMV.

i. Meeting room 3



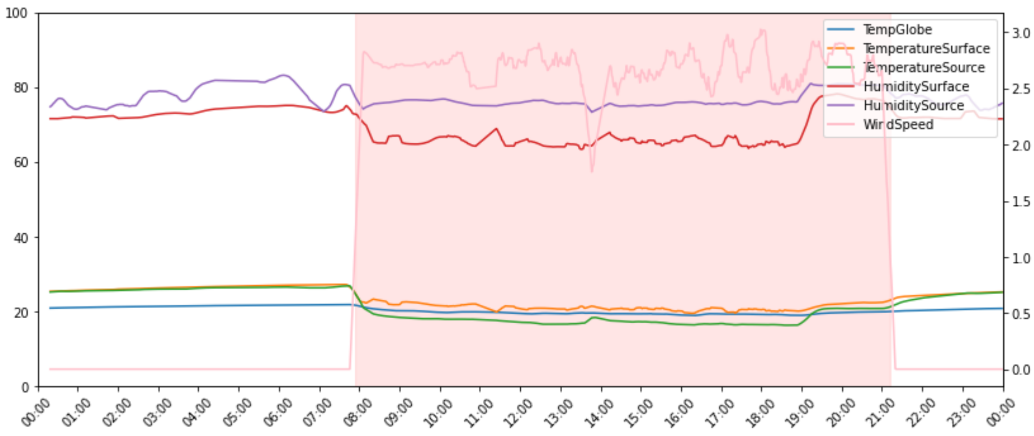


Figure 14. PMV calculations and estimation of MR3

- Number of occupants: 7
- The PMV points calculated from the survey scatter between -2 and 1.5, making it challenging to discern a clear pattern or correlation.
- The estimated PMV trendline suggests that the room remains cool throughout the campus's operating hours.

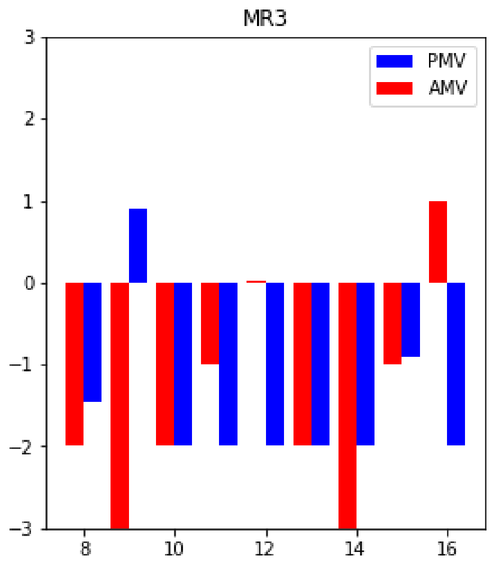
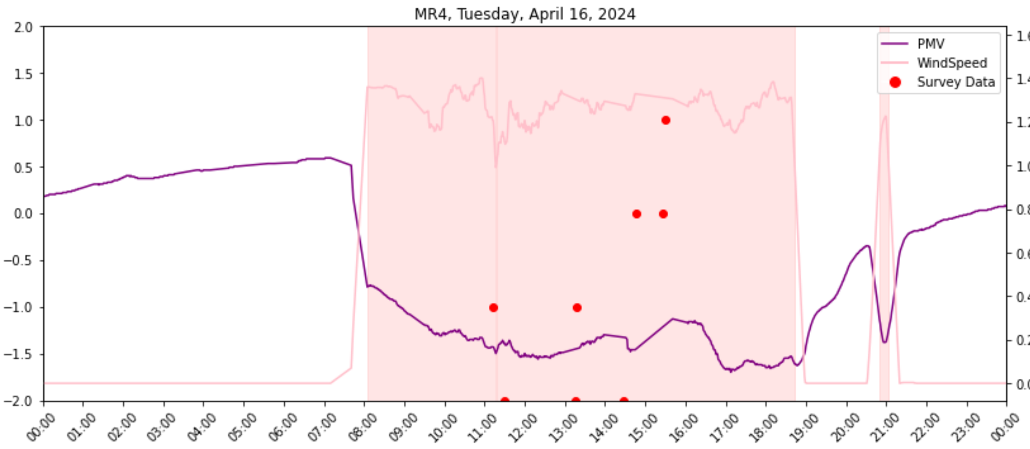


Figure 15. Comparison between AMV and PMV in MR3

- The AMV data confirms that the room maintains a cool, and even cold, environment for the occupants.
- There are three AMV data points that contradict the calculated PMV.

ii. Meeting room 4



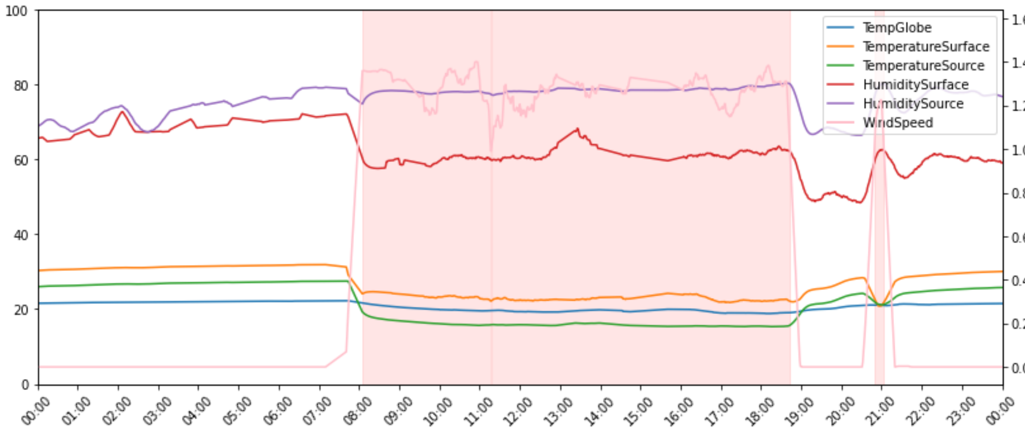


Figure 16. PMV calculations and estimation of MR4

- Number of occupants: 9
- The estimated PMV trendline indicates that the room maintains a cool to slightly cool environment throughout the campus's operating hours.
- Five out of nine calculated PMV Survey Data points are clustered around the PMV trendline.

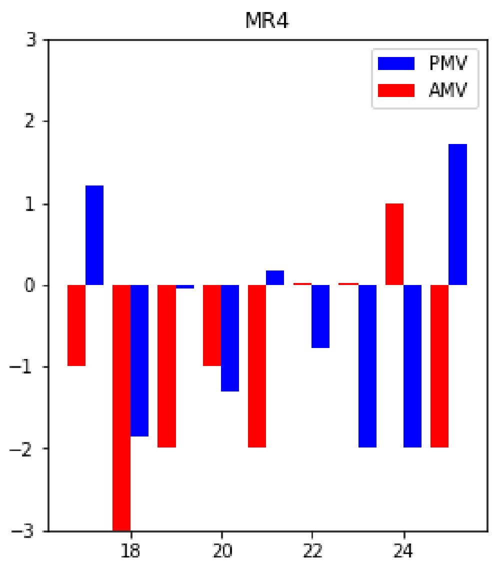


Figure 17. Comparison between AMV and PMV in MR4

- The AMV data confirms that the room maintains a slightly cool to cool environment for the occupants.
- There are six AMV data points that contradict the calculated PMV.

iii. Meeting room 5

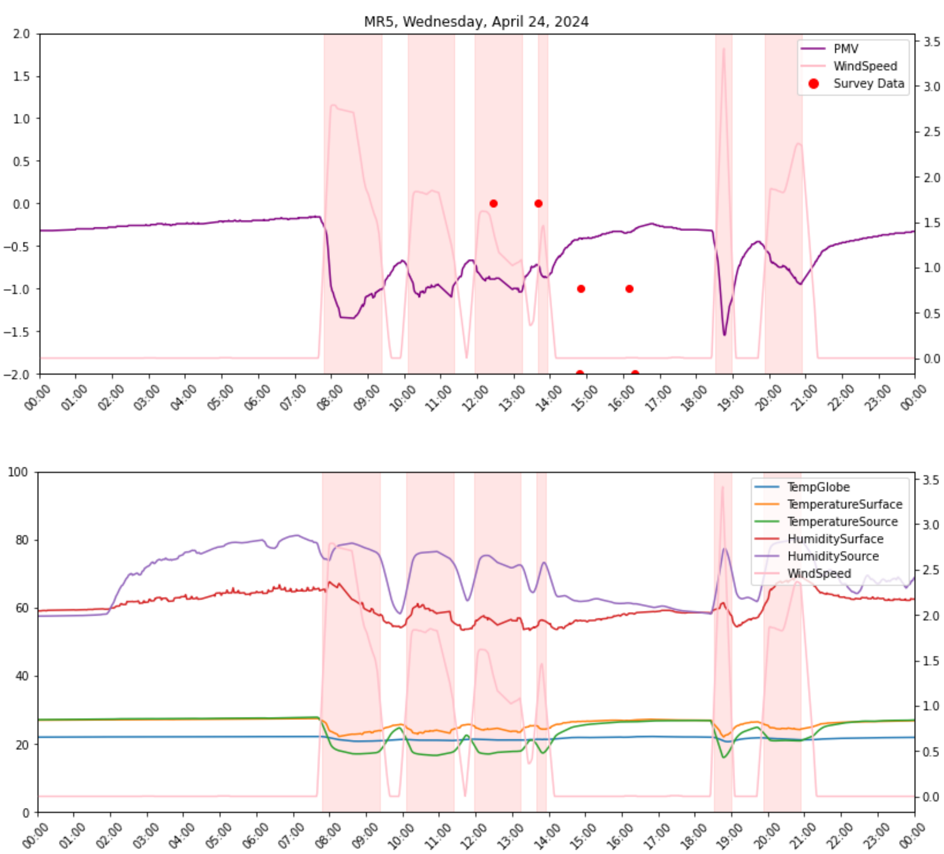


Figure 18. PMV calculations and estimation of MR5

- Number of occupants: 7
- The active supply air velocity helps maintain the room's thermo to stay around cool to slightly cool.
- Four out of nine calculated PMV Survey Data points are clustered around the PMV trendline.

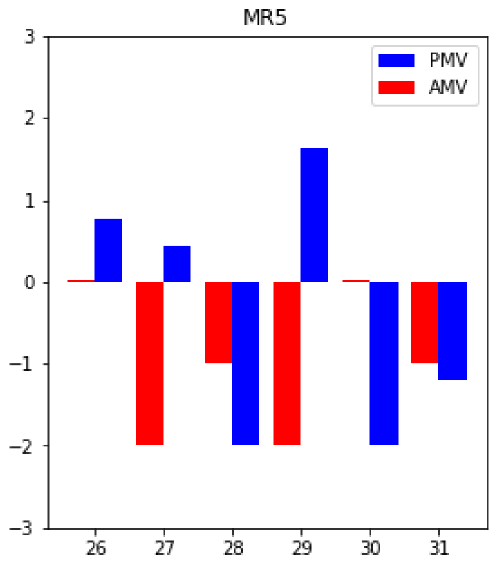


Figure 19. Comparison between AMV and PMV in MR5

- Four out of six AMV data points suggest that the room environment stays from slightly cool to cool.
- There are three AMV data points that contradict the calculated PMV.

iv. Comparison of PMV with simulations results

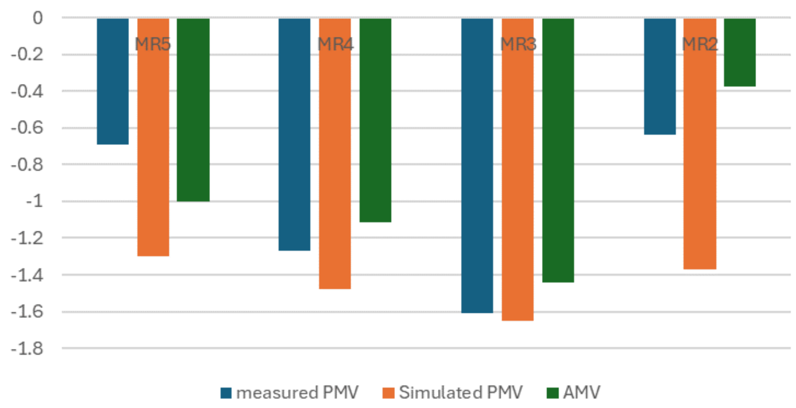


Figure 20. Comparison of PMV and AMV with simulation results

- It is noticeable that the measured average PMV values are closer to the average AMV in all meeting rooms compared to the simulated values. The differences range only from 0.1 to 0.3, whereas the simulated values range from 0.2 to 1.

3. Comparison with ASHRAE Standard 55-2023

The PMV values in accordance with ASHRAE Standard 55-2023 are computed using the CBE Thermal Comfort Tool, developed by the Center for the Built Environment at the University of California, Berkeley.

Input	MR2	MR3	MR4	MR5
Clothing Level (Clo)	0.57			
Metabolic Rate (Met)	1.05			
Air Speed (m/s)	0.1	0.16	0.1	0.1
Operative Temperature (°C)	25.5	21.1	23.5	25
Relative Humidity (%)	60.8	67	59.1	58

Figure 21. Input values in CBE Thermal Comfort Tool

There are a few important notes regarding the input values in the CBE Thermal Comfort Tool:

- Clothing level and metabolic rate are average values derived from the survey data collected by the observation team.
- The air speed of each meeting room is calculated by taking 5% of the average air velocity at the supply air vent during the campus's operating hours (from 8:00 to 21:00). This adjustment is necessary as the air velocity in the middle of the room is not significant enough for the measuring tool to detect accurately.
- The operative temperature of each meeting room is assumed to be similar to the average air temperature of the room during the campus's operating hours.
- The relative humidity of each room is calculated by averaging the relative humidity readings during the campus's operating hours.

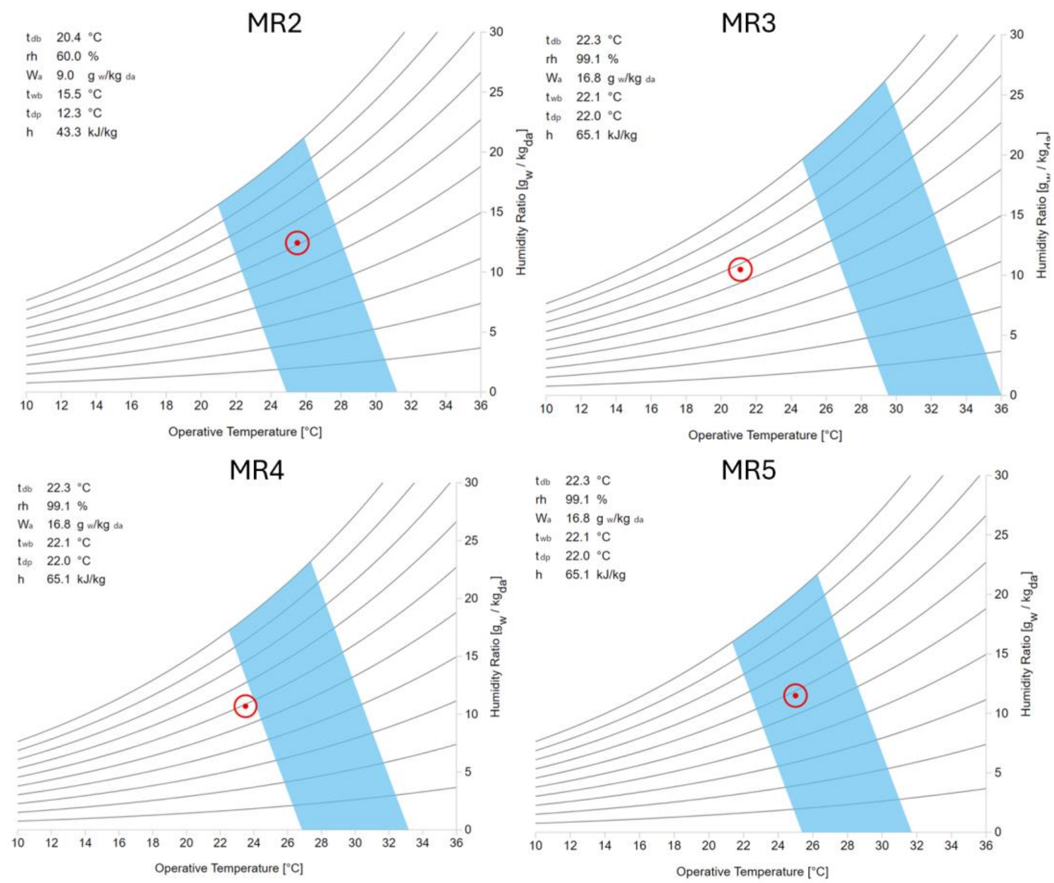


Figure 22. Comparison of measured data with ASHRAE Standard

Drawing from Figure 22, several key observations can be made:

- Only MR2 and MR5 meet the requirements of the ASHRAE Standard in terms of their PMV values.
- MR4 nearly complies with the acceptable range defined by the ASHRAE Standard, while the PMV value for MR3 significantly deviates from its corresponding acceptable range.

4. Discussions

i. Correlations of air velocity with other factors

- With air temperature and relative humidity: It is evident that the presence of supply air velocity during the campus's operating hours plays a crucial role in facilitating thermal comfort within the room, as it introduces cool air from the HVAC system.

- Regarding PMV values: Active supply air velocity contributes to an increase in the room's air temperature and relative humidity, resulting in PMV values maintaining a cooler than neutral range (from -1 to -2). Additionally, it's noteworthy that for meeting rooms MR3 and MR4, where the supply of inlet air velocity remains constant throughout the campus's operating hours, the PMV values calculated using the CBE Thermal Comfort Tool do not fall within the acceptable range defined by ASHRAE Standards.
- In terms of simulation results: The PMV results calculated by the CFD simulation team closely align with those calculated by the measurement team in MR3 and MR4 (where inlet supply air velocity is active throughout daytime), compared to MR2 and MR5 (where inlet supply air velocity is inactive during certain time periods).

ii. Room size

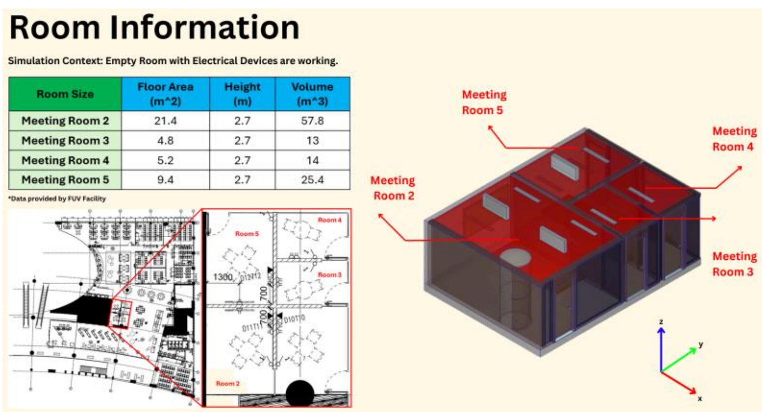


Figure 23. Meeting Room Data and 3D Model (Generated by CFD Simulation Team)

- From the measured data, it is prominent that room size correlates with thermal comfort. The two smallest meeting rooms, MR3 and MR4, which consistently receive supply air velocity throughout the campus's operating hours, emerge as the coldest rooms in both PMV and AMV data.
- When comparing rooms with similar air velocity ranges, the smaller-sized rooms consistently maintain cooler temperatures than their counterparts. Considering the

resolution of the digital anemometer used (at 0.4 m/s), we can observe two pairs of meeting rooms with similar supply air velocity ranges:

- Between MR2 (1.1 m/s to 1.8 m/s) and MR4 (1.0 m/s to 1.4 m/s): Despite MR4 having a smaller volume of 14 m^3compared to MR2's volume of 57.8 m^3, MR4's temperature mostly exceeds MR2's by 2°C. Additionally, MR4's average PMV value is twice as large as MR2's.
- Between MR3 (1.7 m/s to 3.0 m/s) and MR5 (1.5 m/s to 2.9 m/s): Although MR5 has a volume of 25.4 m^3, double that of MR3, MR3 consistently maintains higher temperatures than MR5, by 5°C to 7°C. Furthermore, MR3's average PMV value is 2.5 times larger than MR5's.

iii. Integration with survey findings

- Out of the total 31 AMV data points from the survey, 17 of them contradict the calculated PMV conducted by our team using the pythermalcomfort library, which follows the algorithm in accordance with the ASHRAE Standard.
- Given that the primary activity of meeting room occupants is typically seated, the metabolic rates recorded from most survey respondents hover around 1.0 met. Consequently, it's likely that the variable of clothing level is influencing the PMV results. We assume that respondents may not have provided comprehensive information about what they wear due to both privacy concerns and a lack of thoroughness in completing the survey.
- Furthermore, since there is no recorded data regarding the activities that respondents engaged in before entering the meeting rooms or the duration of their stay in the room prior to the survey, the surveyed data appears subjective and may affect the comparison between PMV calculation and respondents' AMV.

iv. Limitations

- Experimental setup: It is recognized that different positions within the rooms will yield varying levels of thermal comfort. For instance, individuals seated directly under the supply air vent will likely feel cooler than those seated on the opposite side of the room. Therefore, with only two sensory toolkits—one placed at the output of the supply air vent and the other positioned on the meeting room's table—it becomes subjective to provide an assessment of the room's overall thermal comfort.
- Lack of evidence to explain why MR3 and MR4 consistently received a constant supply air velocity, while MR2 and MR5 only experienced consistent supply air velocity during specific time periods.
- Absence of references to validate the accuracy of the measured data: Since it is impractical to access the building's HVAC system to automatically record the data, discrepancies between the measurement team's calculated PMV values and the calculations of the observation team and simulation team may arise from the percentage error between our recorded data and the data measured by the HVAC system's sensors.

IV. CONCLUSION

From the results and discussion, it can be inferred that there exists a robust correlation between air velocity and other measured and calculated factors in the project, such as air temperature, relative humidity, and PMV values of the research rooms. Additionally, aside from supply air velocity, room size emerges as a pivotal factor contributing to variations in thermal comfort among the four meeting rooms. Notably, at similar ranges of supply air velocity, the smaller room consistently registers colder temperatures, with PMV values falling outside the acceptable range defined by the ASHRAE Standard.

Among the four selected meeting rooms, MR2 and MR5 exhibit PMV values that align with ASHRAE Standard 55-023, while the remaining meeting rooms fail to meet the standard. MR3 emerges as the coldest room with the highest level of discomfort, a conclusion consistent with the findings of the simulation team.

By integrating the measured and calculated data with survey findings, there is evidence suggesting that field measurements yield PMV values closer to the AMV values in comparison with PMV values calculated by simulation data from the simulation team.

For future research, we recommend (i) increasing the number of sensors positioned at common seating locations within the room to explore deeper variations in thermal comfort, (ii) expanding the data collection process to include factors such as the presence of occupants and the number of occupants in the room, and (iii) conducting more detailed inspections of the rooms over several days to study patterns of supply air velocity.

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