Journal of Mechanics Engineering and Automation 13 (2023) 100-110
doi: 10.17265/2159-5275/2023.04.002

Effectiveness of PMV-Based Controls for Commercial Buildings in the USA

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Abstract: Using an accurate energy model, this paper simulated existing commercial buildings to compare PMV-based comfort control with conventional thermostatic control and conduct a sensitivity analysis using the Design of Experiments method with monitored energy consumption data. This analysis was applied considering the impact of building envelope characteristics including thermal insulation level of exterior walls and air leakage rate on the ability of both control options to maintain indoor thermal comfort while minimizing cooling energy consumption. The analysis findings indicated that PMV-based comfort control is viable for striking a middle ground between thermal comfort and heating energy consumption with a PPD (predicted percentage of dissatisfied) level at 8% for any combination of walls' *R*-value and air infiltration rate while temperature-based controls result in an unacceptable indoor thermal comfort performance especially for low *R*-values regardless of the air infiltration rate with PPD level reaching over 76%. Also, the results show that in a comfort-controlled space, the average radioactive temperature and occupant-related features like metabolic rate and clothing level have a far bigger effect on energy use than other parameters like relative humidity.

Key words: Thermal comfort, energy savings, Heating, ventilation, and air conditioning.

1. Introduction

Air conditioning is one of the largest energy consumers in buildings. In many commercial buildings, thermal comfort has become a significant issue of concern when designing commercial buildings [1]. This issue has become a significant factor in commercial building design due to numerous complaints about chilly, cold, or hot temperatures [2]. However, a significant concern with this equipment is the air quality inside the building and the energy efficiency [3]. Building controls' primary concern is maintaining a comfortable indoor environment with minimal energy consumption [4]. Current building controls have primarily been designed to minimize energy consumption rather than to maintain thermal comfort [5]. In the United States, a relatively small number of buildings account for a large share of energy use, buildings in the top 25% of energy use account for about 44% of the country's total energy use [6]. A chilled water system is an air conditioning system that uses cold water in a building to cool the air in a small space [7]. But today, it is used to provide cooling to larger spaces like conference rooms and hallways. The primary function of this system is to remove heat from the space being cooled and transfer the heat to a place where it is not needed [8]. This leads to the desired cooler temperature, enhancing thermal conform in commercial buildings.

2. Objective

This project's primary objective is to evaluate the thermal comfort and temperature performance controls. This study's main goal is to develop a design approach to a modern comfort-based control system to strike a balance between energy efficiency and occupant comfort.

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3. Methodology

To conduct the proposed study, the following methodology is used (1) data collection and preprocessing, (2) model development, (3) five-step comparative analysis, (4) discussing the results. The data are collected from an existing building and used to validate and fine-tune the simulation results. A comparison of observed data (taken from utility bills) and simulation results (in kWh) for monthly energy use before and after calibration was conducted. A baseline energy model of the case study building was constructed and validated using monthly power use to guarantee that the simulation analysis findings are accurate. Energy Plus has been used to model and analyze the selected building in 2 model controls. A five-step comparative analysis is used to compare the temperature- and PMV-based management systems by analyzing the data from a variety of real-world scenarios

3.1 Data Collection and Preprocessing

Bluford Library: For this study, a commercial building located at North Carolina Agricultural and Technical State University has been selected to evaluate the effectiveness of temperature- and PMV-based control strategies to maintain indoor thermal comfort while minimizing cooling energy consumption. To condition the building a Standard VAV (Variable Air Volume), HVAC system has been selected to use. Energy Plus has been used to model and analyze the selected school building. A baseline energy model of the institution building was constructed and validated using monthly power use to guarantee that the simulation analysis findings are accurate.

3.2 Model Development

Twenty households' monthly power costs are used to validate and fine-tune the simulation results. A comparison of observed data (taken from utility bills) and simulation results (in kWh) for monthly energy use before and after calibration is shown in Fig. 2.

This model is used to perform a comprehensive analysis of the temperature-based control with the PMV-based control. These controls can be modeled in Energy Plus using the following controls methods.

(1) Thermostatic zone control

This control scheme is the temperature-based control strategy that maintains indoor air temperature at a specified set point temperature. To accurately simulate thermostatic zone control in Energy Plus, temperature setpoint schedules have been created.

(2) Thermal comfort zone control

In this control strategy, the zone air temperature is controlled based on Finger's thermal comfort model. Unlike the temperature-based control strategies, the PMV-based controls allow considering the thermal effects of the surrounding environmental, physiological, and personal variables that influence indoor thermal comfort conditions. The personal variables considered the PMV-based control schemes include the human

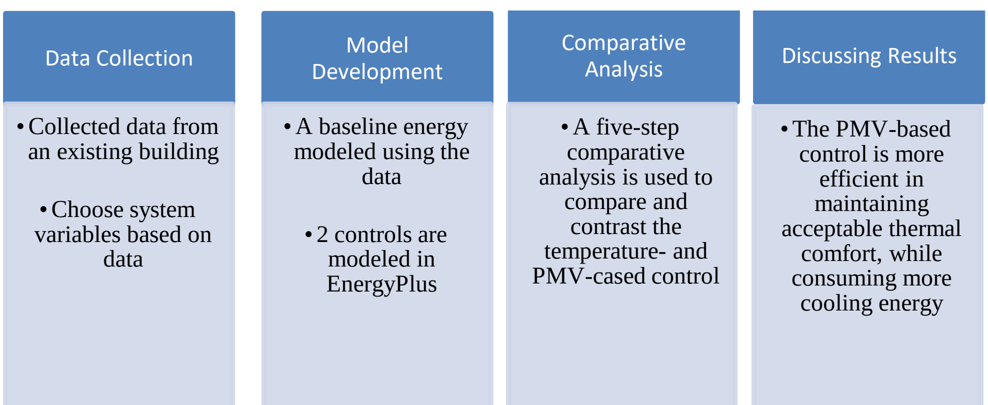


Fig. 1 Workflow diagram of research methodology.

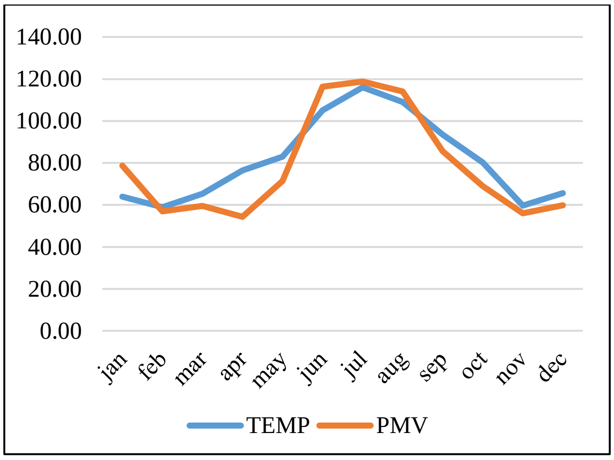


Fig. 2 Comparison between simulation and utility data before and after calibration.

body's metabolic rate and the clothing's thermal resistance. The environmental variables consist of indoor air temperature, air humidity, and the mean radiant temperature.

3.3 Comparative Analysis

A five-step comparative analysis is used to compare the temperature- and PMV-based management systems as briefly described below.

Step 1: Indoor thermal comfort and cooling energy usage are compared between temperature- and PMV-based controls using the school's baseline energy model. The effect of occupancy density on the energy consumption and thermal comfort provided by the two control methods was considered in the comparison study.

Step 2: Examine how the degree of energy efficiency of the building envelope, such as the thermal insulation of the walls and the rate of air infiltration, affects the thermal comfort of the interior and the amount of cooling energy required. The study incorporates both indoor and outdoor environments on typical summer and winter days. To assess the effect of various degrees of wall insulation on thermal comfort and cooling energy consumption in a few rooms throughout a school in city 1, *R*-values from 0.1 to 2 m^2 K/W were chosen. Air infiltration rates between 0.1 and 1 ACH have also been considered.

Step 3: Conduct a sensitivity analysis to examine the impact of wall insulation and air infiltration rate on the efficiency of temperature-based and performance-modulated ventilation-based control strategies.

Step 4: Involve assessing the effect of the temperature- and PMV-based controls' setpoints on interior thermal comfort and cooling energy consumption.

Step 5: We use data from three climatic regions in the United States to assess the impact of weather on the effectiveness of our temperature- and PMV-based controls.

City 1: Hot and humid New Orleans, Louisiana,

City 2: Hot and dry Nevada's Las Vegas,

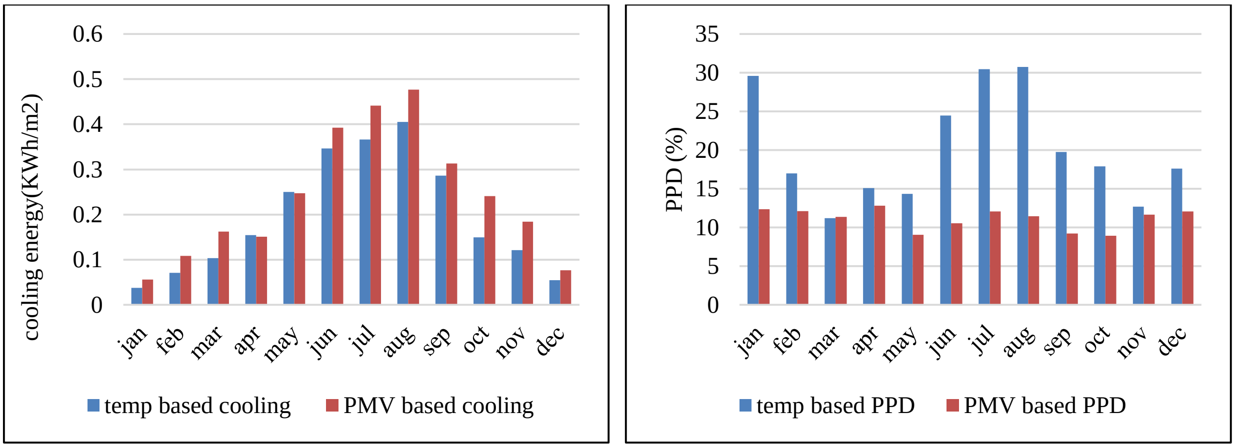
City 3: Atlanta, Georgia, has a mild climate.

4. Discussing the Results

All temperature- and PMV-based techniques are evaluated in this study using the energy modeling of the school building provided in the preceding section. It is assumed that the optimal operating temperature for cooling will be 23 ℃ when using temperature-based control systems. Using a PMV setpoint of 0.1, the control techniques based on the proportional-integral-derivative are implemented.

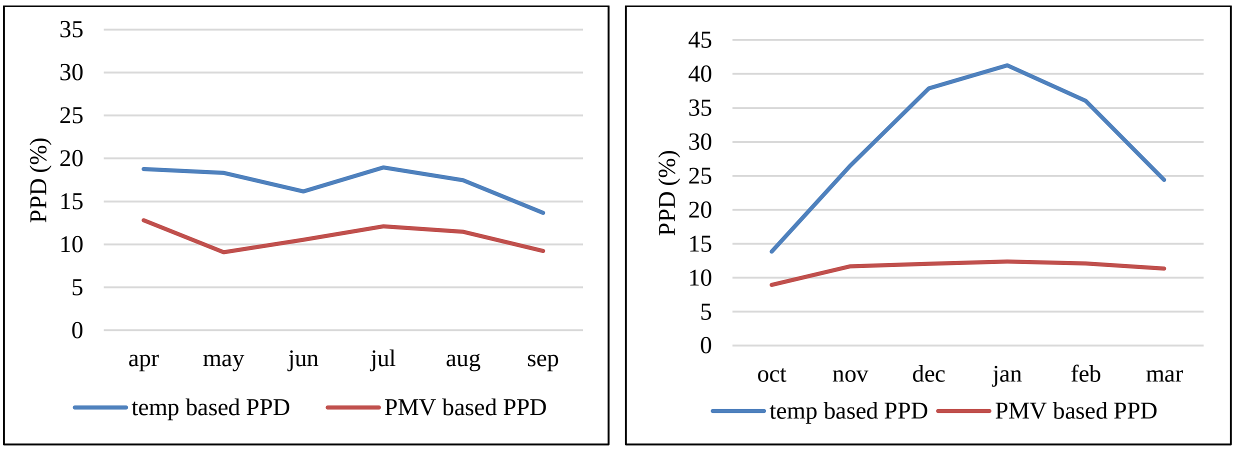
4.1 Indoor Thermal Comfort and Cooling Energy

In this section, we use the baseline energy geometric modeling of *Bluford Library* building to compare the temperature-based controls to the PMV-based controls. The PPD (predicted percentage of dissatisfied) value is used in monthly analyses first to evaluate cooling energy demand and indoor thermal comfort level. Fig 3 (b) shows that the PMV-based control works as intended, confirming that the PPD is kept constant at 12% all year round. PPD values are elevated everywhere across the building because temperature-based controls cannot keep the indoor at a comfortable temperature all through the year. Fig 4 shows that the temperature-based control works well throughout the summer (April-September), keeping the PPD at or around 17%, but it fails miserably during the winter (October-March), when the PPD rises to above 30%. But the high energy usage is a cost of using PMV-based regulation to keep interior temperatures stable and comfortable. Fig. 5 shows that this is indeed the case, with PMV-based control continuously using more cooling energy than temperature-based control.



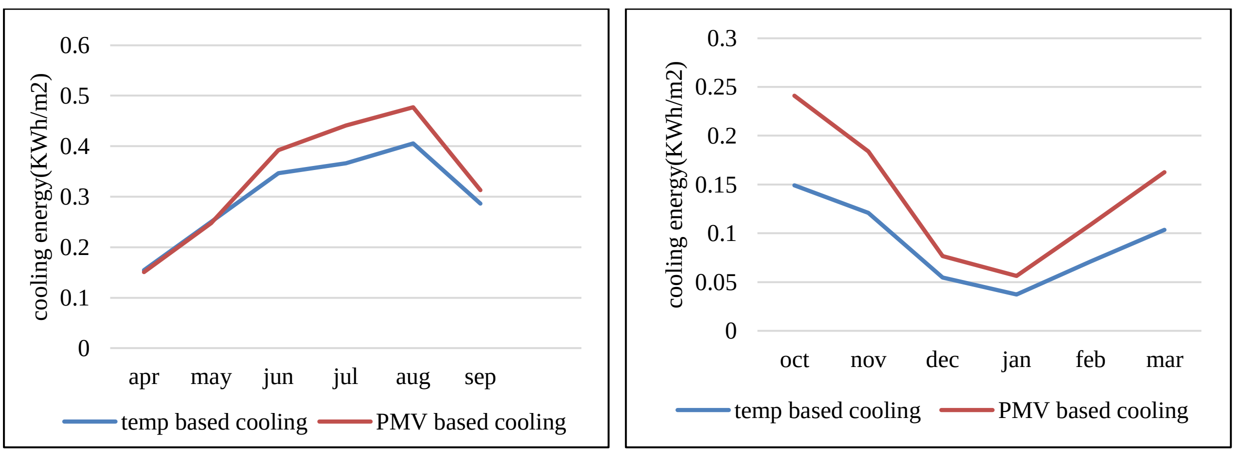
(a) (b)

Fig. 3 (a) Monthly cooling energy use (b) PPD of both PMV-based and temperature-based controls.



(a) (b)

Fig. 4 (a) Hourly PPD and indoor air temperatures in summer (b) in winter of both PMV and temperature controls.

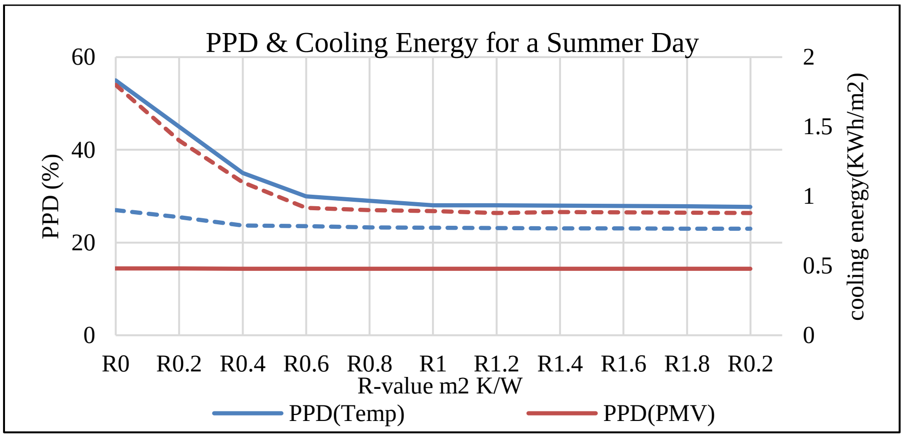


(a) (b)

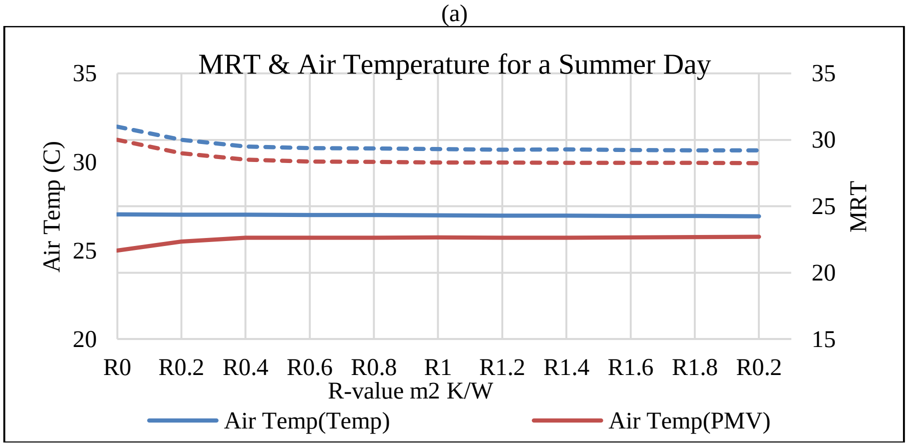
Fig. 5 (a) Hourly cooling energy use in summer (b) in winter of both PMV and temperature controls.

4.2 Influence of the Walls' R-Value

Using the baseline energy model, the thermal insulation level was adjusted so that the exterior walls' *R*-value varied from 0.1 to 2 m^2 K/W. Fig. 6 shows the impacts of the walls' *R*-value on both the indoor thermal comfort and cooling energy use using temperature- and PMV-based controls for a typical summer day (in August 2nd). Fig. 6(a) displays that the *R*-value of the walls has a huge impact on the cooling energy differential between the two control systems. Clearly PMV-based controls could maintain acceptable indoor thermal comfort (PPD = 15%) throughout the day for all walls' *R*-values. However, temperature-based controls result in undesirable indoor thermal comfort levels especially for low walls' R-values with PPD up to 55%. Fig. 6(a) indicates that improving the indoor thermal comfort level, that is, by reducing the PPD value, results in higher cooling energy use. Specifically, the cooling energy required by the PMV-based control is higher than that needed by the temperature-based control. The difference in cooling energy use between the two controls strategies depends significantly on the walls' *R*-value and ranges between 27% for the low and 5% for the high *R*-values. Indeed, the high walls' *R*-values reduce heat gains through the walls lowering the mean radiant temperature. Fig. 6(b) shows there was a difference between the MRT values achieved by the two controls, this difference explains the difference in cooling energy use between the two control strategies. On the other hand, from Fig. 6(b), we notice temperature-based control maintains the indoor air temperature at 27 ℃ (80 F). In contrast, PMV is always lower than the temperature setpoint especially for walls' *R*-values lower than 0.4.



(a)



(b)

Fig. 6 Impact of changing walls' R-value variation (a) on PPD and cooling energy (b) on MRT and indoor temperature for a summer day.

For a day in the winter (January 20th, for example), the same study was run to assess thermal and energy performances of both temperature-based and PMV controls for different wall *R*-values. Fig. 7 displays that PMV could maintain an acceptable PPD level (18%) with high-energy consumption. Temperature-based control operates unacceptable performance in the winter, with PPD levels as high as 75% with low *R*-values. PMV maintained low indoor air temperatures, around 19 ℃ (66 F), compared to the temperature set point around 23 ℃ (73 F). This temperature by the PMV is due to the high direct solar heat gains acquired through the windows during the winter.

4.3 Influence of the Air Leakage

To measure the air infiltration rate, the *R*-value is set to 2 m^2 K/W for both PMV- and temperature-based models while the air infiltration is varied from 0.1 to 1.0 ACH. Any increase in air infiltration rate will culminate into rising indoor humidity levels, increasing the room's thermal discomfort. Additionally, the heat gain associated with air infiltrations will lead to a rise in cooling energy use. It was noted that the PMV-based control would maintain an acceptable range for the PPD index of 15% of all air infiltration. In comparison, temperature-based control is unable to maintain acceptable thermal comfort with PPD level of 30% for the same infiltration rate. Fig. 8 shows how summer air infiltration affects cooling energy usage. Like in the *R*-value study, PMV-based controls consume more cooling energy than temperature-based controllers for all air infiltration rates. The difference in cooling energy

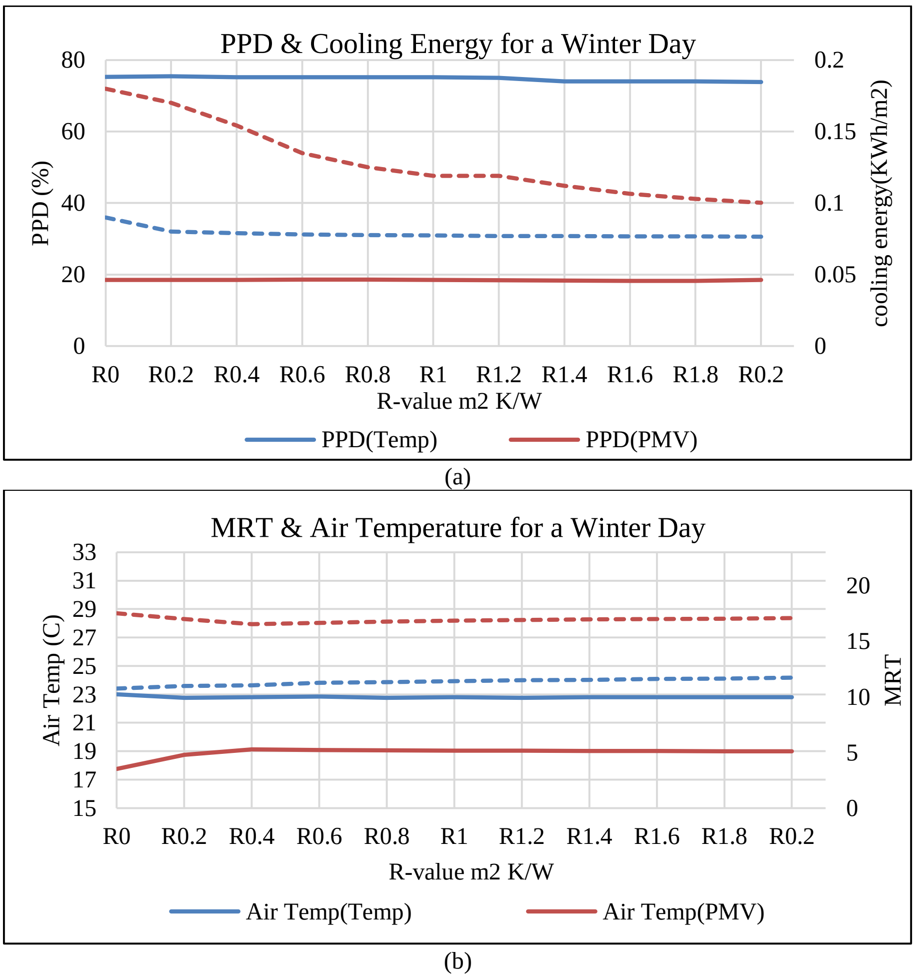
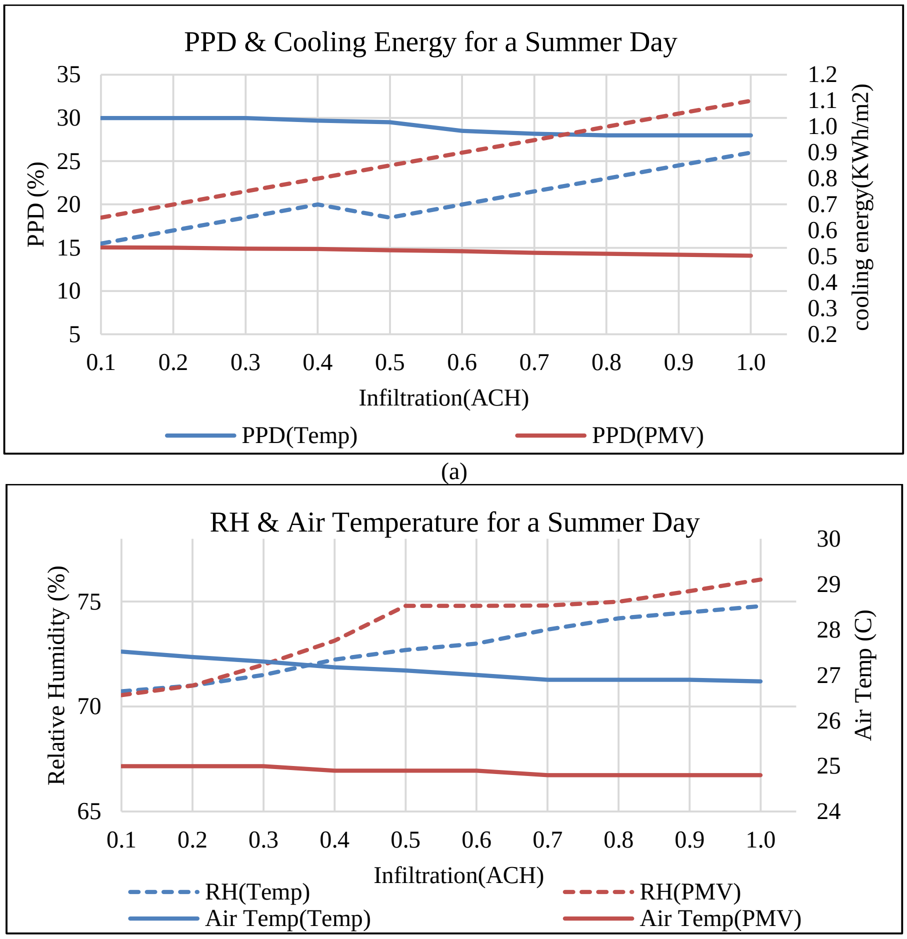


Fig. 7 Impact of changing walls' R-value variation (a) on PPD and cooling energy (b) on MRT and indoor temperature for a winter day.



(a)

(b)

Fig. 8 Impact of changing of air infiltration rate (a) on PPD values and cooling energy (b) on MRT and indoor temperature for summer days.

usage between both control methods rises with changes in air leakage and may approach more than 5% during the summer. PMV-based controls use more cooling energy to maintain a 25 ℃ interior temperature, 2 ℃ lower than temperature-based controls.

The same results were observed during a typical winter day, when the indoor temperatures obtained by the PMV-based controls were lower than the temperature-based controls as shown in Fig. 9. In the winter, solar radiation heat gains via the windows cause more considerable temperature differences between the two control choices than in the summer and hence better temperature controls.

4.4 Combined Effects of Walls' R-Value and Air Leakage

This section uses the calibrated school energy model to perform sensitivity studies when the walls' *R*-value and air infiltration changes. The analyses cover *R*-values range from 0.1 to 2.0 m^2·K/W and air infiltration rates from 0.1 to 1.0 ACH, with 0.1 increments for both variables. Each *R*-value and air penetration rate, thermal comfort, and energy use are compared for PMV- and temperature-based control systems throughout the entire year. The analysis revealed that temperature-based controls are more sensitive to the walls' *R*-value than air penetration. Low *R*-values and high air penetration rates cause the worst interior thermal comfort, with PPD values above 20%. Fig. 10 shows that PMV-based controls may maintain the PPD at 5% for any *R*-value and air infiltration rate, despite seasonal variations in the PPD contour profile. It can be concluded that temperature-based controls result in poor thermal comfort, especially for low *R*-value walls with PPD above 25%.

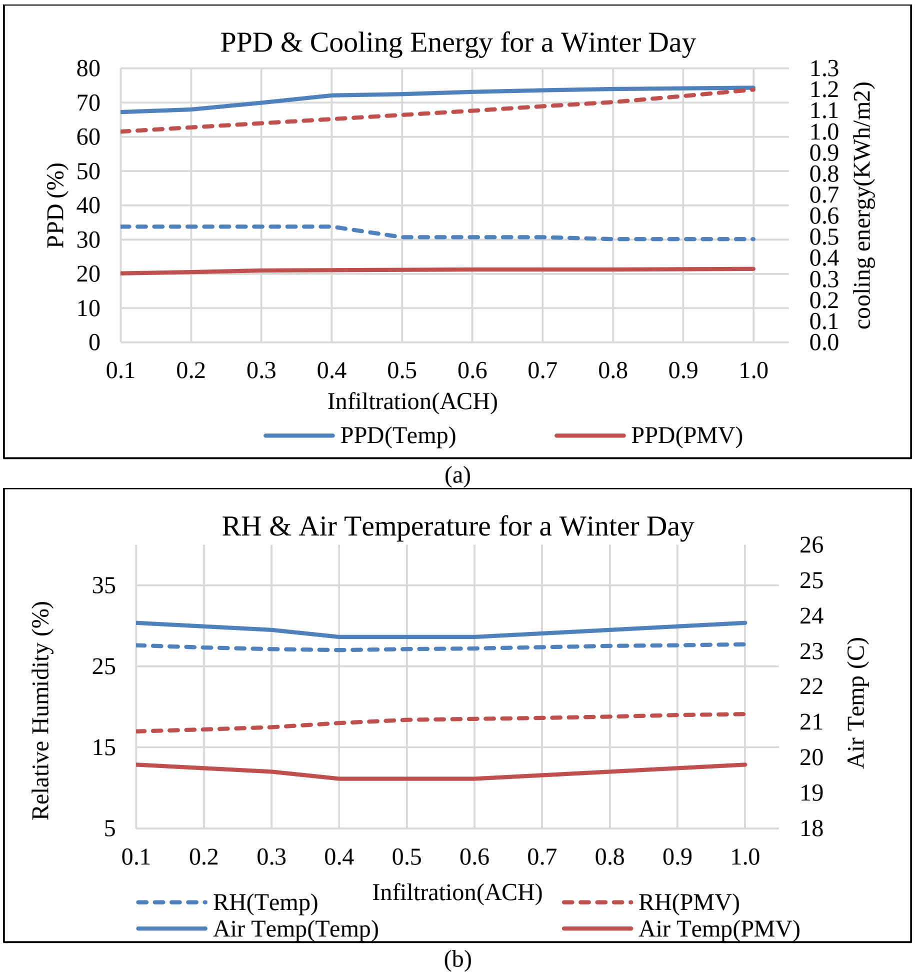


Fig. 9 Impact of changing air infiltration rate (a) on PPD values and cooling energy (b) on MRT and indoor temperature for winter days.

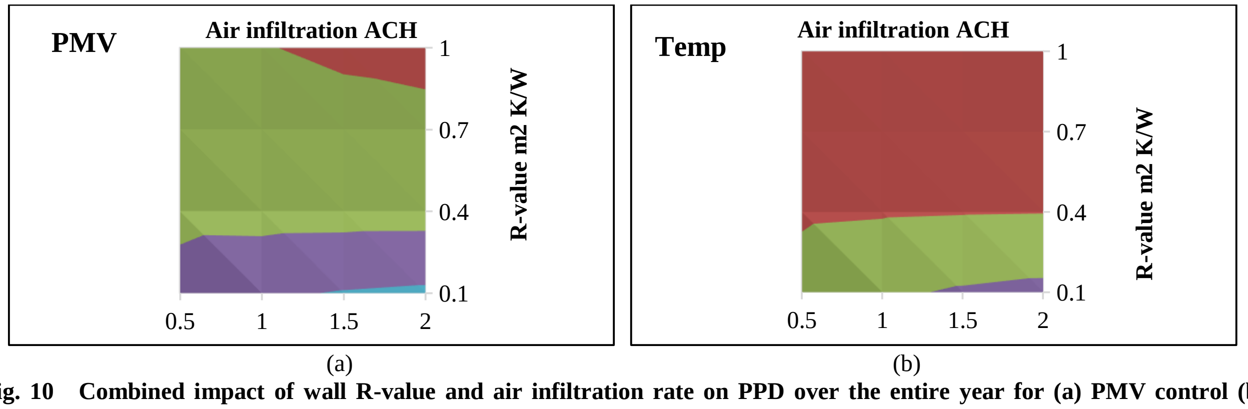
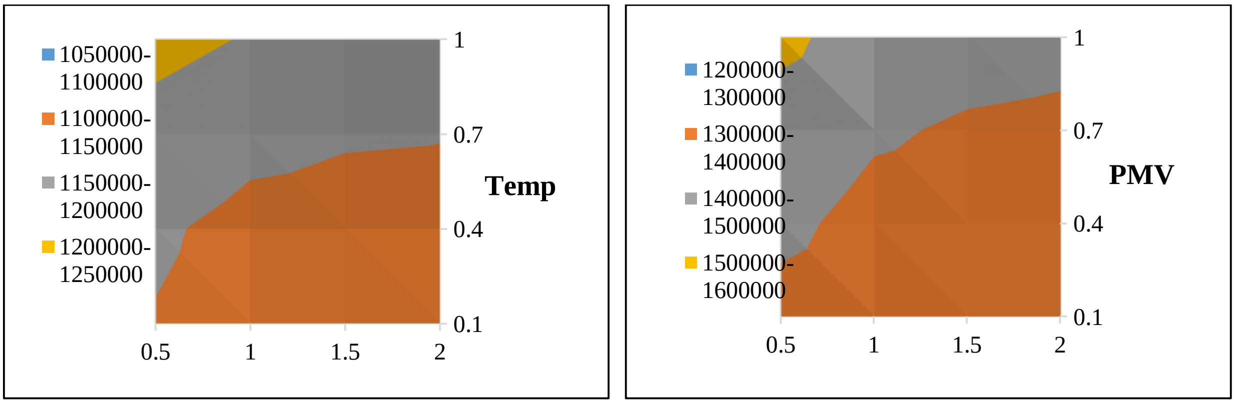


Fig. 10 Combined impact of wall R-value and air infiltration rate on PPD over the entire year for (a) PMV control (b) Temperature control.

Fig. 11 represents contour maps of cooling energy savings for various walls' *R* values and air penetration rates over a year. This section evaluates the cooling energy savings relative to the worst envelope design for a wall with an *R*-value of 0.1 m^2 K/W and an air infiltration rate of 1.0 ACH.

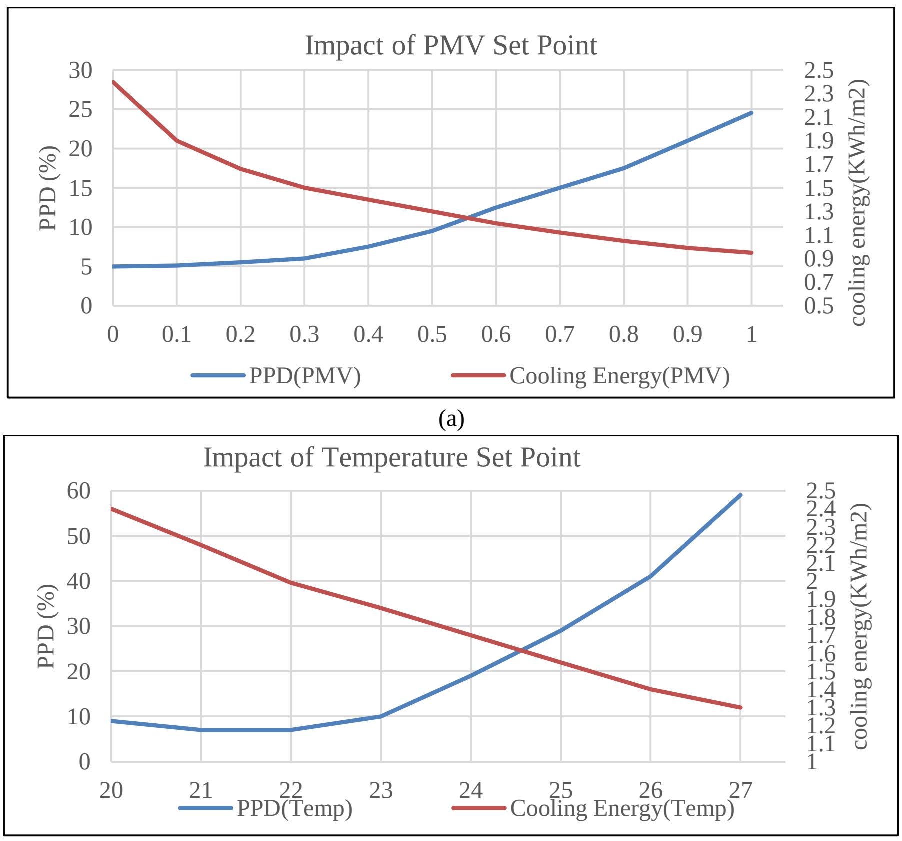
4.5 Impacts of Control Setpoints

This section considers a wide range of setpoints to investigate cooling energy demands and thermal comfort levels achieved by PMV- and temperature-based controls. The setpoint for PMV-based controls is 0-1, and for temperature-based controls, 20-27 ℃ (68-80 F). The walls' *R*-value and air infiltration are set to 2.83 m^2 K/W and 0.3 ACH for this analysis. Fig. 12 summarizes the analysis for an entire year. The PPD rises from 5% to 9.5% when the PMV setpoint is increased from 0.1 to 0.5, which is the same PPD level attained by the temperature-based control with a set point of 23 ℃. In contrast, the cooling energy consumption is decreased by this change in the PMV setpoint. For similar cooling energy use, PMV provides better thermal comfort than temperature-based controls by 5% PPD.



(a) (b)

Fig. 11 combined the impact of wall R-value and air infiltration rate on cooling energy over the entire year for (a) PMV control, (b) Temperature control.



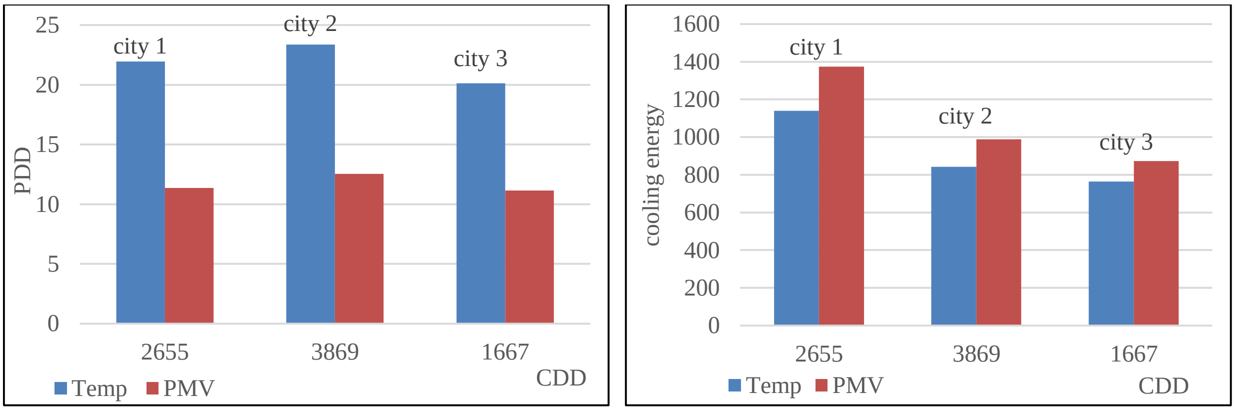
(a)

(b)

Fig. 12 Impact of the set-point variations for (a) PMV-based controls and (b) temperature-based controls on PPD level and cooling energy use in an entire year.

Table 1 Annual cooling energy and average PPD during occupied hours of both PMV- and temperature-based controls for three USA climate zones.

City	Climate	CDD	Annual cooling energy KWh/m^2		Average PPD %	
			PMV	Temp.	PMV	Temp.
1	Hot-humid	2655	1,373,219.05	1,138,935.58	11.36	20.12
2	Hot-dry	3869	987,999.73	842,215.71	12.54	23.37
3	Mild	1667	873,293.97	764,521.06	11.15	21.95



(a) (b)

Fig. 13 Relation between CDD and the change of (a) PPD level and (b) cooling energy use between PMV and temperature-based controls.

4.6 Impacts of Climate

The performance of both PMV- and temperature-based controls is assessed when the school is in different USA cities with different climates. Specifically, three cities in the USA with different climate zones were selected. Table 1 shows that the climate's cooling degree days (CDD) increase the annual cooling energy use difference between PMV-based and temperature-based controls. For both control options with CDD, the variation in the difference in PPD levels follows the same pattern.

Therefore, PMV-based controls can always keep the PPD level at approximately 11.68% in all climates, while temperature-based controls work better in mild climates with low CDD than hot climates to keep PDD level close to acceptable. Fig. 13 shows how PMV-based control continuously uses more cooling energy than temperature-based control in the three different climate zones in USA.

5. Conclusion

This study examined the efficiency of PMV and temperature control in maintaining optimal thermal comfort within a commercial building (Bluford Library) in the USA. The following outlines the key findings:

- The PMV control is more efficient in maintaining acceptable thermal comfort at 15% PPD levels for all R-values across the year. In contrast, temperature control leads to elevated PPD levels that differ with the R-values. However, PMV control does result in higher cooling energy usage for low R-values compared to temperature control.
- PMV control requires higher cooling energy consumption than temperature control, with a difference of around 20% on a typical summer day and more than 40 % on a typical winter day.
- Air leakage lacks significant effects on thermal comfort as assessed by both PMV and temperature control. However, during the summer, an elevated air infiltration rate can increase cooling energy consumption.
- Adjusting the set point for the PMV control raises the PPD level from 5% to 9.5%, aligning it with the thermal comfort achieved when the temperature control is set to 23 ℃ (73 ℉). This adjustment also reduces cooling energy consumption to 1.23, which is lower than what is achieved with a PMV set to 0.1.

- Reducing the set point temperature from 23 ℃ (73F) to 21 ℃ (70F) helps maintain acceptable indoor thermal comfort when utilizing temperature control. However, this adjustment increases cooling energy consumption, rising from 1.87 to 2.16 kW/m^2.
- The climate's cooling degree days (CDD) increase the yearly cooling energy use difference between PMV and temperature control, and the variation in PPD levels follows the same pattern.

Finally, the extra expenses required to install a thermal comfort-based control may not be justified due to the low economic benefits, even with the better indoor thermal comfort levels achieved using it.

Author Contribution

Authors contributed in the design concept, data analysis. Maya Arida contributed to the writing of the manuscript, also worked on collecting the data and transforming it, proposing the model, designing and programming the models, comparative analysis, and conducted results. Dr. Megri has supervised the research and directed the authors through the research. Rand Talib helped throughout the research process.

References

[1] Arida, M., Nassif, N., Talib, R., and Abu-Lebdeh, T. 2017. "Building Energy Modeling Using Artificial Neural Networks." *Energy Research Journal* 7 (2): 24-34.

[2] Kim, J., Schiavon, S., and Brager, G. 2018. "Personal Comfort Models—A New Paradigm in Thermal Comfort for Occupant-Centric Environmental Control." *Building and Environment* 132: 114-24.

[3] da Silveira Hirashima, S. Q., Katzschner, A., Ferreira, D. G., de Assis, E. S., and Katzschner, L. 2018. "Thermal Comfort Comparison and Evaluation in Different Climates." *Urban Climate* 23: 219-30.

[4] Wang, H., Leung, L. K., Wang, W., and Bi, Q. 2018. "A Review of Recent Heat Transfer Studies to Supercritical Pressure Water in Channels." *Applied Thermal Engineering* 142: 573-96.

[5] Talib, R., Nassif, N., Arida, M., and Abu-Lebdeh, T. 2018. "Chilled Water VAV System Optimization and Modeling Using Artificial Neural Networks." *American Journal of Engineering and Applied Sciences* 11 (4): 1188-98.

[6] Di Napoli, C., Barnard, C., Prudhomme, C., Cloke, H. L., and Pappenberger, F. 2021. "ERA5-HEAT: A Global Gridded Historical Dataset of Human Thermal Comfort Indices from Climate Reanalysis." *Geoscience Data Journal* 8 (1): 2-10.

[7] Liu, J., Zhu, C., Liang, W., Li, Y., Bai, H., Guo, Q., and Wang, C. 2019. "Experimental Investigation on Micro-scale Phase Change Material Based on Sodium Acetate Trihydrate for Thermal Storage." *Solar Energy* 193: 413-21.

[8] Luo, J., Tuo, J., Huang, W., Zhu, Y., Jiao, Y., Xiang, W., and Rohn, J. 2018. "Influence of Groundwater Levels on Effective Thermal Conductivity of the Ground and Heat Transfer Rate of Borehole Heat Exchangers." *Applied Thermal Engineering* 128: 508-16.