Simulation-Based Evaluation of Predicted Mean Vote (PMV) Distributions Across HVAC Systems and Climate Zones

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Abstract
Predicted Mean Vote (PMV) is widely used in building performance simulation to evaluate thermal comfort; however, outcomes can vary by HVAC system type, climate zone, and calculation workflow. This study evaluates PMV outcomes in a simulated medium-sized open-plan office across seven ASHRAE climate zones using two HVAC configurations: Variable Air Volume with Reheat (VAV-Reheat) and Radiant with Dedicated Outdoor Air System (Radiant-DOAS). PMV results were calculated using Ladybug PMV Comfort (LB-PMV) and Honeybee PMV Comfort Map (HB-PMV). Hourly occupied PMV distributions, comfort-hour percentages within the −0.5 to +0.5 PMV range, and LB/HB differences were compared. Results show that HVAC system type and climate zone had a stronger influence on PMV outcomes than differences between LB-PMV and HB-PMV workflows. Radiant-DOAS generally produced narrower PMV distributions and higher comfort-hour percentages than VAV-Reheat. Across all climate zones, HB-PMV frequently exceeded LB-PMV, especially for Radiant-DOAS, where this occurred in approximately 95–100% of occupied hours. This shift is likely related to differences in the underlying calculation procedures, particularly HB-PMV's sensor-grid-based comfort mapping and Radiance-based longwave and shortwave mean radiant temperature calculations. These findings show that PMV simulation results should be interpreted with attention to HVAC system type, climate zone, and calculation procedure.

1 Introduction

Thermal comfort, defined as the mental state of satisfaction with the thermal environment (ASHRAE 2017), is crucial for the well-being, health, and performance of people in indoor environments (Zhang et al. 2019). Beginning in the 1960s, a variety of thermal comfort indices have been developed. Among these, the Predicted Mean Vote (PMV) model developed by P.O. Fanger (Fanger 1970) has emerged as the most widely adopted and influential. Fanger's equation evaluates the average thermal sensation of a group of people on a 7-point scale from cold (-3) to hot (+3). This assessment considers a specific combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. A PMV of zero represents Neutral or thermal neutrality, with the comfort zone defined by combinations of six parameters that maintain the PMV within the recommended range of -0.5 to +0.5. While predicting the thermal sensation of a population is crucial for identifying comfortable conditions, assessing people's satisfaction levels is even more useful. To address this, Fanger introduced an equation linking the PMV to the Predicted Percentage of Dissatisfied (PPD) to estimate the percentage of dissatisfied people with thermal conditions. This relationship was based on studies involving subjects in a controlled chamber, where indoor conditions were carefully regulated (de Dear and Brager 2002, p. 55; Fanger 1970).

The PMV equation was primarily derived from data reported by Nevins (1966), and was further developed by Fanger to predict thermal comfort under controlled, air-conditioned, steady-state conditions in a climate chamber. Fanger later expanded the dataset by combining results from multiple studies to increase the sample to 1396 participants to refine the PMV model (Fanger 1970; Van Hoof 2008).

The PMV model, a widely used design tool for thermal comfort standards (ASHRAE 2017; CEN 2007), is suggested to be universally applicable across various climates and building types, such as schools, commercial buildings, and hospitals. However, laboratory experiments and field studies have challenged the accuracy of the PMV model in predicting thermal comfort across different building types and climates (Humphreys and Fergus Nicol 2002; Van Hoof 2008; Schellen et al. 2012; Maiti 2014; Yang et al. 2015). The PMV model often underestimates or overestimates the thermal sensation and dissatisfaction in real applications, particularly in naturally ventilated buildings and under seasonal heating or cooling conditions (Becker and Paciuk 2009). These discrepancies often occur due to simplified assumptions about occupant behavior, clothing insulation, metabolic rate, adaptation, and environmental context (Humphreys and Fergus Nicol 2002; Nicol and Humphreys 2002).

Despite these limitations, PMV remains widely used in building performance simulation and workflows as an indicator of thermal comfort. In simulated environments such as Grasshopper, Ladybug, and Honeybee, components allow designers and researchers to calculate PMV from EPW weather files and indoor environmental conditions and to use these results as evidence of whether a space meets thermal comfort criteria. However, PMV-based simulation outputs should not be interpreted as direct evidence of real occupant thermal comfort. They are influenced by the assumptions embedded in the model, including HVAC system configuration, climate file, envelope properties, setpoint strategy, fixed metabolic rate and clothing insulation, air speed, and the calculation procedure used by each component.

This issue becomes particularly important when PMV results are used to compare design alternatives, such as HVAC systems across different climate zones. Under different modeling assumptions or calculation workflows, the same building model may produce different PMV distributions and comfort-hour percentages, affecting how thermal comfort is interpreted. Therefore, rather than treating PMV outputs as fixed or universal comfort evidence, designers and researchers should consider their sensitivity to HVAC system type, climate zone, and calculation workflow.

This study addresses this issue by examining how PMV-based comfort outcomes vary across HVAC system type, climate zone, and PMV calculation workflow in a simulated open-plan office environment. Two Ladybug Tools workflows are compared: the Ladybug PMV Comfort component (LB-PMV) and the Honeybee PMV Comfort Map component (HB-PMV) (Ladybug Tools [date unknown-a], [date unknown-b]). The analysis compares VAV-Reheat and Radiant-DOAS systems across seven climate zones, focusing on hourly PMV distributions, comfort-hour percentages, and differences between the two PMV calculation workflows.

2 Materials and Methods

2.1 Overview

This study used a simulation-based workflow to evaluate PMV-based thermal comfort outcomes across HVAC systems, climate zones, and PMV calculation methods. Rhino/Grasshopper was used as the modeling interface, with Ladybug Tools components, including Honeybee Energy, Ladybug, and Ironbug, connected to OpenStudio and EnergyPlus for building energy simulation and indoor environmental output generation. Ironbug was used to model the two HVAC system configurations: VAV-Reheat and Radiant-DOAS.

The analysis was conducted for a medium-sized, single-story open-plan office modeled as a single thermal zone. Simulations were performed across seven ASHRAE climate zones using climate-appropriate envelope properties. The study focused on hourly occupied Predicted Mean Vote (PMV) results calculated using two workflows: LB-PMV and HB-PMV Comfort Map. The purpose was not to validate the Fanger PMV model against occupant responses, but to compare PMV-based simulation outcomes across HVAC systems, climates, and calculation workflows under consistent input assumptions.

2.2 Building Geometry and Envelope Properties

Geometry was created using Rhino Grasshopper, providing a digital parametric study environment for an open-plan office building with dimensions of 16 m by 32 m and a floor-to-ceiling height of 4 m. The building was modeled with a 33% Window-to-wall ratio (WWR) on the south and north facades, and the south-facing overhang was included to mitigate direct solar gain. The construction parameters were selected to align with climate-zone-based reference standards, including ASHRAE 90.1-2019 and IECC 2021 (ASHRAE 2019; ICC 2021). The 'metal building' typology was designated as a construction type. Table 1 summarizes the building envelope properties for each climate.

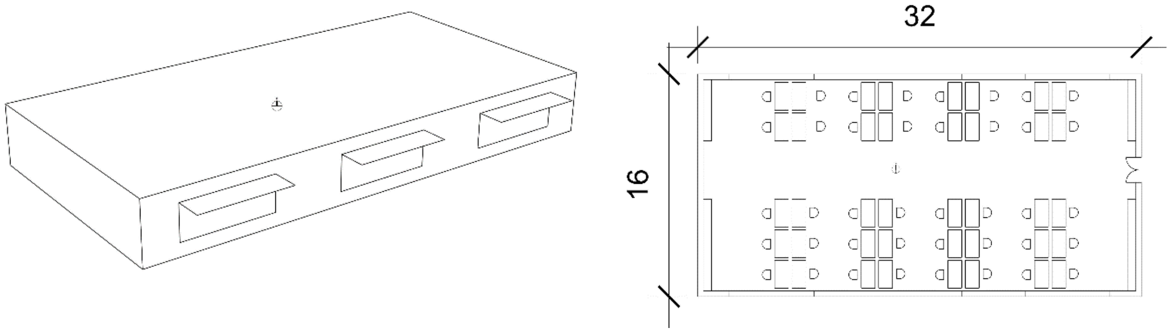


Figure 1. Office geometry, floor plan, and perspective view

Table 1. Envelope construction properties by climate zone

Climate Zone	Exterior Walls Layers	Glazing Layers
Miami (1A)	Typical Insulated Steel Framed Exterior Wall-R9	U 0.5
	25mm Stucco	u-factor {2.839 W/m2-K}
	5/8 in. Gypsum Board	SHGC 0.23
	Typical Insulation-R7	vt: 0.6
	5/8 in. Gypsum Board	
Phoenix (2B)	Typical Insulated Steel Framed Exterior Wall-R12	U 0.45
	25mm Stucco	u-factor {2.5551 W/m2-K}
	5/8 in. Gypsum Board	SHGC 0.25
	Typical Insulation-R11	vt: 0.6
	5/8 in. Gypsum Board	
San Francisco (3C)	Typical Insulated Steel Framed Exterior Wall-R13	U 0.42
Atlanta (3A)	25mm Stucco	u-factor {2.38476 W/m2-K}
	5/8 in. Gypsum Board	
	Typical Insulation-R12	SHGC 0.25
	5/8 in. Gypsum Board	vt: 0.6

Baltimore (4A)	Typical Insulated Steel Framed Exterior Wall-R16 25mm Stucco 5/8 in. Gypsum Board Typical Insulation-R15 5/8 in. Gypsum Board	U 0.36 u-factor {2.04408 W/m2-K} SHGC 0.36 vt: 0.6
Boston (5A)	Typical Insulated Steel Framed Exterior Wall-R19 25mm Stucco 5/8 in. Gypsum Board Typical Insulation-R17 5/8 in. Gypsum Board	U 0.36 u-factor {2.04408 W/m2-K} SHGC 0.38 vt: 0.6
Minneapolis (6A)	Typical Insulated Steel Framed Exterior Wall-R21 25mm Stucco 5/8 in. Gypsum Board Typical Insulation-R19 5/8 in. Gypsum Board	U 0.34 u-factor {1.93052 W/m2-K} SHGC 0.38 vt: 0.6

2.3 Schedules and Programs

The occupancy schedule was set from 9:00–17:00 all days. For the open office plan, the following schedules and program parameters are set within the simulation:

Temperature Setpoints. A fixed setpoint strategy was used across all climate zones, with a heating setpoint of 21°C and a cooling setpoint of 24°C. This fixed range was selected to compare PMV-based comfort outcomes across climate zones and HVAC systems under consistent setpoint assumptions.

Occupancy Density. 9 m^2 of floor area per person, with a total heat gain of 120 W per person.

Lighting and Equipment. The lighting power density was set at 5.5 W/m^2, and the equipment power density was set to 6.25 W/m^2, following the 8-hour occupancy pattern.

Infiltration. Set at 0.0003 (m^2/s per m^2 of facade) for an average building.

2.4 Ironbug's HVAC Systems

Two HVAC systems were modeled using Ironbug's HVAC component library: VAV-Reheat and Radiant-DOAS. The systems were translated into Open Studio and simulated using EnergyPlus. The EnergyPlus Input Output Reference, version 24.1 (EnergyPlus 2024), was used as the technical guideline.

Variable Air Volume (VAV) + Reheat. The VAV system, which has a reheat capability, controls the indoor climate. This system combined both air loops and plant loops. The air loop distributes the conditioned air throughout the space, while the reheat feature allows for precise temperature control in the zone. The plant loops consist of a hot water loop, chilled water loop, and condenser water loop. The hot water loop includes a boiler and variable flow pump, ensuring efficient heating. The chilled water loop comprises a water-cooled chiller, a secondary pump, and variable air volume handlers for cooling.

Radiant + Dedicated Outdoor Air System (DOAS). Contains radiant floor construction for direct and uniform heat distribution. Further, it has an air source heat pump system with chilled and hot water loops that efficiently provide heating and cooling through heat exchange from inside to outside. It also integrates with a DOAS to handle ventilation, improving air quality.

2.5 Thermal Comfort Assessment

Thermal comfort was evaluated using the HB-PMV Comfort Map and LB-PMV Comfort components to compare PMV-based thermal comfort outcomes across two calculation workflows, HVAC systems, and climate zones. The analysis focused on hourly occupied PMV distributions, comfort-hour percentages within the −0.5 to +0.5 PMV range, and differences between LB-PMV and HB-PMV results.

2.5.1 Description of Input Components

HB-PMV Comfort Map. Utilizes Energy Plus to obtain surface temperatures, indoor air, and humidities. It uses outdoor relative humidities, air temperatures, and air speeds directly from the EPW file. The model's Radiance sensor grids determine the comfort mapping location. Longwave radiant temperatures in Radiance are computed by calculating spherical view factors from each sensor to the surfaces in the room. These view factors are multiplied by Energy Plus the output of surface temperatures to yield longwave Mean Radiant Temperature (MRT) at each sensor. A radiation-based method is used for shortwave MRT calculations, accurately representing the direct sun by ray tracing from each sensor to the solar position. The HB-PMV input parameters are determined as follows:

- model: A Honeybee model for which PMV comfort will be mapped.
- epw: Path to an EPW weather file to be used for the comfort map simulation.
- ddy: Path to a DDY file with design days to be used for the initial sizing calculation of the energy simulation.
- air_speed: 0.1 m/s
- met_rate: 1.1 met for a seated person.
- clo_value: 1 clo for three pieces
- radiance_par: -ab 2 -ad 5000 -lw 2e-05

LB-PMV Comfort. Quantifies comfort metrics of the Predicted Mean Vote and the Percentage of People Dissatisfied, using Fanger's original equation, for an indoor environment with operational heating or cooling systems. The PMV component is a Python implementation of the Berkely Center for the Built Environment (CBE) Comfort Tool's (Tartarini et al., 2020) (Doherty & Arens, 1988) JavaScript PMV model. The PMV model used by the CBE Tool and this component follows calculation guidelines by the 2017 ASHRAE-55 (ASHRAE 2017) Thermal Comfort Standard for predicting PMV comfort. The LB-PMV input parameters are determined as follows:

- air_temp: Data induced by HB model + HVAC systems in C
- mrt: Data induced by HB model + HVAC systems, mean radiant temperature (MRT) in C
- air_speed: 0.1 m/s
- met_rate: 1.1 met, for a seated person.
- clothing: 1 clo for three pieces of suits
- pmv_par: PPD threshold of 10%, considered acceptable/comfortable.

LB-PMV parses all the room-level comfort-related results from a SQL file generated from an energy simulation (DOCS.ladybug-tools).

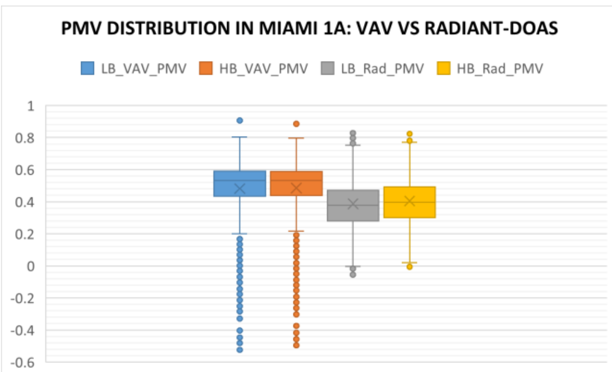
2.5.2 Data Analysis and Outcomes

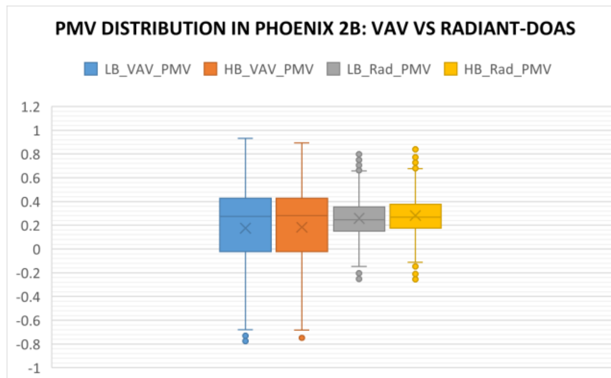
HB-PMV Outcomes. The HB-PMV Comfort Map generates CSV-formatted PMV maps for each sensor grid at each timestep of the analysis. These results were imported into the HB Read Thermal Matrix component, which reads the PMV thermal mapping results from the CSV output. The matrix object was then connected to the LB Deconstruct Matrix component to extract point-by-point and hourly PMV data. For each occupied hour, PMV values from the 512 sensor points were averaged to calculate one hourly spatial-average PMV value. These hourly spatial-average PMV values were used for comparison with the LB-PMV results.

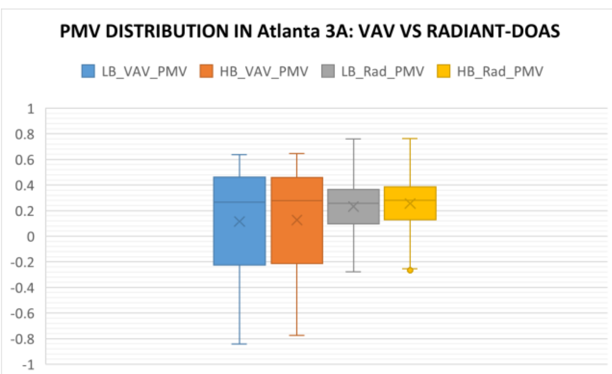
LB-PMV Outcomes. The LB-PMV output was filtered to the same occupied-hour analysis period and compared with the hourly HB-PMV results. Comfort hours were identified as hours in which PMV remained between −0.5 and +0.5.

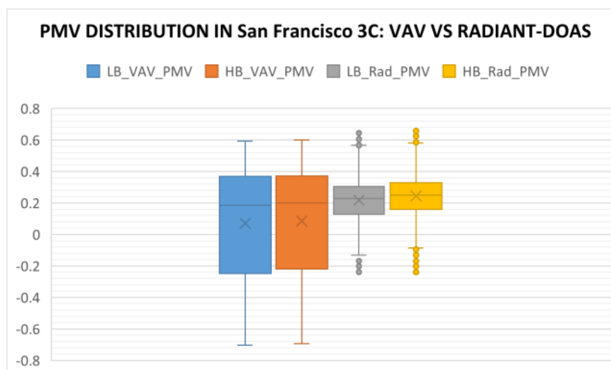
3 Results

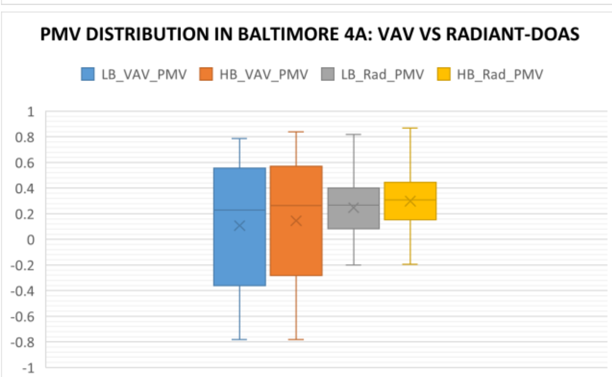
This section presents PMV-based thermal comfort results across seven climate zones for two HVAC systems: VAV-Reheat and Radiant-DOAS. Results are reported for both LB-PMV and HB-PMV calculations. The analysis focuses on hourly occupied PMV distributions, comfort-hour percentages within the −0.5 to +0.5 range, and differences between LB-PMV and HB-PMV.

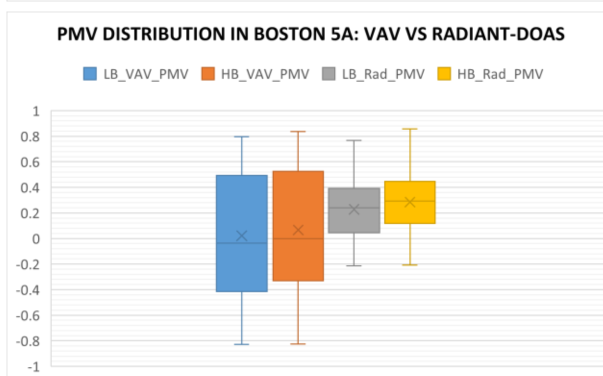












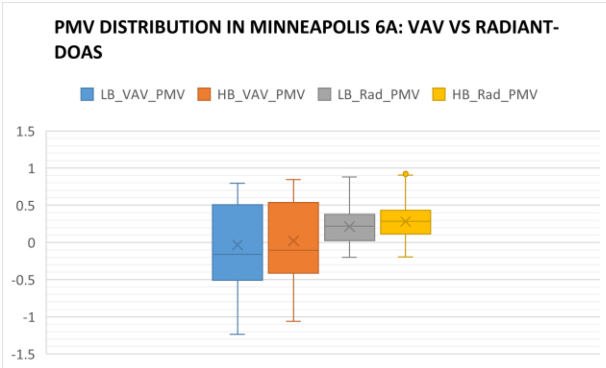


Figure 2. Hourly PMV distributions for VAV-Reheat and Radiant-DOAS systems across seven climate zones using LB-PMV and HB-PMV workflows.

Figure 2 shows that PMV distributions vary noticeably by climate zone and HVAC system. **Miami 1A.** For Miami 1A, the PMV distributions show a clear difference between the two HVAC systems. The VAV-Reheat system produced generally warmer PMV values, with both LB-PMV and HB-PMV centered near the upper side of the comfort range, around +0.45 to +0.50. The VAV distributions also show several lower outliers extending below neutral and toward slightly cool conditions, but most values remain concentrated in the warm-neutral range. In contrast, the Radiant-DOAS system produced lower PMV values, with the distributions centered closer to approximately +0.35 to +0.40. This suggests that, in the hot-humid Miami climate, Radiant-DOAS shifted the simulated thermal sensation slightly cooler compared with VAV-Reheat. However, both systems remained largely within the conventional PMV comfort band of −0.5 to +0.5, with only limited outliers outside the range.

The comparison between LB-PMV and HB-PMV shows strong agreement within each HVAC system. For VAV-Reheat, the LB and HB distributions are nearly overlapping, with similar medians, interquartile ranges, and outlier patterns. For Radiant-DOAS, HB-PMV appears slightly higher than LB-PMV, but the difference is modest. Overall, for Miami, the HVAC system effect is more visible than the difference between the LB-PMV and HB-PMV workflows.

Phoenix 2B. For Phoenix 2B, the PMV distributions show a smaller separation between VAV-Reheat and Radiant-DOAS than in several other climates. Both systems are centered within the acceptable PMV range, with mean/median values generally on the slightly warm side of neutral. The VAV-Reheat system shows a wider distribution than Radiant-DOAS, with values extending from slightly cool conditions to warmer conditions. This indicates greater hourly variability in simulated comfort under the air-based system. The Radiant-DOAS system has a tighter distribution, with most values concentrated between approximately +0.15 and +0.35, suggesting more stable PMV performance.

The LB-PMV and HB-PMV results are closely aligned for both HVAC systems. HB-PMV appears slightly higher than LB-PMV, especially for Radiant-DOAS, but the difference is modest and does not substantially change the overall interpretation. For Phoenix, the main pattern is therefore not a strong LB/HB discrepancy, but rather the reduced PMV variability under Radiant-DOAS compared with VAV-Reheat.

Atlanta 3A. For Atlanta 3A, the PMV distributions show a clearer difference between the two HVAC systems. The VAV-Reheat system has a much wider PMV spread, extending from cool conditions below −0.5 to warm conditions above +0.5. This indicates greater hourly variability in simulated PMV under the air-based system. The Radiant-DOAS system shows a more compact distribution, with most PMV values concentrated on the slightly warm side of neutral, roughly between +0.1 and +0.4. Compared with VAV-Reheat, Radiant-DOAS reduces the lower-end cool discomfort hours and keeps the PMV distribution more stable.

The LB-PMV and HB-PMV outputs remain broadly similar within each HVAC system. HB-PMV is slightly higher than LB-PMV, especially for the Radiant-DOAS case, but the overall distribution pattern is consistent between the two methods. For Atlanta, the dominant difference is therefore the wider variability of VAV-Reheat compared with the tighter Radiant-DOAS distribution, rather than a major discrepancy between LB-PMV and HB-PMV.

San Francisco 3C. For San Francisco 3C, the PMV distributions show relatively favorable comfort performance for both HVAC systems, but with different levels of variability. The VAV-Reheat system has a wider distribution, with PMV values extending from slightly cool conditions to slightly warm conditions. However, most values remain within the conventional comfort range. The Radiant-DOAS system shows a tighter distribution, with PMV values concentrated around the slightly warm-neutral range, approximately +0.2 to +0.3. This indicates more stable hourly PMV behavior compared with VAV-Reheat.

The LB-PMV and HB-PMV results are closely aligned for VAV-Reheat. For Radiant-DOAS, HB-PMV is slightly higher than LB-PMV and shows a few upper outliers, but the overall distributions remain similar. In San Francisco, the mild climate appears to support high comfort performance across both systems, while Radiant-DOAS still produces a narrower PMV distribution than VAV-Reheat.

Baltimore 4A. For Baltimore 4A, the PMV distributions show a strong contrast between the two HVAC systems. The VAV-Reheat system has a wide PMV range, extending from cool conditions below −0.5 to warm conditions above +0.5. This indicates substantial hourly variability, even though the central tendency remains near the neutral to slightly warm range. The Radiant-DOAS system produces a more compact PMV distribution, with most values concentrated between approximately +0.15 and +0.45. Compared with VAV-Reheat, it reduces the lower-end cool PMV values and shifts the distribution toward a more stable slightly warm-neutral condition.

The LB-PMV and HB-PMV outputs follow similar patterns for both HVAC systems. HB-PMV is slightly higher than LB-PMV, especially for Radiant-DOAS, but the overall difference remains modest compared with the difference between HVAC systems. For Baltimore, the main result is therefore the wider PMV variability under VAV-Reheat and the more concentrated distribution under Radiant-DOAS.

Boston 5A. For Boston 5A, the PMV distributions again show a clear difference between VAV-Reheat and Radiant-DOAS. The VAV-Reheat system has a broad PMV distribution, extending from cool conditions below −0.5 to warm conditions above +0.5. This indicates that, even with the same setpoint assumptions, hourly PMV values fluctuate substantially under the air-based system. The Radiant-DOAS system produces a narrower and more concentrated PMV distribution. Most values are clustered in the slightly warm-neutral range, approximately between +0.1 and +0.45, with fewer hours extending into cool discomfort compared with VAV-Reheat.

The LB-PMV and HB-PMV results are generally consistent within each HVAC system. HB-PMV is slightly higher than LB-PMV, particularly in the Radiant-DOAS case, but the difference is modest. For Boston, the main pattern is the larger PMV variability under VAV-Reheat and the more stable PMV distribution under Radiant-DOAS.

Minneapolis 6A. For Minneapolis 6A, the PMV distributions show one of the strongest contrasts between the two HVAC systems. The VAV-Reheat system has the widest PMV range, extending from substantially cool conditions below −1.0 to warm conditions above +0.5. This indicates large hourly variability in the cold climate case, with many values falling below the conventional comfort range. The Radiant-DOAS system produces a much narrower distribution, with PMV values concentrated mostly between approximately 0.0 and +0.45. Compared with VAV-Reheat, Radiant-DOAS substantially reduces the lower-end cool PMV values and shifts the distribution toward a more stable neutral-to-slightly-warm range.

The LB-PMV and HB-PMV output remain broadly consistent, although HB-PMV is slightly higher than LB-PMV in both HVAC systems. For Minneapolis, the HVAC-system difference is much larger than the LB/HB workflow difference. This case strongly supports the finding that, under the modeled assumptions, cold-climate PMV outcomes are highly sensitive to HVAC system type, with VAV-Reheat producing greater variability and Radiant-DOAS producing a more stable distribution.

After examining the hourly PMV distributions, the comfort-hour percentage was calculated to compare how often each case remained within the acceptable PMV comfort range.

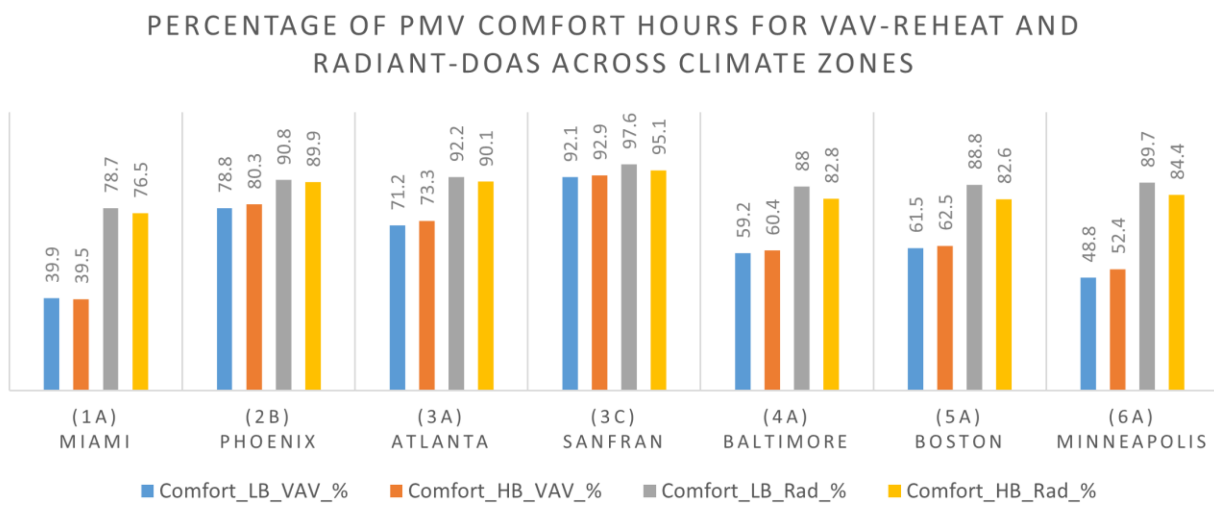


Figure 3. Percentage of occupied hours within the PMV comfort range for VAV-Reheat and Radiant-DOAS systems across seven climate zones. Comfort hours were defined as hours with PMV between −0.5 and +0.5. Results are shown for both LB-PMV and HB-PMV calculations.

As shown in Figure 3, across the seven climate zones, the percentage of occupied hours within the PMV comfort range varied substantially by HVAC system. Radiant-DOAS consistently produced a higher percentage of comfort hours than VAV-Reheat in both the LB-PMV and HB-PMV results. This difference was especially pronounced in Miami 1A, Baltimore 4A, Boston 5A, and Minneapolis 6A, where the VAV-Reheat comfort-hour percentages were noticeably lower, while Radiant-DOAS remained relatively high.

The highest comfort-hour percentages occurred in San Francisco 3C, where both HVAC systems performed well, suggesting that the milder climate reduced the difference between system types. In contrast, Miami 1A and Minneapolis 6A showed the lowest VAV-Reheat comfort-hour percentages, indicating that the fixed setpoint strategy did not produce equivalent PMV-based comfort performance across climate zones.

The comparison between LB-PMV and HB-PMV shows broadly similar comfort-hour percentages within each HVAC system. Differences between the two PMV workflows were generally small compared with the differences between VAV-Reheat and Radiant-DOAS. This suggests that, under the modeled assumptions, HVAC system type and climate zone had a stronger influence on PMV comfort-hour outcomes than the choice between LB-PMV and HB-PMV calculations. To isolate the effect of the PMV calculation method within each HVAC system, LB-PMV and HB-PMV comfort-hour percentages were compared separately for VAV-Reheat and Radiant-DOAS.

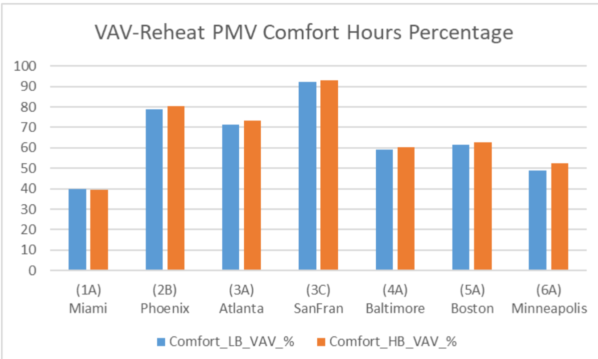


Figure 4. Comparison of LB- and HB-based PMV comfort-hour percentages for the VAV-Reheat system across seven climate zones.

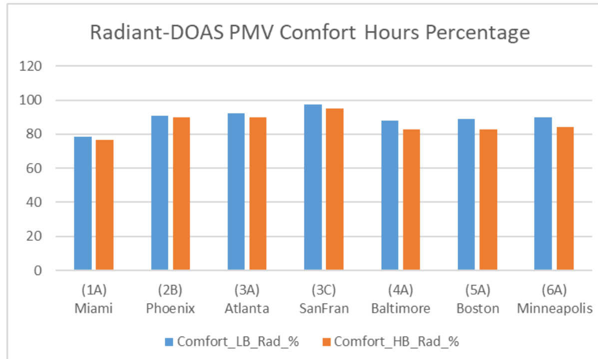


Figure 5. Comparison of LB- and HB-based PMV comfort-hour percentages for the Radiant-DOAS system across seven climate zones.

As shown in Figures 4 and 5, the LB-PMV and HB-PMV calculations produced broadly similar comfort-hour percentages within each HVAC system. For the VAV-Reheat system (Figure 4), the two methods follow nearly the same trend across climate zones. The largest differences are small, and both methods identify the same general pattern: higher comfort-hour percentages in San Francisco 3C and Phoenix 2B, and lower comfort-hour percentages in Miami 1A and Minneapolis 6A.

For the Radiant-DOAS system (Figure 5), LB-PMV and HB-PMV also show similar overall trends, although LB-PMV produces slightly higher comfort-hour percentages than HB-PMV in most climate zones. Despite this difference, both methods indicate consistently high comfort-hour percentages for Radiant-DOAS across all climates, generally above the VAV-Reheat results shown in Figure 4.

Overall, Figures 4 and 5 suggest that the differences between LB-PMV and HB-PMV are relatively modest compared with the differences caused by HVAC system type and climate zone. This supports the interpretation that the two PMV calculation workflows produce broadly consistent comfort-hour classifications when the same model assumptions are used.

Beyond comfort-hour classification, the hourly PMV values were further compared to evaluate whether one workflow systematically produced higher PMV values than the other.

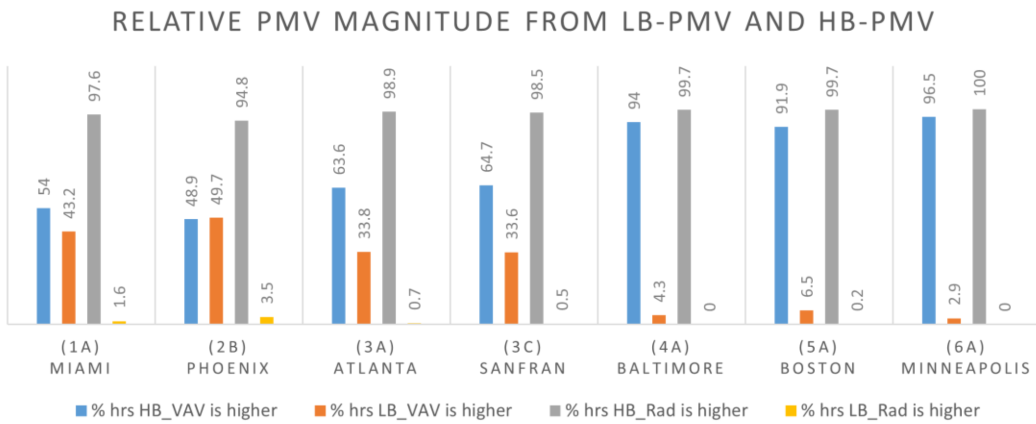


Figure 6. Percentage of occupied hours in which LB-PMV or HB-PMV produced the higher PMV value for VAV-Reheat and Radiant-DOAS across seven climate zones.

As shown in Figure 6, HB-PMV produced higher PMV values than LB-PMV for a large share of occupied hours, especially in the Radiant-DOAS cases. For Radiant-DOAS, HB-PMV was higher than LB-PMV in nearly all occupied hours across most climates, ranging from about 94.8% in Phoenix 2B to 100% in Minneapolis 6A. This indicates a consistent upward shift in HB-PMV relative to LB-PMV for the radiant system.

For VAV-Reheat, the pattern was more climate-dependent. In Miami 1A and Phoenix 2B, the percentage of hours where HB-PMV was higher was closer to the percentage where LB-PMV was higher, suggesting weaker directional separation. However, in Baltimore 4A, Boston 5A, and Minneapolis 6A, HB-PMV was higher in more than 90% of occupied hours. This suggests that the HB-PMV calculation tended to produce warmer PMV values than LB-PMV, especially in cooler climates.

Figure 7 shows that although HB-PMV often produced higher PMV values than LB-PMV, the average size of the difference was generally modest. Mean absolute differences increased from warmer to colder climates, with the smallest differences in Miami 1A and the largest in Minneapolis 6A. Differences were also consistently larger for Radiant-DOAS than for VAV-Reheat. Overall, these results suggest that HB-PMV often shifts PMV values slightly upward relative to LB-PMV, but the average magnitude of the difference remains small compared with the broader HVAC-system and climate effects observed in the PMV distribution and comfort hour results.

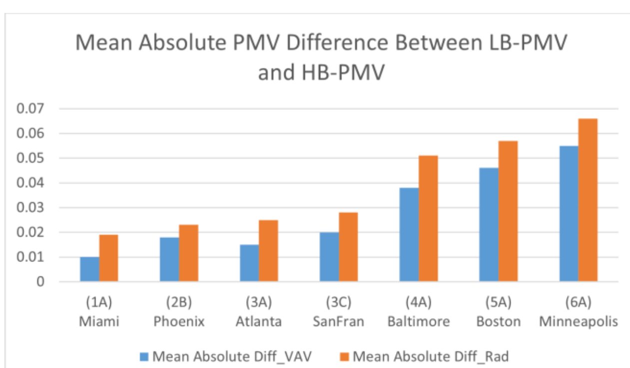


Figure 7. Mean absolute difference between LB-PMV and HB-PMV values for VAV-Reheat and Radiant-DOAS systems across seven climate zones.

Table 2. Summary of annual occupied-hour PMV results across seven climate zones. The table reports mean PMV, percentage of occupied hours within the PMV comfort range, and mean absolute PMV difference between LB-PMV and HB-PMV for VAV-Reheat and Radiant-DOAS systems. Comfort hours are defined as hours with PMV between −0.5 and +0.5

Metric	**Miami 1A**	**Phoenix 2B**	**Atlanta 3A**	**San Francisco 3C**	**Baltimore 4A**	**Boston 5A**	**Minneapolis 6A**
Mean PMV: LB-VAV	0.482	0.176	0.116	0.071	0.107	0.022	-0.034
Mean PMV: HB-VAV	0.485	0.184	0.127	0.085	0.145	0.067	0.021
Mean PMV: LB-Rad	0.387	0.259	0.232	0.217	0.248	0.228	0.213
Mean PMV: HB-Rad	0.405	0.282	0.257	0.245	0.299	0.285	0.28
Comfort Hours: LB-VAV (%)	39.9	78.8	71.2	92.1	59.2	61.5	48.8
Comfort Hours: HB-VAV (%)	39.5	80.3	73.3	92.9	60.4	62.5	52.4
Comfort Hours: LB-Rad (%)	78.7	90.8	92.2	97.6	88	88.8	89.7
Comfort Hours: HB-Rad (%)	76.5	89.9	90.1	95.1	82.8	82.6	84.4
Mean |ΔPMV|: VAV	0.01	0.018	0.015	0.02	0.038	0.046	0.055
Mean |ΔPMV|: Rad	0.019	0.023	0.025	0.028	0.051	0.057	0.066

Table 2 summarizes the main PMV metrics across all climate zones and HVAC systems. The results confirm the trends observed in the figures: Radiant-DOAS produced higher comfort-hour percentages than VAV-Reheat in every climate zone, while VAV-Reheat showed greater variation in comfort performance across climates. The lowest VAV comfort-hour percentages occurred in Miami 1A and Minneapolis 6A, whereas San Francisco 3C produced the highest comfort-hour percentages for both systems. The mean absolute PMV difference between LB-PMV and HB-PMV was relatively small in all cases but increased from warmer to colder climates and was generally larger for Radiant-DOAS than for VAV-Reheat.

Overall, the results indicate that HVAC system type and climate zone had a stronger effect on PMV-based comfort outcomes than the difference between LB-PMV and HB-PMV.

4 Discussion

The results indicate that PMV-based thermal comfort outcomes were more strongly affected by HVAC system type and climate zone than by differences between the LB-PMV and HB-PMV calculation workflows. Across the seven climate zones, Radiant-DOAS generally produced narrower PMV distributions and higher percentages of occupied hours within the conventional PMV comfort range compared with VAV-Reheat. This pattern was especially visible in Baltimore 4A, Boston 5A, and Minneapolis 6A, where VAV-Reheat showed wider PMV distributions and more hours outside the −0.5 to +0.5 comfort range. These findings suggest that, under controlled input assumptions, HVAC system type and heat-transfer mechanism had a substantial influence on simulated thermal comfort outcomes.

The narrower PMV distributions and higher comfort-hour percentages observed for Radiant-DOAS indicate improved PMV-based thermal comfort performance relative to the air-based VAV-Reheat system. Unlike VAV-Reheat, which primarily conditions the entire air volume in the room to maintain occupant comfort through convective heating and cooling, heat exchange in the radiant system occurs through radiation and conduction, affecting comfort partly through surface temperature and mean radiant temperature. Because PMV is influenced by both air temperature and mean radiant temperature, these different heat-transfer mechanisms help explain why the two HVAC systems produced different PMV distributions. However, the results should not be interpreted as evidence that one HVAC system is universally superior across all climates, setpoint strategies, and system configurations. Rather, they show that PMV-based thermal comfort performance is shaped by the interaction among HVAC system type, heat-transfer mechanism, indoor environmental conditions, and climate zone.

The results also show that a fixed setpoint strategy did not produce equivalent PMV-based comfort outcomes across climate zones. Although the same heating and cooling setpoints were applied across the simulations, comfort-hour percentages varied substantially by climate. San Francisco 3C showed the highest comfort-hour percentages across both systems, while Miami 1A and Minneapolis 6A showed lower VAV-Reheat comfort-hour percentages. This indicates that maintaining the same thermostat setpoints does not necessarily lead to comparable PMV-based comfort performance in different climates. Since PMV depends on multiple environmental inputs, including air temperature, mean radiant temperature, humidity, air speed, metabolic rate, and clothing insulation, setpoint control alone cannot fully explain or guarantee simulated comfort outcomes.

The comparison between LB-PMV and HB-PMV showed similar overall patterns. In most cases, both workflows identified comparable relative differences between HVAC systems and climate zones. However, HB-PMV often produced slightly higher and wider PMV distributions than LB-PMV, especially in the Radiant-DOAS cases. Although this shift was observed across many cases, the average difference between the two workflows remained small, as shown by the mean absolute PMV differences. Therefore, the LB-PMV and HB-PMV differences did not substantially change the main comfort interpretation, but they indicate that PMV outputs can shift when different calculation workflows are used to represent indoor environmental conditions and mean radiant temperature.

These differences are consistent with the different calculation procedures used by the two workflows. The LB-PMV component calculates PMV from input values or data collections for air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. By contrast, the HB-PMV Comfort Map is a spatially resolved comfort-mapping workflow. According to the component documentation, HB-PMV uses EnergyPlus to obtain surface temperatures, indoor air temperatures, and indoor humidities, while Radiance sensor grids determine the locations where comfort is evaluated. Longwave mean radiant temperature is calculated from spherical view factors between sensors and room surfaces, combined with EnergyPlus surface-temperature outputs. Shortwave mean radiant temperature is calculated using a Radiance-based enhanced two-phase method, which accounts for direct sun and solar transmission through the envelope.

The more spatially detailed calculation of radiant conditions in HB-PMV may explain why it produced slightly higher or wider PMV values than LB-PMV in several cases. HB-PMV evaluates PMV across sensor-grid locations and includes more detailed longwave and shortwave radiant calculations, while LB-PMV depends on the environmental data collections provided as inputs and does not represent the same level of spatial radiant detail. The relatively small difference between the two workflows in this study may be partly related to the simplified single-zone open-office model. Larger differences may occur in more spatially complex models, multi-zone layouts, or spaces with greater solar exposure, surface-temperature variation, or localized radiant effects.

Overall, the findings suggest that PMV-based simulation results should be interpreted as model-dependent outcomes rather than standalone measures of thermal comfort performance. In this study, HVAC system type and climate zone had a stronger influence on PMV distributions and comfort-hour percentages than the differences between LB-PMV and HB-PMV calculations. Because the analysis is based on simulation outputs rather than measured occupant responses, the results should be understood as a comparison of PMV-based simulation outcomes rather than a validation of occupant comfort.

4.1 Limitations

This study has several limitations. First, the analysis is based entirely on simulation outputs and does not include field measurements, occupant surveys, or actual thermal sensation votes. Second, the analysis was conducted using single-zone, medium-sized open-plan office geometry. The results may differ for other building types, envelope properties, internal load, occupancy patterns and more complex spatial configurations, including multi-zone layouts, greater solar exposure, and surface-temperature variation. Similarly, the study used one fixed setpoint strategy across all climate zones. While this helped isolate differences among HVAC systems, climate zones, and PMV calculation workflows, it does not represent optimized operation for each climate or system type.

Third, the study focused only on PMV-based comfort assessment. Adaptive comfort models, local thermal discomfort criteria, and personal comfort models were not included. This is important because PMV assumes standardized occupant characteristics, such as fixed metabolic rate and clothing insulation, while actual thermal comfort varies across individuals based on physiological, behavioral, psychological, and environmental factors. Finally, the HVAC systems were simulated using specific system configurations and control assumptions. Different system configurations, radiant surface designs, ventilation strategies, control sequences, or setpoint ranges could produce different PMV distributions and comfort-hour percentages.

4.2 Future Work

Future work should extend PMV-based simulation studies toward more occupant-centered and data-driven thermal comfort assessment. While this study compares PMV outcomes under controlled simulation inputs, real thermal comfort depends on a wider range of occupant-centric and contextual factors than those represented in standard PMV assumptions. Future studies should therefore combine simulated environmental variables, such as air temperature, mean radiant temperature, relative humidity, and air speed, with measured occupant responses, physiological factors, clothing and activity level, thermal history, and individual comfort preferences. Importantly, these datasets should include more diverse participant populations so that comfort models can better reflect variation in age, gender, body mass, cultural background, adaptation, and personal thermal preference.

A further research direction is the development and integration of machine-learning-based personal comfort models into building simulation workflows. While PMV remains widely used, it assumes average thermal sensation of a group of people and cannot fully represent individual differences in thermal sensation and comfort preference. Data-driven personal comfort models could be developed as complementary tools or future simulation components within platforms such as Ladybug and Honeybee. This would allow comfort prediction to move beyond generic group assumptions and toward more personalized, real-world-responsive comfort assessment.

Future work should also test additional building and system scenarios. Although this study used climate-appropriate envelope properties for each climate zone, the analysis was limited to one office geometry and one fixed setpoint strategy. Future studies could examine different building geometries, spatial layouts, internal load programs, HVAC configurations, radiant surface designs, ventilation strategies, and control sequences. Additional setpoint strategies, including climate-specific setpoints, wider comfort bands, and adaptive control approaches, could also be evaluated to determine how operating assumptions affect PMV distributions and comfort-hour percentages.

Finally, future work could further examine the underlying calculation procedures and modeling assumptions used in the LB-PMV and HB-PMV workflows. This could include sensitivity testing of mean radiant temperature calculation, spatial sensor-grid resolution, longwave and shortwave radiation treatment, aggregation methods, and input-data handling. Such analysis would improve transparency in PMV-based simulation workflows and help designers and researchers interpret comfort outputs more reliably.

5 Conclusion

This study evaluated PMV outcomes in a simulated open-plan office across seven ASHRAE climate zones using VAV-Reheat and Radiant-DOAS systems. The results showed that HVAC system type and climate zone had a stronger influence on PMV distributions and comfort-hour percentages than differences between the LB-PMV and HB-PMV workflows. Radiant-DOAS generally produced narrower PMV distributions and higher percentages of thermal comfort within the −0.5 to +0.5 range compared with VAV-Reheat, although the magnitude varied by climate.

The comparison between LB-PMV and HB-PMV showed broadly similar trends across HVAC systems and climate zones. However, HB-PMV frequently exceeded LB-PMV, especially for Radiant-DOAS, likely due to differences in the underlying calculation procedures, particularly HB-PMV's sensor-grid-based comfort mapping and Radiance-based longwave and shortwave MRT calculations. Overall, the findings suggest that PMV simulation results should not be interpreted as direct evidence of occupant thermal comfort without considering the simulation assumptions and calculation workflow. Instead, they should be reported and evaluated with attention to HVAC system type, climate zone, setpoint assumptions, and the calculation workflow used to generate thermal comfort outputs.

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