Computation of Active and Passive Thermal Comfort Models in Warm-Humid Climates

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Abstract

This essay gives a comparative analysis of active and passive thermal comfort models, with specific reference to their usability in warm-humid climates like Mumbai. Active models, based on the exact control of indoor thermal parameters, lay stress on mechanical cooling and dehumidification for comfort. Conversely, passive or adaptive strategies acknowledge the potential of the occupants to adapt by behavioral and psychological adjustment and thus stretch comfort boundaries and minimize dependence on high-energy systems. Psychrometric analysis was used to analyze the annual distribution of comfort hours and show the impact of temperature, humidity, solar radiation, and ventilation potential on indoor conditions. Results indicate that active models provide a strict comfort zones that require ongoing mechanical adjustment, specifically during the pre-monsoon and monsoon seasons when high latent loads prevail. Passive models, in contrast, shows better flexibility, providing a wide range of comfort, and promotes the use of methods like solar shading, natural ventilation, and increased air movement. The research concludes that even though active strategies are required for well-conditioned environments, passive models provide more reliable and sustainable solutions for the buildings in warm-humid climates. An integrated design approach that combines passive and selective active control is suggested as the most viable route to gaining thermal comfort while minimizing energy use.

Keywords-Thermal comfort, Active models, Passive models, Adaptive comfort, Warm-humid climate, Psychrometric analysis, Solar heat gain, Natural ventilation, Dehumidification, Sustainable building design.

1.INTRODUCTION

Thermal comfort is a basic requirement for indoor environmental quality to determines both occupant's health and building energy efficiency [1, 2]. In hot-humid climates like Mumbai, it is especially difficult to achieve comfort due to continuously high temperatures, high humidity, and strong solar radiation for most of the year [3]. Such climatic conditions cause not only discomfort but also put a major strain on building systems, usually resulting in greater dependency on mechanical dehumidification and cooling [4]. There are several factors that have influence on thermal comfort, the most affective on human thermal comfort are environmental factors which cover many aspects, the important ones being air, temperature, humidity, radiant and air movement. Also, metabolic rate which is generated by human activity and body insulation which is clothing. Thermal comfort is the condition of mind which expresses satisfaction with the indoor environment. When majority of the people will not feel discomfort in the climatic condition that can be termed as thermal comfort. The comfort is measured on the basis of Discomfort Degree hours (DDH). DDH is the sum of the hourly room air temperature outside comfort zone.

India has a diverse climatic condition. Many different climatic regions can be identified in the country like cool of mountains in the North to Composite climate of Gangetic Plain, the hot desert of Rajasthan and the warm and humid breeze of the South and East. Every region has its own flavour of Architectural and Cultural traditions showing its particular climate. Also, in most areas there are yearly extremes of the weather between the high summer of May and June and the cold winter of January. Hence it is not logical to use a single temperature throughout the country. The approach using the theory of adaptive model of thermal comfort is to relate thermal comfort indoors to the conditions prevailing outdoors. A field reconnaissance should be carried out to study the thermal comfort in each of the climatic zone for different seasons and different times of the year.

The selection of thermal comfort model thus has a critical function to ascertain design strategy and operational practices for buildings in such conditions. Active thermal comfort models, founded on the maintenance of steady-state indoor conditions within very narrowly defined boundaries, stress the value of accurate control of environments [5]. They tend to prescribe constant mechanical intervention, calling for both cooling and humidity control to maintain comfort. Even though they have efficient system in the design of homogeneous indoor conditions, such models have a tendency to ignore the natural adaptability of human beings [6]

Adaptive or passive models, on the other hand, takes into account that comfort is dynamic rather than constant and is determined by external weather, personal behavior, and social expectations [7]. They recognize that people can adapt by modification of clothing, modification of activity levels, space use modification, or the use of simple environmental controls like windows and fans. This approach broadens the acceptable indoor range, especially in naturally ventilated or hybrid buildings, and opens the potential for the incorporation of passive strategies like shading, cross-ventilation, and increased air movement into building design. Active versus passive comparison is highly important in hot-humid climates, where the both issues of high solar heat gains and high latent loads dominate thermal discomfort. Active strategies guarantee effectiveness but at the cost of high energy use, whereas passive strategies promote sustainability and flexibility [7-10]. This research explores the effectiveness of active and passive thermal comfort models for the climate of Mumbai using psychrometric analysis and solar exposure evaluation. using the assessments of comfort hour distribution, the solar radiation influence, ventilation and dehumidification roles by season. The study focuses on the limitations and advantages of both approaches. The results offer a platform for creating combined strategies that balance comfort with energy efficiency, helping to make sustainable buildings in warm-humid climates.

Table I: Classification of Passive Cooling Strategies

Strategy Type	Passive Cooling Technique	Cooling Mechanism
Ventilation-Based	Cross Ventilation	Heat removal via air movement
	Stack Ventilation	Buoyancy-driven airflow
	Wind Towers	Wind-induced air circulation
Heat Gain Control	Shading Devices	Solar radiation blockage
	Reflective Roofs / Cool Roofs	Reduction of heat absorption
	Thermal Insulation	Slowing heat transfer through walls
Heat Dissipation	High Thermal Mass	Delayed heat release (night cooling)
Evaporative Techniques	Water Bodies / Fountains	Heat loss through water evaporation
Landscaping	Vegetative Shading / Green Roofs	Shading, evapotranspiration
Architectural Planning	Orientation and Layout	Optimizing solar and wind exposure

2. METHODS AND MATERIALS

The study was conducted using a combination of climate data analysis and psychrometric evaluation to compare active and passive thermal comfort models in the context of Mumbai's warm-humid climate. The methodological approach consisted of three main components: climatic data collection, thermal comfort analysis, and interpretation of design implications.

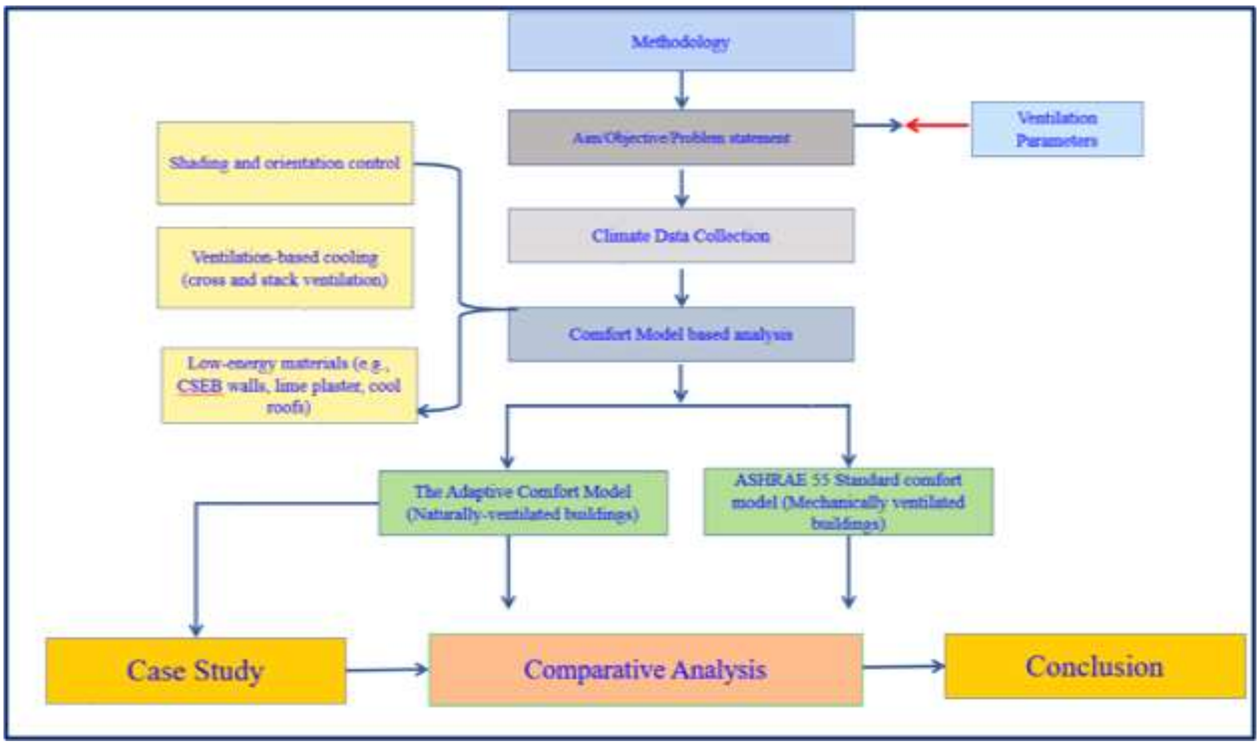

Fig. 1 Methodology for the study.

2.1 Climatic Data Collection

Hourly climatic data for Mumbai were obtained from a standard weather dataset, including parameters such as dry bulb temperature, relative humidity, dew point temperature, wind speed, and solar radiation. These datasets were selected to provide an accurate representation of typical meteorological conditions in the region and were used as the basis for all subsequent thermal comfort assessments. The warm-humid nature of the climate, characterized by extended periods of high temperature and humidity, makes Mumbai an appropriate case study for testing the applicability of both active and passive comfort approaches.

Following figure shows the monthly climate parameter used as input for Adaptive comfort model

2.2 Thermal Comfort Analysis

Thermal comfort conditions were evaluated using two different modeling approaches. The first approach, referred to as the active model, was based on maintaining comfort within fixed indoor parameters through precise control of temperature and humidity. This model assumes steady-state conditions and highlights the need for mechanical cooling and dehumidification. The second approach, referred to as the passive or adaptive model, accounted for occupant adaptation to outdoor conditions and seasonal variability. This method allows for a broader comfort range by incorporating behavioral and psychological adjustments, such as changes in clothing, the use of ceiling fans, and reliance on natural ventilation.

Psychrometric analysis was carried out using specialized software tools to map climatic data onto comfort zones defined by the two models. The analysis included identifying the number of annual hours falling within each comfort zone and determining the percentage of hours that required intervention through strategies such as shading, ventilation, dehumidification, or mechanical cooling. Solar exposure charts were also employed to examine the influence of solar angles on building façades, providing insights into the design of shading devices.

2.3 Interpretation of Design Implications

The comparative results from the active and passive models were used to assess the suitability of different strategies for Mumbai's climate. The analysis highlighted the distribution of comfort hours under each approach and identified critical periods when discomfort is driven by solar heat gain, high humidity, or a combination of both. This evaluation formed the basis for deriving design recommendations, emphasizing integrated approaches that balance passive techniques with selective active intervention.

2.4 Residential building comfort based on Adaptive model

In this study, the Adaptive Comfort Model was used to evaluate thermal comfort in a naturally ventilated school building located in a warm-humid region. Unlike the static PMV (Predicted Mean Vote) model, the adaptive model recognizes that occupants in naturally ventilated buildings can adjust their behavior based on the outdoor environment—by changing clothing, opening windows, or using fans—thus "adapting" to varying temperatures.

This model is based on field studies and is especially suitable for climates where indoor spaces are not mechanically conditioned. It relates indoor comfort temperature directly to outdoor air temperature, reflecting real-world adaptation by building occupants.

For Mumbai region, study has been carried out between Jan-Dec 2024 and following data has been used in Climate Consult software.

ASHRAE Standard 55 [48] gives guidelines for Thermal Environmental Conditions for human occupancy. This Standard was accepted in 1966 and since then become a golden standard for evaluating thermal comfort for human occupancy. The standard is based on Fanger's PMV index [48], which is a widely accepted model for thermal comfort research. AHSRAE 55 is also referenced in international standards like Europe's EN 15251, ISO 7730, and China's GB/T 50785. ASHRAE 55 outlines an extensive framework for designing indoor environments to achieve thermal comfort. It considers factors like temperature, humidity, air velocity, metabolic rate, and clothing insulation of the occupants. To access thermal comfort it uses models such as PMV/PPD and other adaptive comfort models. This standard ensures that a majority of the occupants will be satisfied with their thermal environment.

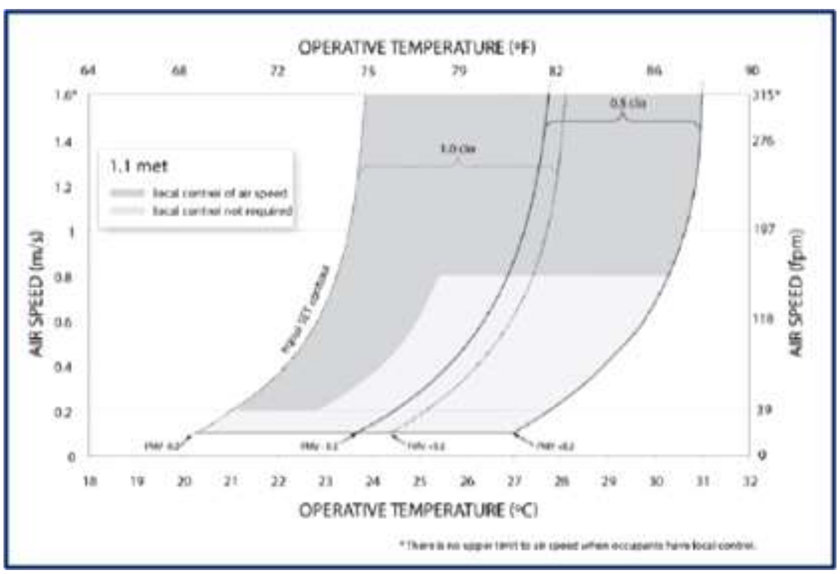

Fig 2 Acceptable ranges of operative temperature (Based upon ASHRAE 55, [48])

One more important term given by ASHRAE is Operative temperature. Operative temperature is a key concept in ASHRAE Standard 55, combining the effects of air temperature and mean radiant temperature to provide a measure of the overall thermal environment perceived by occupants. The acceptable ranges of operative temperature vary depending on several factors such as clothing insulation, metabolic rate, and the type of building (e.g., naturally ventilated vs. mechanically ventilated).

Operative temperature (***To***) is defined as the average of the air temperature (***Ta***) and the mean radiant temperature (***Tr***), weighted by their respective heat transfer coefficients. It is given by:

$$T_0 = \frac{(h_a.T_a) + (h_r.T_r)}{h_a + h_r} \quad \text{-------(1)}$$

where ***ha*** and ***hr*** are the heat transfer coefficients for air and radiant heat, respectively.

This operative temperature can be used to recognize comfort zones. The comfort zone is the range of operative temperatures in which 80% or more of occupants are expected to find the thermal environment acceptable. According to ASHRAE 55, the acceptable ranges depend on seasonal clothing levels and activity levels. For naturally ventilated buildings, ASHRAE 55 incorporates an adaptive comfort model, which recognizes that occupants in these buildings can adjust their behavior (e.g., by opening windows) to achieve comfort. In adaptive thermal models, the operative temperature range is determined by mean indoor temperature. This means temperature in usually higher for mechanically conditioned spaces. if the outdoor temperature is 25°C (77°F), the acceptable indoor temperature might range from 23°C to 30°C (73°F to 86°F).

ASHRAE's 7-point thermal scale is the most widely used scale for assessing occupant's thermal comfort. Although this scale is subjective it it offers a means of quantifying occupants' perception about its environment. This scale is the backbone of ASHRAE standard 55 and is accepted as the industry standard for assessing human thermal comfort. This scale ranges from -3 to +3, with each point representing a specific thermal sensation as shown in the above figure.This scale is used as a benchmark indicator to improve the occupants' well-being as well as productivity by ensuring that thermal conditions are well maintained.

3. RESULTS AND DISCUSSION

3.1 Residential building comfort based on Adaptive model

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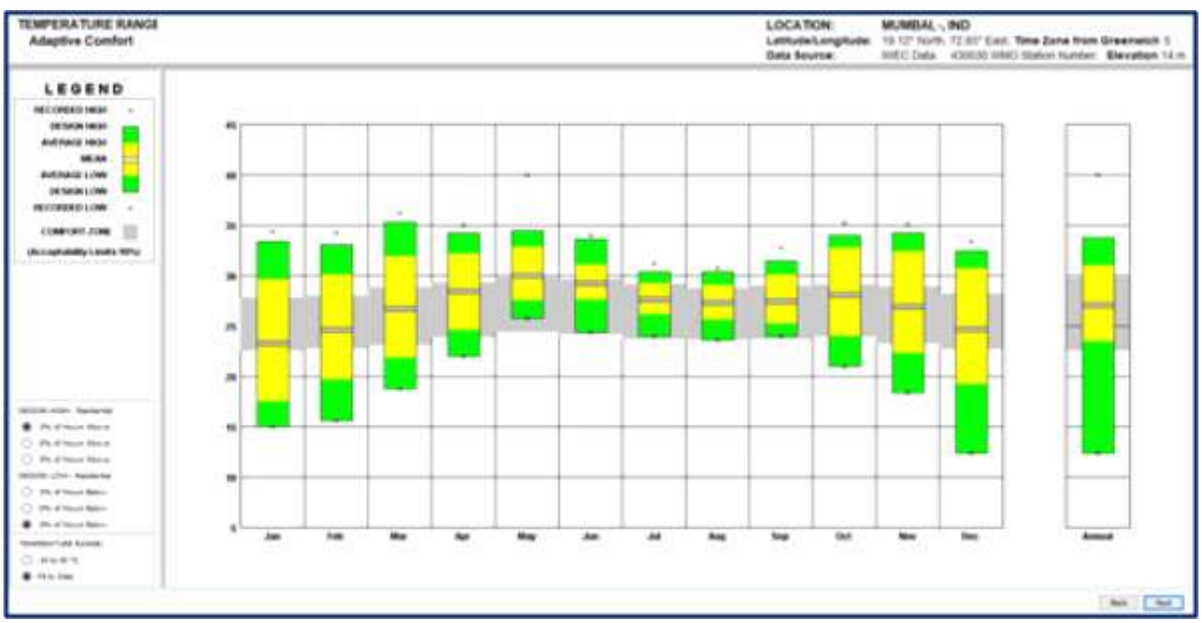
For Mumbai region, study has been carried out between Jan-Dec 2024 and following data has been used in Climate Consult software.

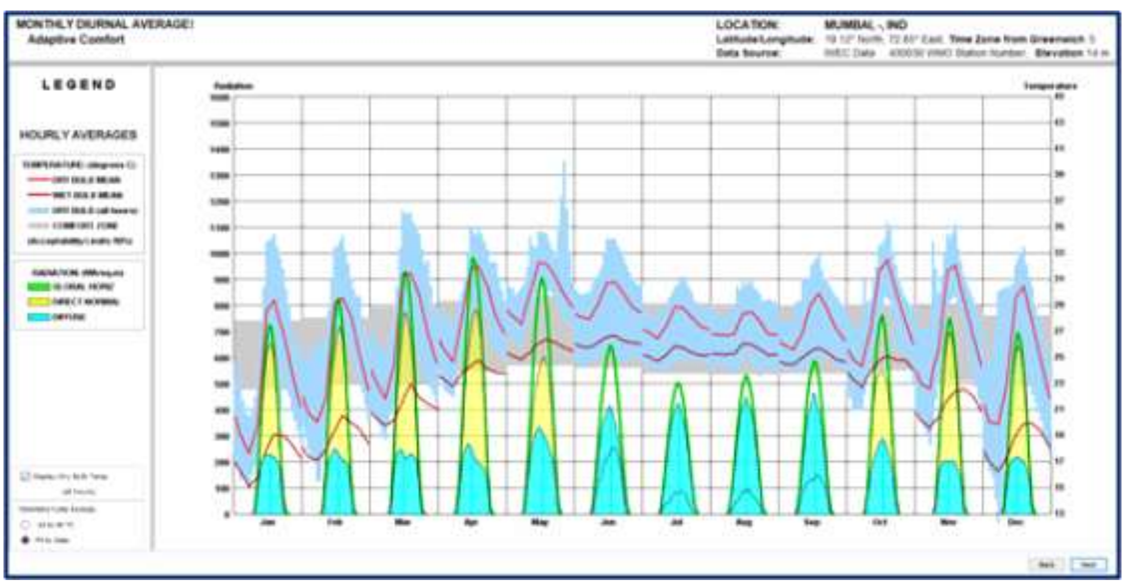
Results of Adaptive comfort model based on ASHRAE 55 (Passive ventilation only)



Temperature range and thermal comfort zone for residential building in Mumbai.

The above temperature range chart is based on the adaptive comfort model show how seasonal variations in thermal human comfort levels. The adaptive comfort zone is represented by the gray band shows 90% acceptability limits in accordance with ASHRAE Standard 55, is compared to the recorded and average temperature bands for each month. The majority of the temperature ranges from January to March are within or just little above the comfort zone. This data point suggests ideal condition for natural ventilation. The average temperature rises during the April to June which are summer months and average temp. frequently crossing the upper limit of the comfort zone. This implies that even though passive cooling techniques might still be beneficial, extra design elements like more shading, thermal mass, or mechanical support may be required to ensure comfort. Increased cloud cover and rainfall during the July–September monsoon season moderates temperatures, bringing them back within the adaptive comfort range.

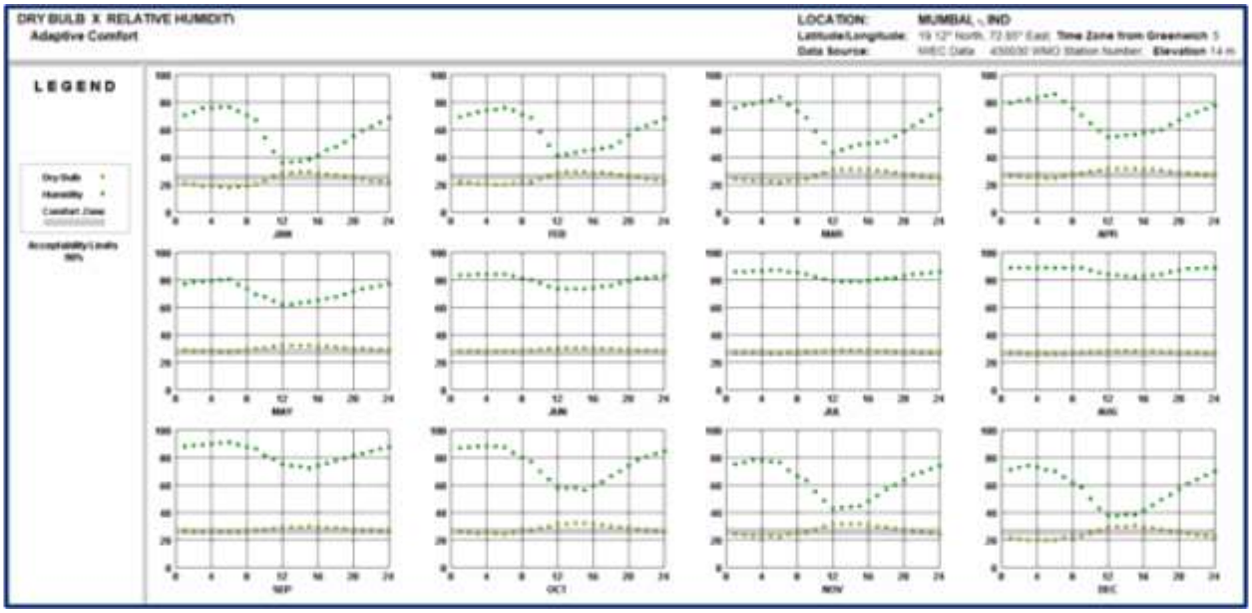
Temperatures progressively drop from October to December, and the majority of the monthly temperature distribution once more falls within or close to the comfort zone. For a large portion of the year, Mumbai's warm-humid climate is generally compatible with adaptive comfort strategies, according to the annual summary. Therefore, throughout the majority of the year, passive design strategies like cross ventilation, night flushing, and shading can effectively improve a building's indoor thermal comfort.



<u>Monthly diurnal average adaptive comfort chart for Mumbai.</u>

The monthly diurnal average adaptive comfort chart effectively showed the relationship between temperature, solar radiation, and thermal comfort. The adaptive comfort zone (gray band representing 90% acceptability limits) is superimposed on the graph along with the hourly averages of dry bulb temperature (in red), wet bulb temperature (brown), and the full range of dry bulb temperatures (blue shaded area). The graph also shows solar radiation components: global horizontal radiation (green), direct normal radiation (yellow), and diffuse radiation (cyan), highlighting solar gain throughout the day and year. Average temperatures from January through March stay within or just above the comfortable range, particularly in the morning and evening, suggesting that these are good times for natural ventilation. Elevated dry bulb temperatures in April and May crosses above the comfort threshold in the middle of the day. This is highlighting the necessity of passive measures like increased ventilation, thermal insulation, or shading. During the monsoon season months of June, July, and August, temperatures moderately drop and remain close to or within the comfortable range and there is a noticeable decrease in direct radiation. This reduction corresponds with cloudy skies and more rain. This time of year is good condition for passive cooling because it is naturally cooler and benefits from increased wind flow and diffused light.

While solar radiation and dry bulb temperatures gradually increase in the post-monsoon months of September and October, the majority of values remain within or slightly outside the comfort zone. The majority of temperature ranges fall comfortably within the adaptive zone by November and December, when the weather returns to milder levels. All of the data points to the fact that Mumbai's climate, especially during the monsoon and from November to March, encourages the use of adaptive comfort-based passive cooling techniques, such as cross ventilation, high thermal mass, and nighttime cooling, while the transitional months of April through June call for more intensive passive interventions to reduce heat stress.



Dry Bulb Temperature vs Relative Humidity adaptive comfort chart.

above figure provides Dry Bulb Temperature vs. Relative Humidity adaptive comfort chart. It is an hourly and monthly analysis of temperature and humidity levels in relation to the adaptive comfort zone. The y-axis shows the corresponding values for the comfort temperature band (gray zone), relative humidity (green), and dry bulb temperature (brown), while the x-axis shows the time of day (0 to 24 hours). The 12-month chart shows a visual representation of the year-round climatic fluctuations. The relative humidity continuously rises from morning to evening in January and February and the dry bulb temperature stays within the comfort zone for the majority of the day. These months gives ideal conditions for passive cooling and natural ventilation. The temperatures in March and April rise a little bit, reaching slightly above comfortable levels in the middle of the day, while the humidity starts to decrease in the morning and then rises again in the evening. This shows a transitional stage that requires for ventilation planning and shading techniques to save indoor comfort.

Higher daytime temperatures in May changes largely from the comfort zone, while moderate to high humidity levels remains. The monsoon season from June to August shows a decline in dry bulb temperatures that, for the majority of the hours, fall near or within the comfort band. Still, the constant high humidity levels (More than 80%) indicate the necessity of humidity management techniques like dehumidification or improved air circulation. In September and October, the temperature gradually rises and the humidity stays high, which somewhat lowers thermal comfort, particularly during the middle of the day. By November and December, both parameters closely match comfort thresholds, with temperatures spending most of the day in the adaptive comfort range and humidity levels remaining moderate.

If we considered over all situation, the graph demonstrates that Mumbai's climate permits passive cooling for a large portion of the year, particularly during the rainy and cooler months. In order to maintain indoor comfort, pre-monsoon months (April–June) require improved passive strategies like thermal insulation, ventilated shading, and night flushing because of the heat and discomfort caused by high temperatures. Following tables give monthly analysis of entire data.

January Comfort Zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	22–24°C	75–80%	Within
07:00–12:00	24–26°C	60–70%	Within
13:00–18:00	26–28°C	50–60%	Within
19:00–24:00	24–25°C	60–70%	Within

February comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	23–25°C	70–75%	Within
07:00–12:00	25–28°C	55–65%	Within
13:00–18:00	28–30°C	45–55%	Slightly Above
19:00–24:00	25–26°C	60–70%	Within

March comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	25–26°C	70–75%	Within
07:00–12:00	27–30°C	55–65%	Slightly Above
13:00–18:00	30–32°C	45–55%	Above
19:00–24:00	27–28°C	60–70%	Slightly Above

April comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	26–28°C	70–75%	Slightly Above
07:00–12:00	30–33°C	55–60%	Above
13:00–18:00	33–35°C	45–55%	Above
19:00–24:00	28–30°C	60–70%	Slightly Above

May comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	28–30°C	75–80%	Above
07:00–12:00	31–34°C	60–70%	Above
13:00–18:00	34–36°C	50–60%	Far Above
19:00–24:00	30–31°C	65–70%	Above

June comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	27–28°C	85–90%	Within
07:00–12:00	28–30°C	80–85%	Within
13:00–18:00	29–30°C	75–80%	Slightly Above
19:00–24:00	28–29°C	80–85%	Within

July comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	26–27°C	90–95%	Within
07:00–12:00	27–28°C	85–90%	Within
13:00–18:00	28–29°C	80–85%	Within
19:00–24:00	27–28°C	85–90%	Within

August comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	26–27°C	90–95%	Within
07:00–12:00	27–28°C	85–90%	Within
13:00–18:00	28–29°C	80–85%	Slightly Above
19:00–24:00	27–28°C	85–90%	Within

September comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	27–28°C	85–90%	Slightly Above
07:00–12:00	28–30°C	80–85%	Slightly Above
13:00–18:00	30–32°C	70–75%	Above
19:00–24:00	28–29°C	75–80%	Slightly Above

October comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	27–28°C	80–85%	Slightly Above

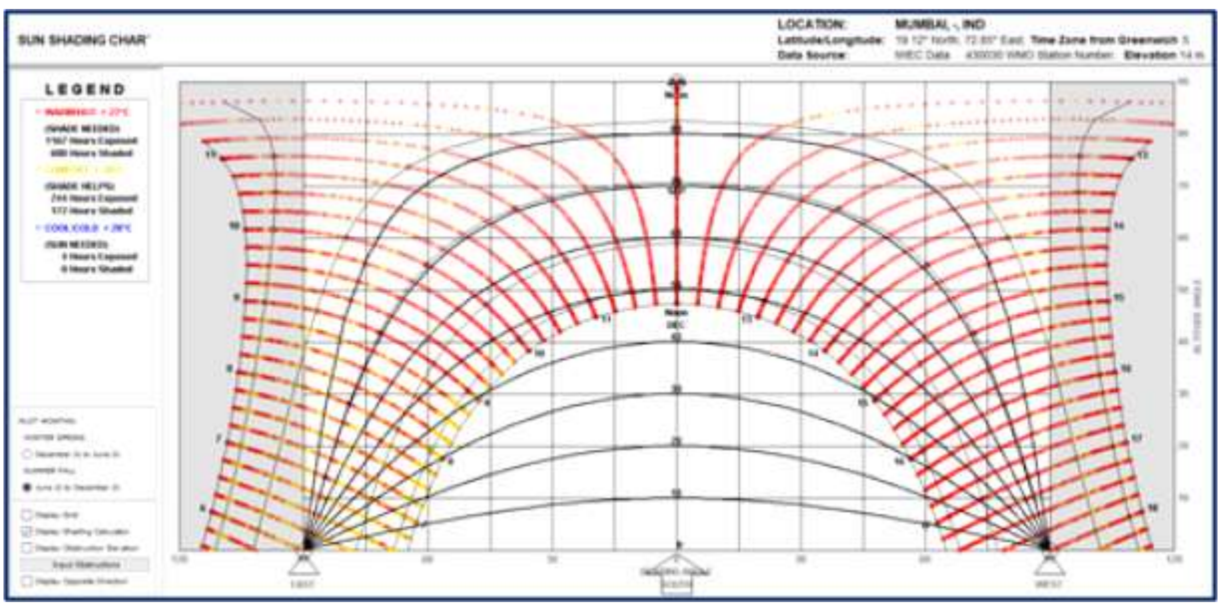
07:00–12:00	29–31°C	70–75%	Above
13:00–18:00	31–33°C	60–70%	Above
19:00–24:00	28–29°C	70–75%	Slightly Above

November comfort zone and time

Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	26–27°C	75–80%	Within
07:00–12:00	27–30°C	65–70%	Slightly Above
13:00–18:00	30–32°C	55–65%	Slightly Above
19:00–24:00	27–28°C	70–75%	Within

December comfort zone and time

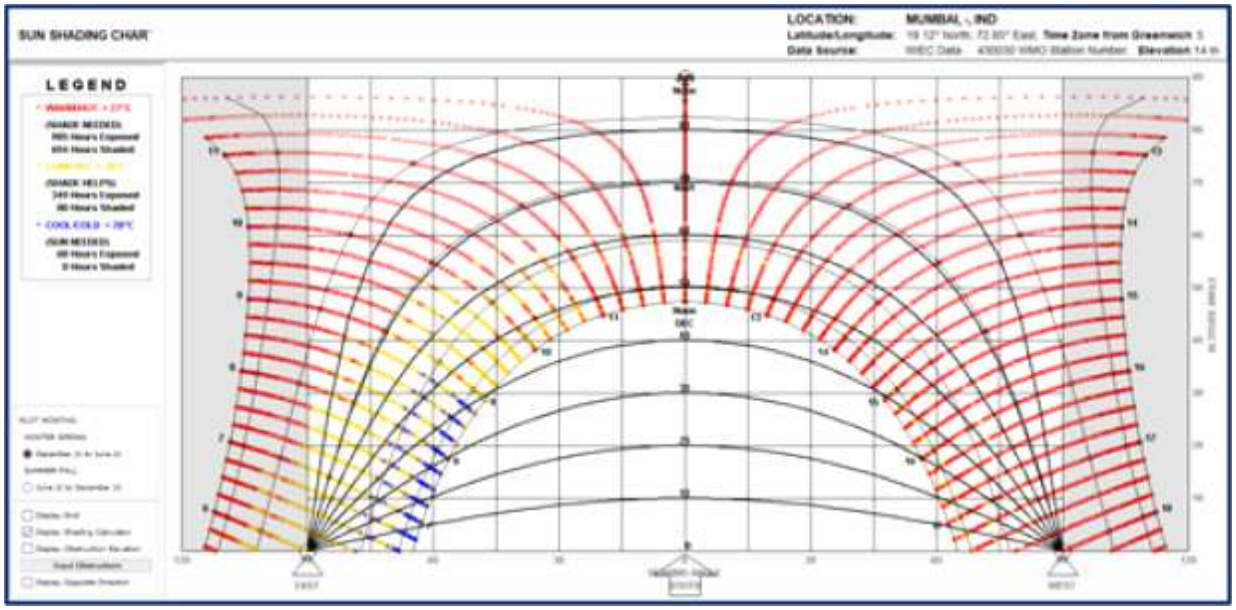
Time of Day	Dry Bulb Temp	Relative Humidity	Comfort Zone Alignment
00:00–06:00	24–26°C	70–75%	Within
07:00–12:00	26–28°C	60–70%	Within
13:00–18:00	28–30°C	50–60%	Slightly Above
19:00–24:00	25–26°C	65–70%	Within



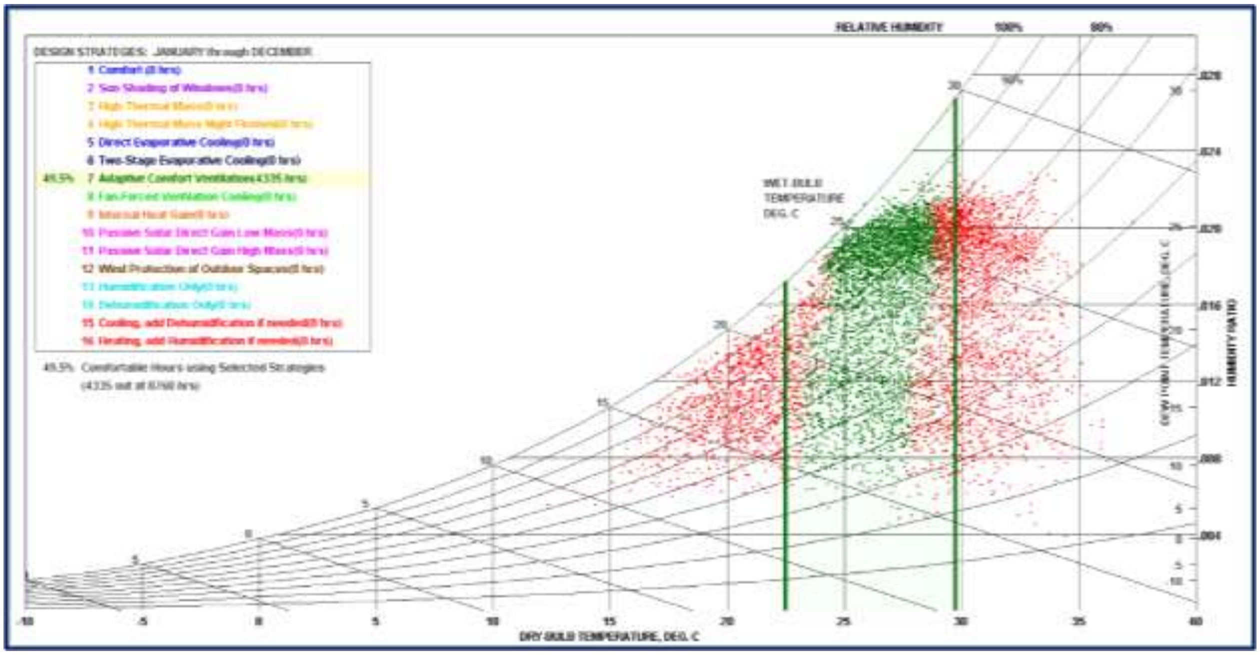
<u>Sun shading chart for Winter spring from December 21 to June 21.</u>

The sun shading chart shows how the shading requirements shift seasonally in Mumbai's warm-humid climate, reinforcing the importance of orientation-sensitive shading design in passive cooling strategies. Following tables shows the comparison of these two seasons in shading requirements.

Sun shading chart for summer fall from June 21 to December 21.



Parameter	Winter/Spring	Summer/Fall
Warm/Hot Hours (>27°C)	985 hours exposed, 694 hours shaded	1167 hours exposed, 600 hours shaded
Comfortable Hours (20–27°C)	349 hours exposed, 80 hours shaded	244 hours exposed, 172 hours shaded
Cool/Cold Hours (<20°C)	68 hours exposed, 0 hours shaded	4 hours exposed, 0 hours shaded
Shading Recommendation	Shade needed in morning & late afternoon	Extensive shading required throughout day
Solar Altitude & Azimuth Trends	Moderate angles, especially early/late	High altitude angles near midday
Sun Exposure Critical Times	9 AM – 12 PM, 2 PM – 5 PM	8 AM – 4 PM
Shading Focus (Orientation)	East and West elevations	All facades with emphasis on South, West
Design Implication	Horizontal shading + vertical fins useful	Deep overhangs and extended shading needed



Psychrometric chart

Comfort zones and possible passive design techniques are superimposed on the psychrometric chart shown above. It is graphically depicting the range of temperature and humidity conditions encountered throughout the year. Because warm-humid climates are characterized by high relative humidity, the chart shows that a sizable portion of the mumbai falls outside the typical thermal comfort zone. In areas with high temperatures and relative humidity above 60%, the annual hourly climate data are heavily clustered. This is suggesting the role of passive cooling strategies centered on ventilation, dehumidification, and shading.

Crucially, the results show that the adaptive comfort zone, which is based on models of naturally ventilated buildings and overlaps with a moderate amount of the data. This implies that if design techniques like cross ventilation, high thermal mass, night flushing and shading are successfully applied,the thermal comfort can be attained for a number of hours of the year without any of the need for active cooling systems. The existence of comfort hours in this area shows the effectiveness of the adaptive thermal comfort strategies used in this study. These results also emphasizes how strategies like dehumidification, window shading from the sun, and internal heat gain control can prolong comfort hours. These are the necessity for design features that reduce solar heat gain and improve natural ventilation is supported by the presence of data points above the comfort envelope. Thus, this data points chart turns into a crucial analytical and visual tool for confirming the suitability of the passive design interventions suggested in this research. By offering climate-specific proof in favor of the choice of passive cooling strategies suited to warm-humid climates, this psychrometric analysis strengthens the thesis' methodological framework. It supports the claim that low-energy thermal comfort can be achieved by designing building envelopes that complement the climate.

4. CONCLUSIONS

4.1 Design strategy based upon psychrometric analysis

Design strategy based upon psychrometric analysis is shown in the table below.

Strategy No.	Design Strategy	Effective Hours	% of Total Annual Hours
1	Comfort	0 hrs	0.0%
2	Sun Shading of Windows	0 hrs	0.0%
3	High Thermal Mass	0 hrs	0.0%
4	High Thermal Mass Night Flushed	0 hrs	0.0%
5	Direct Evaporative Cooling	0 hrs	0.0%
6	Two-Stage Evaporative Cooling	0 hrs	0.0%
7	**Adaptive Comfort Ventilation**	**4335 hrs**	**49.5%**
8	Fan-Forced Ventilation Cooling	0 hrs	0.0%
9	Internal Heat Gain	0 hrs	0.0%
10	Passive Solar Direct Gain Low Mass	0 hrs	0.0%
11	Passive Solar Direct Gain High Mass	0 hrs	0.0%
12	Wind Protection of Outdoor Spaces	0 hrs	0.0%
13	Humidification Only	0 hrs	0.0%
14	Dehumidification Only	0 hrs	0.0%
15	Cooling with Dehumidification	0 hrs	0.0%
16	Heating with Humidification	0 hrs	0.0%

The comparative evaluation of active and passive thermal comfort models for Mumbai's warm-humid climate highlights the critical role of integrated design strategies in achieving sustainable comfort. The design strategy analysis revealed that only a small fraction of the year falls naturally within the comfort zone, while the majority of hours require some form of intervention. Active strategies, particularly cooling combined with dehumidification, dominate as the primary requirement, accounting for nearly 60% of the annual hours, reflecting the persistent influence of high temperatures and latent loads. However, reliance on mechanical systems alone leads to high energy demand and increased environmental impact, making such approaches unsustainable if used in isolation.

Passive strategies demonstrate significant potential to complement active systems and reduce energy dependency. Sun shading of windows emerged as the most effective passive intervention, contributing nearly 30% of comfort hours by mitigating solar heat gain, particularly on east and west façades. Natural ventilation also showed applicability during limited periods, especially in the cooler months and transitional seasons, allowing for cross-ventilation and enhanced air movement to improve comfort. The analysis also revealed that strategies such as thermal mass and evaporative cooling are of little relevance in this climate, underscoring the importance of tailoring passive approaches to regional climatic realities.

The findings suggest that future building design in Mumbai should prioritize solar control through fixed and adjustable shading devices, enable selective natural ventilation when outdoor conditions permit, and integrate these with targeted mechanical cooling and dehumidification systems. Such a mixed-mode approach not only extends the number of comfort hours but also minimizes energy consumption, balancing occupant needs with environmental sustainability. The design strategy-based conclusion therefore affirms that the most effective pathway to comfort in warm-humid climates lies in the synergy between passive measures and selective active control, supported by context-specific architectural decisions.

Design Implications for Passive Strategies

Strategy	Implication from Chart
Natural Ventilation	May be effective in shoulder seasons; limited in peak summer due to high temperatures and monsoon humidity.
Thermal Mass	Less effective due to small diurnal range (night and day temperatures don't vary much). Night flushing won't offer significant benefits.
Solar Shading	Essential to reduce solar heat gains from March to June. Use overhangs, louvers, and vegetation.
Evaporative Cooling	Not viable during monsoon months due to already high humidity.
Insulation	Moderate use recommended for upper floors and roof to prevent overheating.
Mechanical Cooling	Necessary for summer months; design HVAC with moderate capacity due to low winter cooling/heating load.
Adaptive Comfort Opportunities	Consider **adaptive thermal comfort models** rather than strict PMV criteria, especially in naturally ventilated buildings.

In warm-humid climates, passive strategies such as natural ventilation and thermal mass offer limited effectiveness, particularly during peak summer and monsoon months due to high temperatures, humidity, and low diurnal temperature variation. Solar shading emerges as a critical strategy to control heat gains during the pre-monsoon period, while moderate insulation on roofs and upper floors can help prevent overheating. Evaporative cooling is largely ineffective during high-humidity periods, making mechanical cooling necessary for maintaining comfort in summer. However, the HVAC system can be designed with moderate capacity because of the minimal heating or cooling requirements in winter. Adaptive thermal comfort approaches are recommended for naturally ventilated spaces, as they allow more flexibility compared to conventional PMV-based design criteria.

5. REFERENCES

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