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Achieving Thermal Comfort in Classrooms through Hybrid Strategies in Mumbai's Hot-Humid Climate

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Abstract

Classroom spaces in hot and humid climate often become inhabitable and non-welcoming due to excessive concentrated heat, exposure to direct radiation and poor ventilation. In today's world, cities are becoming denser and climate change is happening at a much faster rate than ever. Ensuring thermal comfort in public spaces becomes important not only for enhancing quality of life and experience but also for promoting social interaction, health and overall mental and physical well-being. Passive methods like natural ventilation, shading, selection of material are all very essential but to achieve complete thermal comfort, an integration of both active and passive means is required. Active means include systems like fans, misting, HVAC. This research aims to improve thermal comfort and achieving comfort where mass is satisfied by the temperature range achieved during the operational hours. This study aims at evaluating how integration of both passive and active methods can create more energy efficient and sustainable environment. This study specifies academic spaces in public spaces as primary area of research. Analyzing case studies across different academic spaces in hot and humid climate will be used to understand building performance as well as user comfort. The research seeks to find practical design solution which respond not to just climatic conditions but also to human behavior and public patterns. The final goal is to set flexible, dynamic guidelines which assist in designing academic spaces that are both sustainable and socially engaging.

Keywords; Thermal Comfort, Hot-Humid Climate, Passive-Active Integration, Academic Public Spaces

INTRODUCTION

Rapid urbanization and climate change have intensified thermal discomfort in indoor environments, particularly in warm-humid regions such as Mumbai. Academic spaces, including classrooms and studios, are especially sensitive to thermal conditions as they directly influence student concentration, productivity, and overall well-being.

Conventional design approaches in institutional buildings often rely heavily on mechanical cooling systems, resulting in high energy consumption and reduced environmental sustainability. However, research indicates that passive design strategies, when effectively integrated with controlled active systems, can significantly enhance thermal comfort while minimizing energy demand.

In the Indian context, adaptive thermal comfort models such as IMAC suggest that occupants can tolerate a wider range of temperatures compared to international standards, particularly in naturally ventilated or hybrid buildings. This opens opportunities for rethinking classroom design through climate-responsive and user-centric approaches.

This study explores how hybrid cooling strategies can be effectively applied to classroom spaces in Mumbai's hot-humid climate to achieve both comfort and sustainability.

AIM

To analyse thermal comfort in academic spaces by exploring how integration of both passive design strategies and usage of active systems can help achieve comfortable temperature range in hot and humid climate.

OBJECTIVES

- 1 To understand the primary factors affecting thermal comfort in institutional spaces.
- 2 To critically analyse and study public spaces through the lens of thermal performance in warm and humid climate.
- 3 To evaluate the role and integration of passive strategies and active systems in achieving thermal comfort.
- 4 To collect and study thermal conditions, adaptations and various thermal comfort standard models in the same climate.

METHODOLOGY

This study uses an approach that revolves around environmental science, architectural understanding and user comfort research method all at once.

- **Literature review** : The research starts off by reviewing primary factors in thermal comfort. Integration of passive and active system in tropical climates.
- **Case Studies** : A diverse set of various case studies who have achieved significant thermal comfort in academic spaces. They will be in hot and humid climate and selection criteria will include space type, user volume and exposure to direct heat.
- **User survey and data collection** : Interviewing and asking relevant questions to various stakeholders involved to get user's ideas and thoughts on thermal comfort, preferred temperature range and necessary adaptations like preferring shaded areas, timing the usage will be understood.
- **Simulation and testing** : Various simulation with different inputs will be tested to get much broader insights and quantifiable results. These simulations will run both passive and active methods.
- **Environmental data gathering** : Parameters to measure comfort will include dry bulb temperature, wet bulb temperature, Relative humidity, Radiant temperature, Wind speed and direction, Surface temperature, Intensity of light and direct solar exposure.

LITERATURE REVIEW

Classroom or studio environment play a crucial role in shaping students' learning outcomes, academic performance and overall physical and mental well-being. Thermal comfort levels in learning space directly affect concentration and thus the performance of the students using the space. In hot and humid climates, challenges such as high temperature, high relative humidity, make it essential to integrate both passive and active systems to maintain comfort.

Research papers referred :

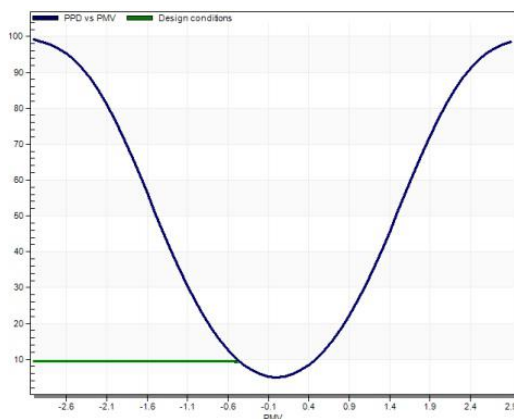
- 1 **Olgyay, V. ; 1963.** Design with Climate: Bioclimatic Approach to Architectural Regionalism. Olgyay's work is a standard base set by him for climate-responsive architecture. The bioclimatic chart provided acts as a tool for identifying comfort ranges and corresponding passive strategies. For classrooms, the paper suggests the orientation of buildings to reduce solar heat gain. Implementation of cross ventilation and shading is also told in this paper.
- 2 **Givoni, B. (1994).** Passive and Low Energy Cooling of Buildings. Givoni insists passive cooling as the foremost strategy in hot-humid climates. In relevance to classrooms, his findings highlight the effectiveness of verandahs, shaded courtyards and natural ventilation in reducing heat gain in the structure.
- 3 **Fanger, P. O. (1970).** Thermal Comfort: Analysis and Applications in Environmental Engineering. Fanger's Predicted Mean value; PMV and Predicted Percentage of dissatisfied; PPD are important standards in defining thermal comfort. Comfort is very subjective and such standards which takes mass opinion into consideration are more authentic.
- 4 **De Dear, R., & Brager, G. S. (1998).** "Developing an Adaptive Model of Thermal Comfort and Preference." ASHRAE Transactions, 104(1). De Dear and Brager's adaptive comfort model can be considered relevant to classrooms in naturally ventilated buildings. It points out that the user experiencing the space can tolerate wider comfort ranges when provided with design.
- 5 **Rajasekar, E., & Ramachandran, A. (2013).** "Indoor Thermal Comfort Expectations and Adaptive Behaviour of Students in Naturally Ventilated Classrooms in a Hot and Humid Climate." Building and Environment, 66, 307–320. This paper is based on classroom studies conducted in South India. The research presented in this paper is direct result of the interaction done with the students regarding their expectations for thermal comfort. The study indicates that students generally

prefer hybrid models with both natural ventilation along with air conditioning to lower the temperature. The study also talks about the importance of understanding and then designing according to the user comfort needs rather than imposing international standards which are not meant for the climate zones in the country.

- 6 **Kwok, A. G., & Rajkovich, N. B. (2010).** "Addressing Climate Change in Comfort Standards." Building and Environment, 45(1), 18–22. Kwok and Rajkovich argue that the comfort standards that exist today are overly dependent on mechanical cooling and must be adapted for natural ventilation, orientation, shading and all the other passive means as well. This is also very essential for spaces like classrooms where hybrid model can demonstrate superior performance.

CONCLUSION AND FINDINGS

Key findings to be taken from review of literature: Passive Strategies are foundation of creating thermally comfortable spaces. They just won't give comfortable temperatures but also reduce EPI and ultimately reducing loads on the mechanical systems. Active systems, while essential must be carefully monitored and integrated with the overall working to ensure sustainable energy efficient solution. Adaptive models are model suitable for academic spaces like classrooms in tropical hot and humid climate as student show flexibility when provided with environmental control.



PMV scale being central when addressing thermal comfort in classrooms. It works by predicting average thermal sensation of a large group of people.

where:

- 3 = Cold
- 2 = Cool
- 1 = Slightly cool

- 0 = Neutral
- +1 = Slightly warm
- +2 = Warm
- +3 = Hot

Then it calculates the mean value to get the thermal comfort of the space.

PMV parameters in Academic spaces:

The PMV model of determining thermal comfort is based on different key factors

which include:

Air temperature: This is the ambient temperature inside the classroom space. **Mean radiant temperature; MRT:** It is the temperature which takes into account the temperature of the surrounding surfaces as well like the walls, ceilings and furniture.

Relative Humidity: It calculates the moisture levels in the classroom and how they are experienced by the user. This is very critical in hot and humid climates as this changes how the temperature is actually experienced by the user.

Air velocity: Movement of air happening due to mechanical systems or natural ventilation.

Metabolic rate: Activity of the users of the space (In this case the students). **Clothing level; Clo:** Clothing worn by the user experiencing the space. Why is PMV relevant for classrooms in hot and humid climate In hot and humid climate, students face discomfort due to high humidity and limited air flow. This causes discomfort even when the temperatures are not that high. PMV will help determine whether the space is inclined towards being warmer or slightly warm. This approach will guide in making the suitable design decisions.

Method for implementing PMV model

- Collecting environmental data related to the factors mentioned above.
- Gather personal factors: This includes the aspects like the clo levels and activity rates.
- Feed input in software: Collect this data and then feed in into software such as CBE thermal comfort tool, Ladybug Tool or Climate consultant.
- Compare and analyse the PMV data and findings with actual user surveys to validate the PMV's accuracy with local adaptations.

- Test the scenarios in simulations to check how mean vote changes by design interventions.

CASE STUDIES

Case Study 1 :

National University of Singapore



Climate Context : Located near equator, hot and humid climate all year round. Avg. temp. ranges from 25-33 C with relative humidity above 70%. Rainfall being very often and

Climate Context : Located near equator, hot and humid climate all year round. Avg. temp. ranges from 25-33 C with relative humidity above 70%. Rainfall being very often and

Design strategies implemented: National university of Singapore has implemented huge windows which are operable in its classrooms. They are positioned in a way where cross ventilation is maximized through venturi's effect. This is achieved by managing the opening sizes of the windows. A venturi effect window utilizes the venturi effect, which causes a change in air pressure and an increase in the velocity of the air flow to achieve effective natural ventilation and thermal regulation. This pressure difference brings in fresh indoor air into the space.

Operational Aspects: Classrooms are monitored with sensors that track indoor temperature, humidity and carbon dioxide levels. This helps in maintaining the indoor air quality of the space. The user of the space (which are the students in this case) are given an option of controlling their environment to some level where they can open window.

Outcomes: Surveys and studies done by National University of Singapore shows that the users are very satisfied with the learning environment created due to architecture which also affects the performance of the students. Energy consumption was reduced by 30% when hybrid model was applied instead of going with fully air-conditioned spaces.

Case Study 2:

IIT Madras, Chennai Indian Institute of technology in Chennai has shown great performance when it comes to providing thermal comfort in its spaces.



Climate Context: Chennai's coastal tropical climates have high humidity and harsh direct solar radiation. Temperatures peak during March to June Monsoon season adds dampness and humidity significantly.

Design strategies implemented :

Orientation : Classroom blocks in the campus are located and oriented in a way such that east-west solar exposure is reduced which directly reduces solar heat gain significantly.

Courtyards : Courtyards have been tested and proven in Indian context to enhance building performance in the coastal areas. IIT campus has also incorporated into academic block. The also reduce the thermal shock experienced by the user when coming out from a air-conditioned space.

Cross - ventilation : Long passage ways and moveable windows on opposite sides of the facade enable increased air velocity to enhance cross ventilation.

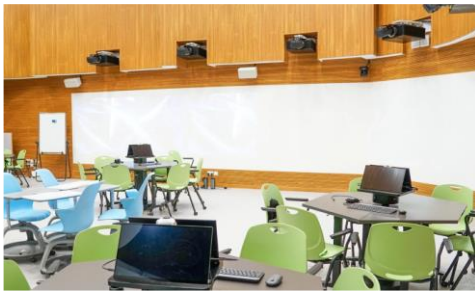
Air conditioned spaces : Only some high density or areas with heavy technological equipments which increase internal heat gain are air conditioned but this is not uniform across the campus.

Operational Aspects : A number of classrooms have ceilings at a increased clear height which reduces radiant heat coming from the ceiling and allows the hot air to rise up and vent out. Shaded spaces and passages act as an alternative to the indoor learning spaces which can be used for informal interactions.

Outcomes : Hybrid approach of using Air conditioner for shorter and intense bursts to improve comfort are much preferred way of achieving thermal comfort which also reduces load on the energy systems.

Case Study 3 :

University of Hong Kong (HKU) - Experimental Classrooms HKU emphasizes experiential learning through initiatives like the Gallant Ho Experiential Learning Centre.



Climate Context: Subtropical climate with hot and humid summers and mild winters. Dense urban fabric has a harsh urban heat island effect. High footfall in every public space due to high population density in the immediate vicinity.

Design strategies implemented: The entire system is based upon an adaptive thermal comfort model. Windows open and fans run when conditions are within the adaptive band. Air conditioning is worked up only when the indoor temperatures rise above what is normally considered to be comfortable. Shading louvers and insulated glazing is introduced as design interventions to reduce the effect of solar heat gain.

Parameter	NUS	IIT Madras	HKU
Climate	Hot-Humid	Hot-Humid	Subtropical
Strategy	Venturi Ventilation	Courtyard + Orientation	Adaptive Hybrid
Cooling Type	Hybrid	Mostly Passive + Select AC	Adaptive
Energy Reduction	~30%	Moderate	High
Comfort Model	Hybrid	Passive	IMAC-based

IMAC MODEL FOR UNDERSTANDING THERMAL COMFORT

Background about the Model: The study around the subject of thermal comfort has been dominated by models developed by Fanger's PMV - PPD index. Standards like ASHRAE 55 and ISO 7730. Though it is a very elaborate mode, its use for global adaptations is still debated. People in

India, mostly in the tropical regions show more tolerance to increased indoor temperatures than the PMV model suggests. This happens as the PMV model was based upon western centric adaptations and standards. To address this, the Indian Model for Adaptive Comfort (IMAC) was proposed in 2014 by Manu, Shukla, Rawal, Thomas and de Dear which is based on the studies done across the country.

Conceptual Framework : The IMAC model is an adaptive comfort model specifically calibrated for Indian conditions. Adaptive models are based on the principle that people continuously adapt to their thermal environment by adjusting clothing, altering activity, using fans, or simply recalibrating their comfort expectations. While the PMV model focuses on achieving a strict balance of heat exchange between body and environment, The IMAC model acknowledges that comfort is context-dependent and flexible, particularly in buildings with natural or mixed-mode ventilation. Thus, IMAC is more representative of actual classroom conditions in India, where airconditioning is either absent or selectively used, and occupants often adapt through behavioral and physiological means.

Methodology of IMAC : The IMAC model was developed using field data from 6,000+ comfort surveys across 160 buildings in 16 cities in India, covering diverse climatic zones: hot-dry, warm-humid, composite, and temperate.

The key methodological steps were: Comfort Surveys: Occupants were asked their thermal sensation, preference, and acceptability using standard ASHRAE 7-point scales.

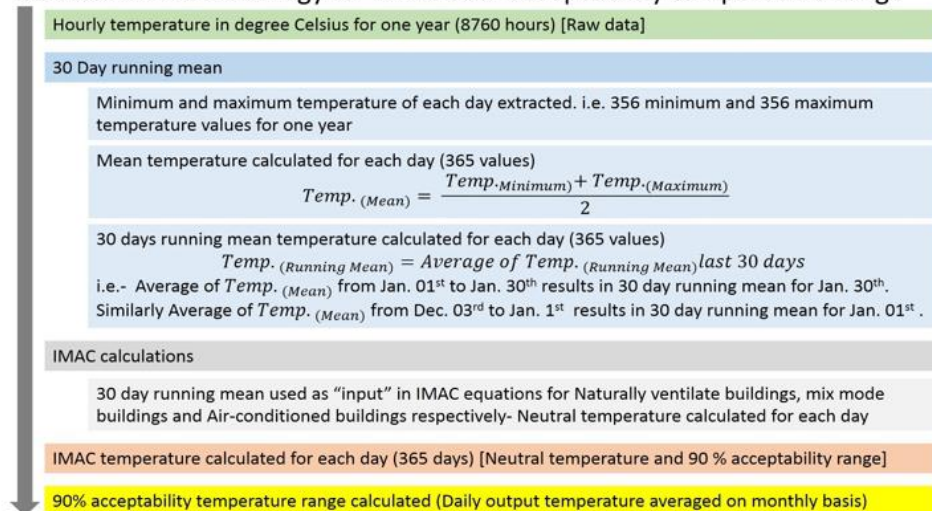
Environmental Measurements: Indoor and outdoor conditions were measured simultaneously, including air temperature, humidity, air speed, and radiant temperature. Regression Analysis: The comfort votes were statistically correlated with outdoor running mean temperature, producing an adaptive comfort equation for India. The resulting IMAC comfort band is wider and shifted to higher temperatures compared to ASHRAE's adaptive model, reflecting Indian occupants' higher tolerance levels.

IMAC Comfort Equations :

The IMAC model defines acceptable indoor operative temperature ranges as a function of the outdoor running mean temperature (T_{rm}):

Neutral temperature (T_n): $T_n = T_{rm} + 3.5$ This means, for example, if the outdoor running mean temperature is 30°C , the neutral comfort temperature indoors is $\sim 27^\circ\text{C}$, with an acceptable range from $\sim 24.5^\circ\text{C}$ to $\sim 29.5^\circ\text{C}$.

Calculation methodology for IMAC 90% acceptability temperature range



The IMAC acceptability table which accepts the rate of 90% for Mumbai city highlights the thermal comfort ranges on a monthly basis by giving temperature ranges across four variety of building types. These include naturally ventilates, mixed-mode, air conditioned based on temperature of air and air conditioned based on standard effective temperature data. The data is straight reflection of how Mumbai's warm and humid climate affects indoor comfort expectations and needs. This is seen when naturally ventilated and mixed mode usage buildings show higher acceptable temperature ranges due to adaptive occupant behaviour pattern. Air-conditioned buildings on the other hand showcase a narrower and lower comfort range which tells about more controlled thermal requirements for conditioned spaces. This table will help in deciding climate responsive strategies for all types of spaces which will enable more strategic planning of massing, ventilation, envelope design and cooling loads to achieve optimal comfort across entire year.

Application in Classroom Spaces

Hot-Humid Context In hot-humid climates, such as Mumbai, Chennai, or Kolkata, IMAC proves highly relevant: Classrooms without AC often operate at indoor temperatures between 28–32°C.

PMV would predict discomfort at these conditions, but IMAC shows that students can still report thermal acceptability, especially when fans or natural ventilation are present. This adaptive tolerance reduces the need for continuous mechanical cooling.

Practical Implications Passive design (orientation, shading, ventilation) can reduce indoor operative temperatures to fall within IMAC bands, avoiding the need for full AC.

Hybrid systems (fans + intermittent AC) are often sufficient to keep classrooms within acceptable IMAC ranges. User surveys in classrooms show strong alignment with IMAC predictions, where students often report satisfaction in conditions warmer than PMV neutrality.

Relevance to Research Framework:

For this thesis, the IMAC model will serve as:

A benchmark for evaluating classroom comfort conditions in hot-humid climates. A tool to compare measured indoor temperatures and student survey responses. A framework for assessing the effectiveness of passive and hybrid cooling strategies. By integrating IMAC analysis with PMV calculations and user surveys, the research will achieve a holistic understanding of thermal comfort that is both scientifically robust and contextually relevant to India's classrooms.

Final Design Guidelines:

Climate-Responsive Planning

Orient primary studio and major learning spaces which will focus on maximizing intake of diffused daylight and will cut direct solar exposure. Optimizing maximum usage of north-lighting by introducing architectural interventions

like courtyard and shaded verandahs. These features work best in warm and humid climate. Integration of cross ventilation by studying windward-leeward sides and then design openings accordingly. The openings can be reinforced with landscaped funnels for airflow.

Adaptive Thermal Comfort model:

Adopt IMAC adaptive comfort standard to get accurate and relevant temperature comfort range which will ultimately reduce dependence on mechanical means. In warm and humid climate, temperature range should be maintained within 24.5 C to 29.5 C. Usage of mechanical cooling and dehumidifying methods should be done during peak periods and in areas where large gathering happens.

Hybrid ventilation strategy:

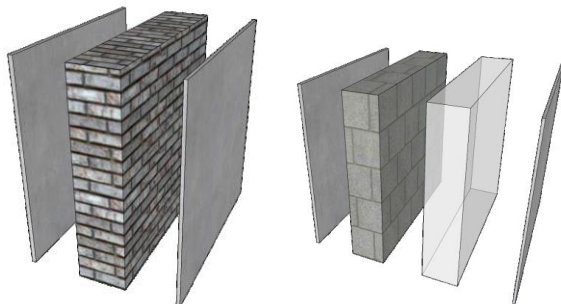
In warm and humid climate, combination of natural + mechanical ventilation gives best performance and can achieve comfort for most operating hours. Every informal area, studio or workshop has operable openings which enables user control. All architectural interventions which optimize passive air movement must be prioritized.

Daylighting and Visual Comfort:

A minimum sDA of 55-65% in learning spaces to support well-being and cognitive thinking. Limited ASE to prevent glare, especially in spaces like galleries. This can be achieved by strategies like light shelves, louvers and external shading devices. Prioritising north facing skylights in large spaces to prevent darkness.

Material and construction guidelines:

Usage of breathable and materials with low thermal mass for external walls to avoid heat retention. Prioritise locally available materials, passive shading screens and construction techniques which support modularity. Finishes which support creative activities. These materials should have high durability and daylight neutral colour.



Base case Wall (Conventional Brick wall)

Proposed Wall (Breathable, Heat rejecting)

BASE CASE WALL (Conventional Brick Wall – High Thermal Mass)

(This represents what typical buildings in Mumbai use and why they retain heat.)

Layering (Outside → Inside)

External Cement Plaster – 20 mm

- **Conductivity:** ~0.72 W/mK
- **Purpose:** Weather protection Solid Burnt Clay Brick – 230 mm
- **Conductivity:** ~0.81 W/mK Thermal Mass: High
- **Purpose:** Structural, but stores heat and radiates it indoors Internal Cement Plaster – 15 mm
- **Conductivity:** ~0.72 W/mK
- **Purpose:** Internal finish and protection
- **Issues:** Heat retention, slow cooling at night, discomfort in warm-humid climate

PROPOSED WALL (Breathable, Low Thermal Mass, Heat-Rejecting)

(Optimized for Mumbai warm-humid climate and IMAC comfort.) Layering (Outside → Inside) External Lime Plaster – 20 mm

- **Conductivity:** ~0.6 W/mK
- **Breathability:** High
- **Purpose:** Solar reflectivity + vapor permeability Autoclaved Aerated Concrete (AAC) Block – 150 mm or 200 mm
- **Conductivity:** 0.16 W/mK Thermal Mass: Low
- **Purpose:** Reduced heat gain, fast heat dissipation Breathable Air Gap (optional) – 25–40 mm
- **Purpose:** Decouples heat, improves comfort Internal Gypsum Plaster – 12 mm
- **Conductivity:** 0.25 W/mK
- **Purpose:** Smooth, breathable interior finish

Landscape and Microclimate:

Introducing dense perimeter planting, water bodies and shaded pathways to achieve comfort. This will also reduce the thermal shock effect when coming from indoors to outdoor. Using courtyards as thermal buffers, designing them to bring airflow into adjacent studios and classrooms.

Energy and Environmental Performance:

Intent to reduce cooling load using shading, optimizing daylight, natural ventilation and high performance glazing.

Considering rooftop PV to generate in house electricity. Targeting 25-40% total annual reduction in cooling energy through hybrid ventilation and passive strategies.

Services and Operational guidelines:

Design for zoned HVAC systems - only condition the spaces that require strict temperature / Humidity control. Providing sensor-based lighting, low energy fixtures which also radiate less heat. Ensuring flexible service ducts so that the studios can be reconfigured with major interventions.

CONCLUSION

Achieving thermal comfort in classroom spaces within a warm and humid climate needs a approach which is adaptive, passive design strategies driven which focusses on minimizing heat gain while also enhancing airflow. Classrooms must have cross ventilation, shaded openings, high ceilings and breathable materials. This is all necessary for maintaining the temperature within the comfort range. Ceiling fans, operable windows, shaded courtyards all act as essential components that allow users to modulate the temperature according to their comfort needs. Combining these passive and active means of achieving comfortable temperatures will assist in creating energy efficient learning spaces which support creative work and overall mental and physical well-being.

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