Investigating the Role of Humidity on Indoor Wellness in Vernacular and Conventional Building Typologies

Suchi Priyadarshani – Indian Institute of Science, Bangalore, India – suchip@iisc.ac.in
Roshan R Rao – Indian Institute of Science, Bangalore, India – roshanrao@iisc.ac.in
Monto Mani – Indian Institute of Science, Bangalore, India – monto@iisc.ac.in
Daniel Maskell – University of Bath, United Kingdom – D.Maskell@bath.ac.uk

Abstract

Moisture in air is essential for human life. It drives all physiological processes and determines occupant wellness. As a crucial parameter of Indoor Environmental Quality (IEQ), it is regulated by building typology and its constituent materials. Besides affecting heating and cooling energy requirements, indoor moisture also determines occupants' comfort and health.

Occupant comfort, commonly referred to as thermal comfort, is paramount for building and indoor environment design. Currently available building simulation tools majorly incorporate temperature-related comfort models like PMV, PPD, and adaptive thermal models. In conjunction with temperature, indoor moisture levels impact occupants' skin-related and respiratory comfort, resulting in health issues such as skin irritation, allergies, respiratory infections, asthma, etc. Humidity has not been adequately dealt with in comfort studies. This study proposes a novel computational approach derived from an existing model to explain and assess humidity-related comfort in buildings. The study also involves real-time monitoring of indoor-outdoor temperature and humidity and occupant comfort-votes.

The hygroscopic properties of building materials impact the regulation of indoor moisture, thereby impacting occupant comfort and health. This article examines humidity-related comfort aspects between conventional and vernacular building typologies. Results from the simulation have been used to explain the comfort votes obtained from an on-field survey of occupants. Skin temperature and wettedness derived through energy balance between the human skin and the indoor air parameters can be used as an indicator to assess skin-related comfort in indoor environments.

Comfort is an essential indicator of wellness in an indoor environment. Clarity on approaches to evaluate different aspects of comfort attributed to building materials is crucial for built environment design for occupant wellness. Incorporating humidity-associated comfort parameters in building simulation tools could be beneficial in selecting materials for building design to cater to varying functionalities and health co-morbidities.

1. Introduction

Moisture is omnipresent and fundamental to life. The human body comprises 70 % water. Water balance between the surrounding air and the human body is essential for life. Human beings spend 90 % of their time indoors. Indoor surfaces (building envelope) determine the Indoor Air Quality (IAQ), impacting occupant comfort and health (al Horr et al., 2016; Petty, 2017). Indoor air is the connecting link between the building typology (and materials used) and the occupant. Moisture in the air is a critical determinant of IAQ. Indoor air moisture (as affected by building typology due to heat and moisture transport mechanisms) determines the occupant's thermo-physiological balance, thereby determining comfort. Unregulated (high/low) moisture is generally considered detrimental to health.

Majorly, simulation-based indoor comfort analysis accounts for thermal comfort using indices like PDD (Predicted Percentage of Dissatisfied) and PMV (Predicted Mean Vote). Thermal comfort is determined majorly by environmental (air temperature, relative humidity, wind velocity, and radiation) and personal (metabolism and clothing) factors. Heat-Stress indices like WBGT (Wet-Bulb Globe Temperature) Index, Oxford index, and Effective Temperature are used for varied applications other than indoor comfort like sports, clothing design etc.

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Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

Numerous empirical studies have also indicated the impact of (de Dear et al., 1991; de Dear et al., 2015; Jokl, 2002; Kong et al., 2019; Parsons, 2003; van Hoof et al., 2010) indoor humidity on thermal comfort.

While humidity is also accepted as a significant determinant of skin-related and respiratory comfort (Wolkoff & Kjærgaard, 2007); it has not been dealt with explicitly. Tools for evaluating skin-related or respiratory comfort due to changing indoor air parameters are not incorporated in commonly used building simulation softwares.

Vernacular (earth-based materials) and conventional (standardized bricks and RCC) buildings in Jamgoria village, Jharkhand (India), situated in composite climate zone, were monitored (Priyadashani et al., 2021a) for indoor air parameters. This study revealed a significant moderation of indoor RH exhibited by vernacular building typology. The variations in humidity seen in different building typologies provided clear grounds for understanding the humidity-related comfort parameters of occupants with varying indoor environments. Thus, further extension of this study (Priyadarshani et al., 2021b) was carried out to record the response of occupants to skin and respiratory comfort throughout the year in both the building typologies.

Skin acts as the interface with the ***indoor air moisture*** and can be witnessed as wettedness/dryness. The aims of this work are:

1. To compute diurnal/seasonal variations of skin temperature (T_{sk}) and wettedness (w) in vernacular and conventional dwellings using an energy balance-based simulation approach.
2. To explain the changing skin-related comfort votes (oily/very-dry skin) of occupants in vernacular and conventional dwellings using computed Tsk and w.

2. Applied Approach and Methods

2.1 Energy Balance of the Human Body (Core-Skin-Indoor Air)

Simulation-based analysis was done to derive the skin wettedness and temperature corresponding to diurnally/seasonally varying indoor temperature and RH in conventional and vernacular building typologies. The Gagge 2-node model, validated for occupants in indoor environments (Atmaca & Yigit, 2006), was used to represent the energy balance between the human body and indoor air. Factors concerning ethnicity and regional stereotypes were not examined. The model considers 16 cylindrical segments (see Fig. 1) representing different human body parts, each comprising two nodes (core and skin).

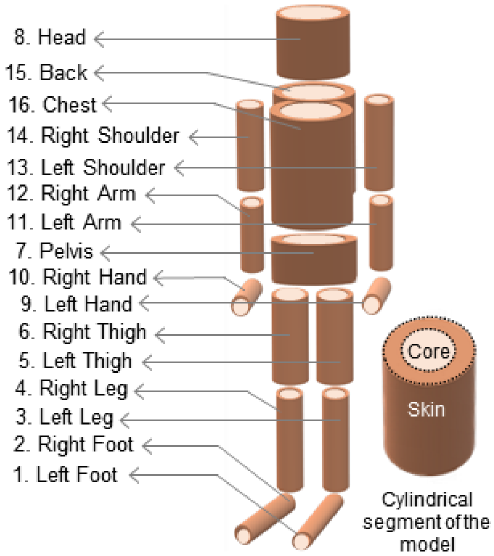

Fig. 1 – Description of segments of the human body in Gagge-2 Core, 16 segment model

Indoor temperature and RH data obtained from real-time monitoring of vernacular and conventional building typologies were used as input parameters for the model. The energy balance between the core and the skin for each segment was expressed as:

$$S_{cr}(i) = M - W[C_{res}(i) + E_{res}(i)] - Q_{cr,sk}(i) \quad (1)$$

$$S_{sk}(i) = Q_{cr,sk}(i) - [C(i) + R(i) + E_{sk}(i)] \quad (2)$$

Here, $C_{res}(i) + E_{res}(i)$ correspond to the respiration at the core of the chest segment.

The rate of change of internal energy in the core and the skin layers is given by:

$$S_{Cr}(i) = \frac{[1-\alpha(i)]m(i)c_{p,b}\left[\frac{dt_{cr}(i)}{d\theta}\right]}{A(i)} \quad (3)$$

$$S_{sk}(i) = \frac{\alpha(i)m(i)c_{p,b}\left[\frac{dt_{sk}(i)}{d\theta}\right]}{A(i)} \quad (4)$$

Heat losses from each segment, and exchange from the core to the skin (and vice versa) within the segment are given by:

$$C(i) + R(i) = \frac{[t_{sk}(i) - t_o]}{R_t(i)} \quad (5)$$

$$C_{res}(i) + R_{res}(i) = [(0.0014)M(34 - t_o)] + [(0.0173)M(5.87 - p_{wv,a})] \quad (6)$$

$$E_{sk}(i) = w(i)\frac{[p_{sk,s}(i) - p_{wv,a}]}{R_{e,t}(i)} \quad (7)$$

$$Q_{cr,sk}(i) = [K + c_{p,bl}m_{bl}(i)][t_{cr}(i) - t_{sk}(i)] \quad (8)$$

For the analysis, air temperature [t_o] was assumed to be the same as operative temperature. RH recorded on-field was used to calculate the partial pressure of ambient air [$p_{wv,a}$]. The total thermal resistance [R_t] and evaporative resistance [$R_{e,t}$] were computed for single-layer, 1.2 mm-thick cotton weave cloth for each body segment using Equations 9 and 10, respectively. Head, left foot, right foot, left hand, and right-hand segments were considered unclothed.

$$R_t(i) = R_a(i) + [R_f(i) + R_{al}(i)] \quad (9)$$

$$R_{e,t}(i) = R_{e,a}(i) + [R_{e,f}(i) + R_{e,al}(i)] \quad (10)$$

Segment-wise convective heat transfer coefficients were obtained from (de Dear et al., 1997). Metabolic heat loss [M] and heat loss due to external work [W] was taken as 60 and 30 W/m2, respectively.

2.2 Aggregated Comfort Survey

A questionnaire-based field survey was conducted using an aggregated comfort survey approach (Shastry et al., 2016). 62 occupants living in conventional (Total=32, M=18 and F=14) and vernacular (Total=30, M=13 and F=17) building typologies, aged between 20-56 years, were interviewed. The survey was conducted when the subjects were indoors and not involved in any exhaustive physical activity. Their comfort votes (thermal, respiratory, and skin-related) and health symptoms were recorded for each month of the year. Indoor Air Quality (IAQ) is determined by the constituents of the indoor air (water vapor, carbon dioxide, volatile organic compounds etc.); however, in this study, only indoor air humidity-related skin stickiness/dryness was examined. Also, their clothing, activity (standing, walking, sleeping, lying down), environmental temperature, and RH during the interview were recorded.

3. Results and Discussions

The comfort votes of the occupants (Thermal, Skin-related, and Respiratory) for all the months are shown in Fig. 2. There is a close relation between thermal comfort and the skin-related (IAQ) comfort votes of occupants, suggesting that the occupants felt that their skin was stickier/oilier during warmer months. During the colder months, occupants experienced dry skin. However, the response varied within the building typologies. The response of occupants in vernacular dwellings is more consistent than that of the occupants of conventional buildings. Comfort votes of occupants represents their expectations from the built environment, reflecting adaptive strategies. Skin-related comfort/discomfort is often manifested as a change in thermal comfort vote, making it challenging to discern.

Occupants report neutral respiratory comfort mostly, other than the cold winter months when the Humidity Ratio (HR) of the air goes low. Low HR values can cause serious difficulty in respiration due to inefficient nasal mucociliary clearance, especially in the elderly. As regulated by the building material and anthropogenic factors, the humidity of the indoor air is responsible for maintaining the homeostasis of the human airways (Hugentobler, 2021). Even though the average daily humidity ratio was higher than that suggested by ASHRAE for comfort, i.e., 0.012 kg-wv/kg-da in both the building typologies, a deficit was observed from the saturated (trachea) airway HR of 0.041kg-wv/kg-da (at saturated core temperature 36.7 °C), more so in the winter months. The humidity ratio in the conventional building remains lower than in the vernacular building throughout the year. Also, as illustrated in Fig. 3 and Fig. 4, the diurnal variation of the moisture deficit remains very high in the conventional room, especially when the HR of outdoor air is low in the winters (see Fig. 4).

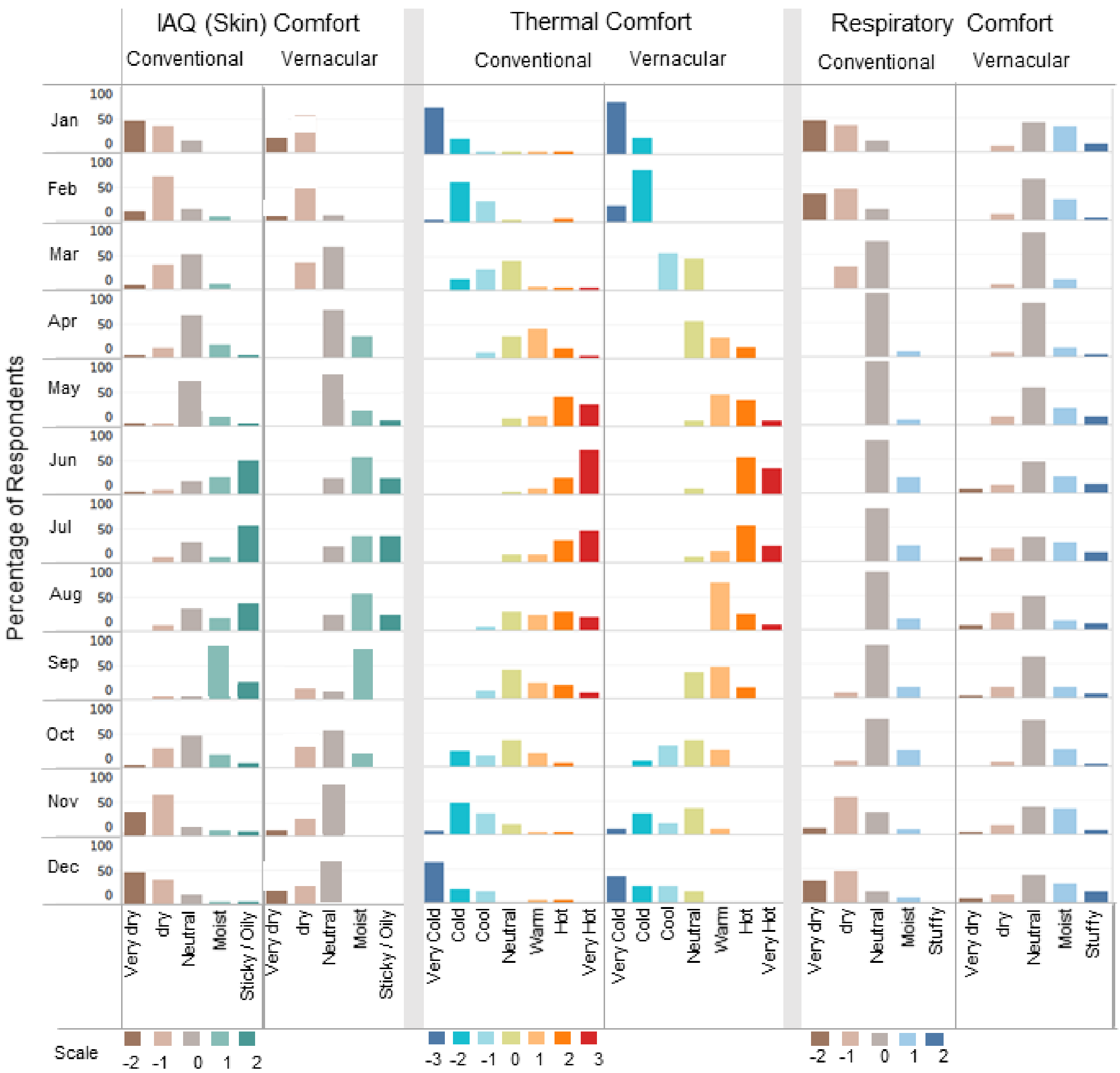

Fig. 2 – Aggregated Comfort Votes of occupants

The equilibrium (heat and mass) between the skin and the indoor air is associated with heat loss or gain by the human body, leading to thermal comfort perception. The local changes in the skin's temperature due to the heat loss/gain to attain equilibrium leads to skin-related discomfort.

In this article, skin temperature and wettedness, computed using the Gagge-2 core model, were used to understand the interaction of skin with indoor air. The system of differential equations for energy balance was solved using an iterative approach until the difference between two consecutive skin temperature values was less than 10^{-8} °Celsius. Convergence of the model was ensured in the entire range of temperature and humidity conditions recorded during the field study.

The trends of Mean Skin Temperature (MTsk), Evaporative heat loss (Esk), and skin wettedness (w) of occupants in different buildings (and outdoors) for four typical seasons, Spring (March), Summer (May), Monsoon (September), and Winter (November) are shown in Figs. 5, 6 and 7, respectively. During September, the average MTsk variation is close to the neutral MTsk; occupants report feeling hot and humid. The corresponding Esk is lower, with higher values of w. This implies that the evaporative losses are restricted in the humid months from the skin causing sweat accumulation on the skin surface, resulting in the occupants feeling sticky.

In November, when the occupants feel cold and dry, the variation in average MT_{sk} is the highest, implying more deviation from the neutral MT_{sk}. However, even though the MT_{sk} is lower than the neutral, and the human body needs to gain heat, E_{sk} is higher, and the skin is still losing energy. This negative response of the skin is due to active perspiration from the skin (high HR) into the outdoor air (low HR) to attain mass equilibrium, further cooling the skin. This loss of moisture leads to skin dryness.

In May, even though the MT_{sk}, E_{sk}, and w remain the highest, the skin-related (IAQ) comfort vote remains close to neutral. High E_{sk} and moderate w have a cooling effect on the skin, promoting the lowering of skin temperature to the neutral MT_{sk}.

The building clusters in the survey locality are designed to accommodate open, closed, and semi-open spaces (courtyard/verandah). Transitions from outdoor/semi-outdoor to indoors are inevitable for daily activities. Thermoregulation on the skin's surface is perturbed in this transition.

Human skin tries to maintain a balance through active perspiration, leading to a spontaneous skin temperature change. These variations in the skin temperature and wettedness due to environmental air parameters can cause dryness.

In Fig. 8 and Fig. 9, the computed skin temperatures of each body segment in the courtyard (outdoors), vernacular room, and conventional room at different times of the day are illustrated. The indoor environmental parameters in the vernacular buildings are very close to the outdoor environment on the low humidity cold days, implying lowered discomfort. It may be noted that some segments reach MT_{sk} as high as 40° C, which may not occur in reality. The calculated MT_{sk} indicates an equilibrium temperature between the skin and the indoor air. However, the skin responds instantaneously with indoor air temperature/RH perturbation, not necessarily after the equilibrium is reached.

Nonetheless, the temperatures illustrated are valid for understanding the stress that human skin may undergo. Also, the thermal stress on the skin in the courtyard, conventional and vernacular rooms is contrasted.

The change in temperature and RH outdoors diurnally also changes skin parameters. Vernacular indoor environments are regulated, moderating the thermal exchanges between the human body and the indoor air throughout the day.

Other reported health outcomes like colds, coughs, headaches, etc., need further scrutiny for their association with Indoor Environmental Quality (IEQ). Also, the present humidity-related comfort standards need to be validated for their applicability given the varying building typologies, acclimatization, personal habits, and occupants' preferences.

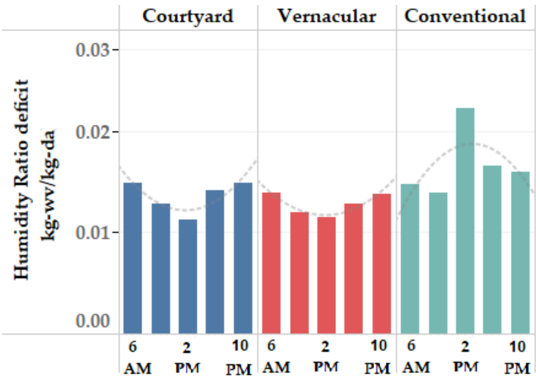

Fig. 3 – HR deficit on highest outdoor humidity day (23 Sept 2020)

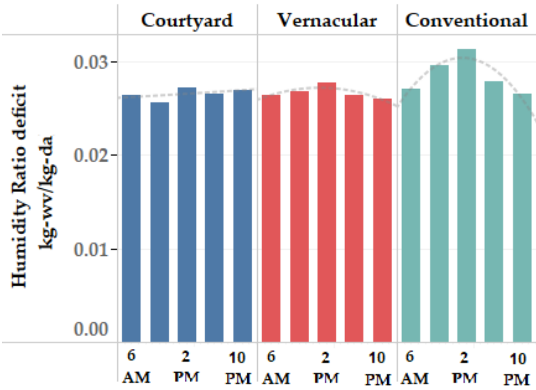

Fig. 4 – HR deficit on lowest outdoor humidity day (4 Nov 2020)

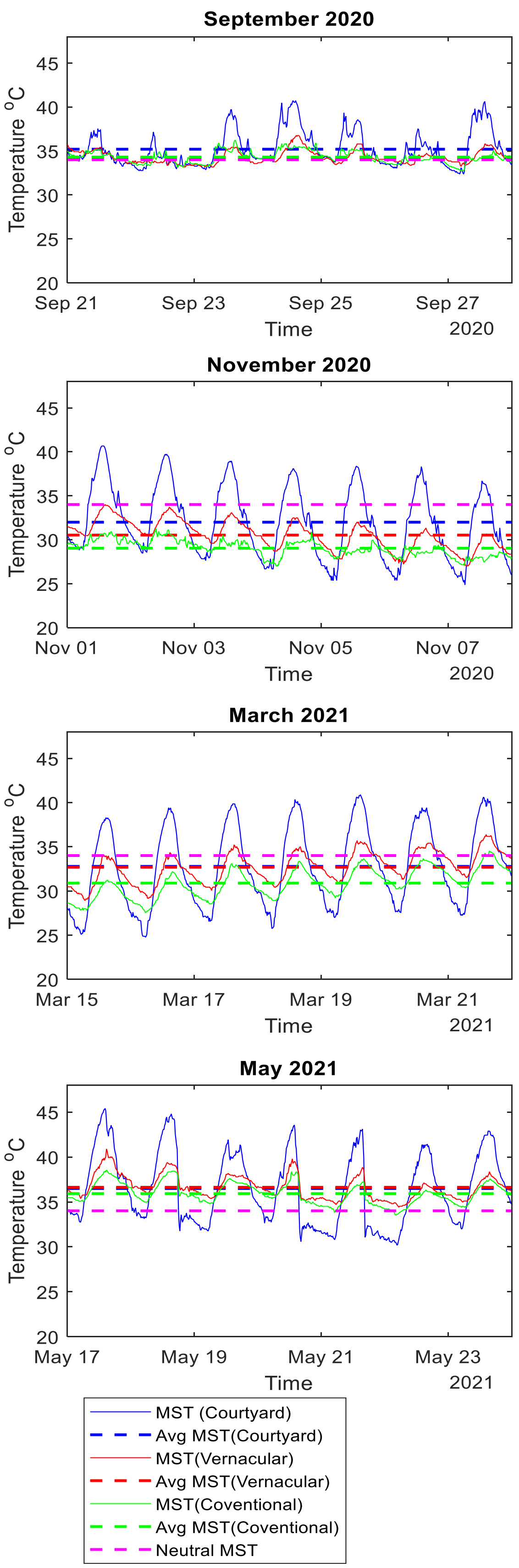

Fig. 5 – Seasonal variations of Mean Skin Temperature in Courtyard, Vernacular and Conventional Rooms

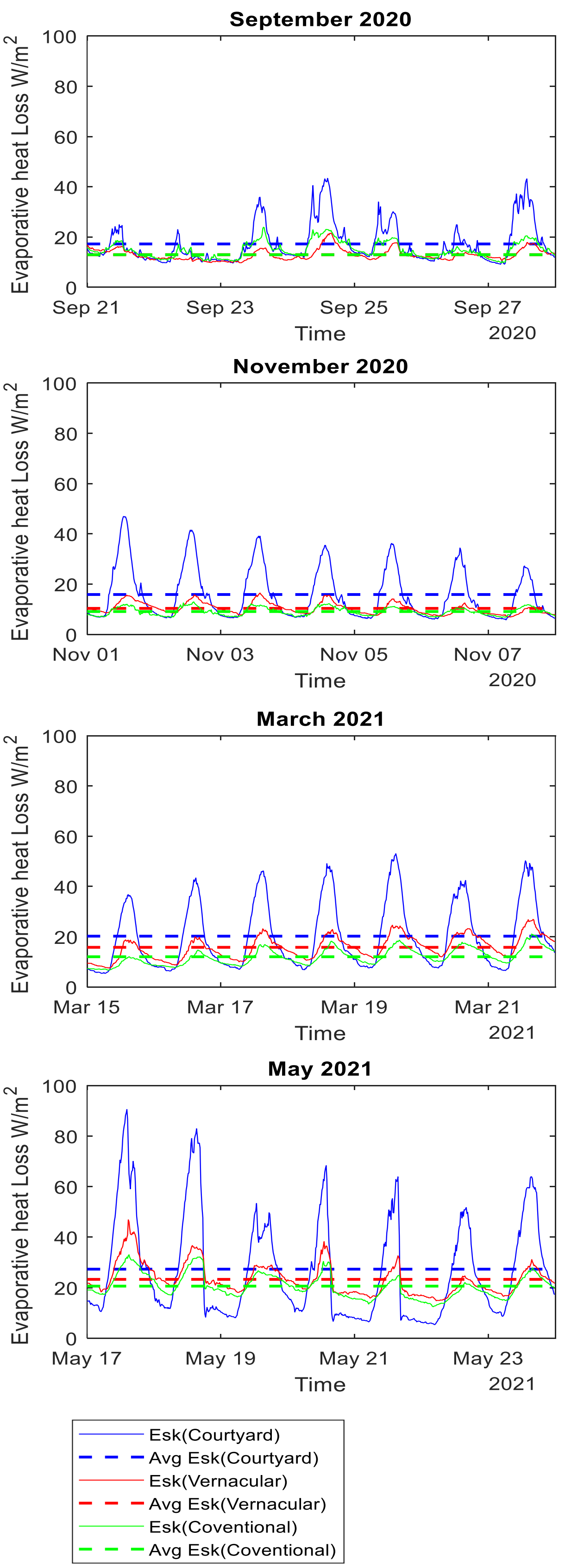

Fig. 6 – Seasonal variations of Evaporative heat loss in Courtyard, Vernacular and Conventional Rooms

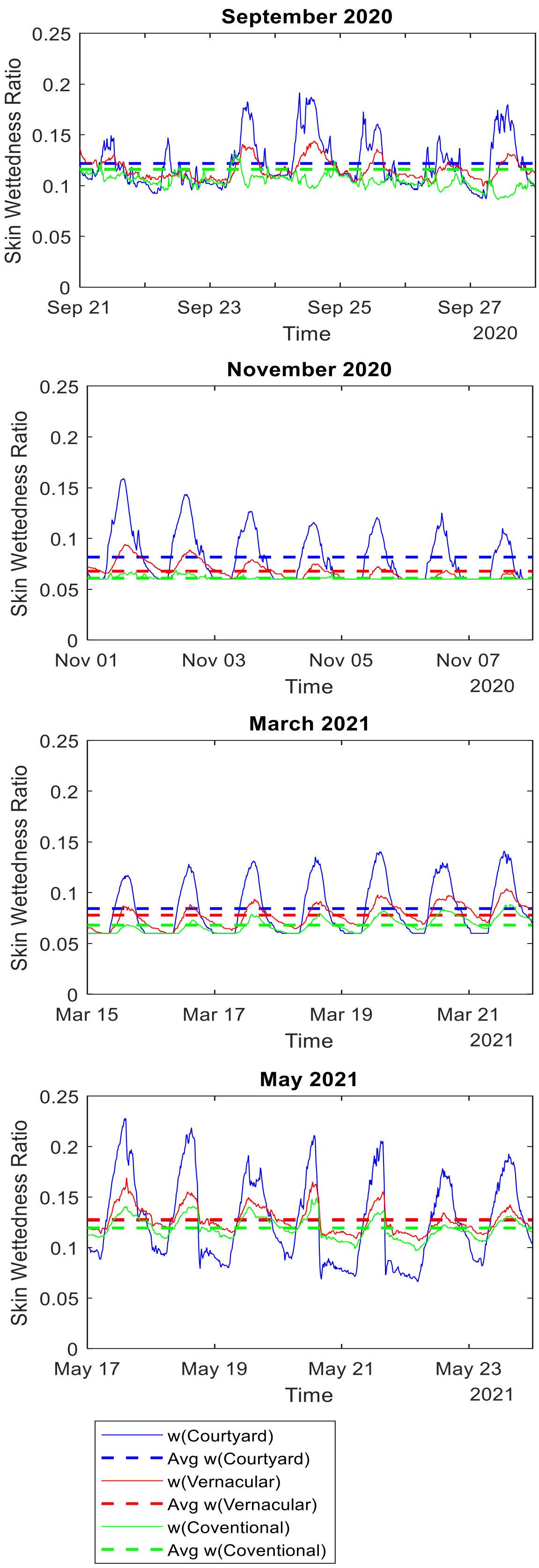

Fig. 7 – Seasonal variations of skin wettedness in courtyard, vernacular and conventional rooms

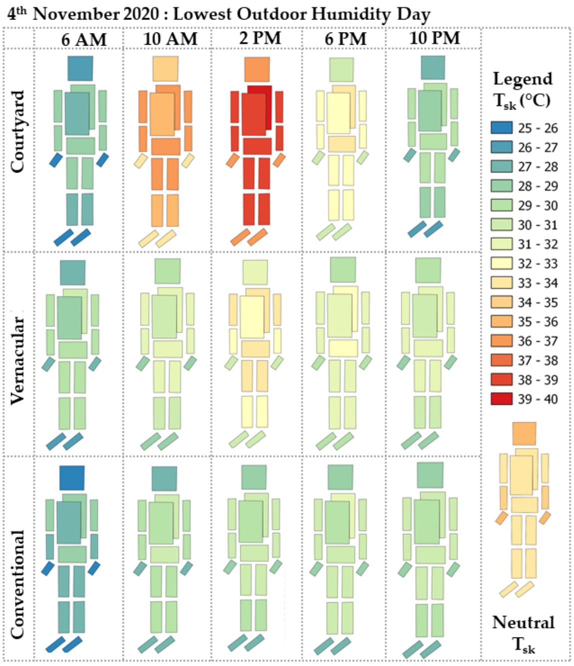

Fig. 8 – Variation of skin temperatures diurnally in the courtyard, vernacular dwelling, and conventional dwelling on lowest outdoor humidity day (4 Nov 2020)

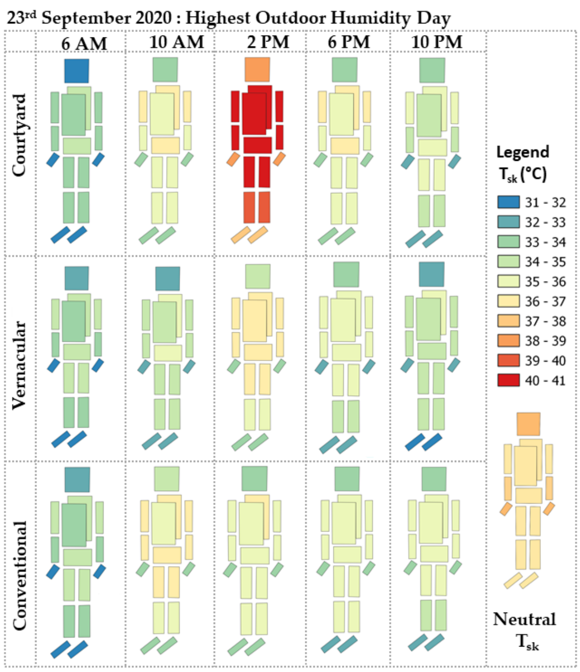

Fig. 9 – Variation of skin temperatures diurnally in the courtyard, vernacular dwelling, and conventional dwelling on highest outdoor humidity day (23 Sept 2020)

4. Conclusion

This study attempts to explain the impact of varying indoor RH in vernacular and conventional building typologies on humidity-related comfort and health outcomes. It involves real-time monitoring and a computational approach. Skin temperature and wettedness were computed corresponding to real-time indoor conditions in vernacular and conventional buildings based on the energy balance between the skin and indoor air. Humidity is an essential determinant of thermal, respiratory, and skin-related comfort, determining everyday habits like clothing, use of cosmetics etc., water intake etc. thereby impacting health. Although the current building simulation tools incorporate examination of thermal comfort associated with humidity, skin and respiratory comfort are not explicitly examined. Integration of this approach in building simulation tools could improve understanding into occupants' skin and respiratory comfort. The results show that building typology (materials) is vital in enhancing humidity-related IEQ parameters. Vernacular dwelling was more conducive to occupants' comfort and health in this study. Vernacular dwellings are earth-based and carry a lower carbon/ecological footprint. There is immense scope for occupant wellness in their adoption in modern buildings.

Acknowledgment

This study was supported by Prime Minister's Research Fellowship at the Indian Institute of Science and the British Academy's Wellbeing achieved from Earthen Residence (WAFER) project (UWB190086).

Nomenclature

Symbols

A	Surface Area (m^2)
$c_{p,b}$	Constant pressure specific heat of tissue (kJ/(kg K))
$c_{p,bl}$	Constant pressure specific heat of blood (kJ/(kg K))
C	Convective heat transfer (W/m^2)
C_{res}	Sensible heat loss due to respiration (W/m^2)
E_{res}	Evaporative heat loss due to respiration (W/m^2)
E_{sk}	Evaporative heat loss from the skin (W/m^2)
HR	Humidity Ratio (kg-wv/kg-da)
i	Body segment (dimensionless)
K	Effective conductance between core and skin ($W/(m^2K)$)
m	Mass (kg)
m_{bl}	Blood flow (core-skin) ($kg/(m^2s)$)
M	Metabolic heat production (W/m^2)
$p_{sk,s}$	Partial pressure of saturated water vapor at skin temperature (kPa)
$p_{wv,a}$	Partial pressure of water vapor in the air (kPa)
$Q_{cr,sk}$	Heat flow from core to skin (W/m^2)
R	Radiative heat transfer (W/m^2)
R_a	Thermal resistance of outer air layer ($m^2°C/W$)
R_{al}	Thermal resistance of intermediate air layer ($m^2°C/W$)
$R_{e,a}$	Evaporative resistance of outer air layer (m^2kPa/W)
$R_{e,al}$	Evaporative resistance of intermediate air layer (m^2kPa/W)
$R_{e,f}$	Evaporative resistance of fabric layer (m^2kPa/W)
$R_{e,t}$	Total evaporative resistance (m^2kPa/W)
R_t	Total thermal resistance ($m^2°C/W$)
S_{cr}	Heat storage in the core (W/m^2)
S_{sk}	Heat storage in the skin (W/m^2)
t_o	Air temperature (°C)
t_{cr}	Core temperature (°C)
$t_{cr,n}$	Neutral core temperature (°C)
t_{sk}	Skin temperature (°C)
$t_{sk,n}$	Neutral skin temperature (°C)
w	Skin wettedness ratio (dimensionless)
W	Heat due to external work (W/m^2)
α	Body mass fraction at the skin (dimensionless)
θ	Time (s)

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