An Appraisal of Vernacular Architecture of Bikaner: Climatic Responsiveness and Thermal Comfort of Havelis

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Abstract

The building sector is a significant energy-consuming sector. Sustainable and climate-responsive architecture offers possible solutions to these challenges. The principles evolved over many generations as observed in the vernacular architecture, constructed with locally available materials applying the local construction techniques and confined to the traditional knowledge system are more responsive to the climate than the newly built contemporary houses. This however is unexplored with scientific methods.

This research does so by exploring vernacular haveli and the contemporary house within the walled city of Bikaner. The vernacular havelis of Bikaner, a town in India's desert region are climate responsive. They have evolved from centuries of experience and observations of climate and Nature. The research looks at the Vernacular havelis of Bikaner, which is in use and also shares the same scale and location with the contemporary house. The thermal performance along with other parameters of the two housing types are compared in the two climatic extremes i.e. summer and winter. The comparison is done by physical data logging and in the adaptive behavior analysis of the users of the two. The research looks at the qualitative and quantitative evaluation of the vernacular haveli and the contemporary house in Bikaner. The process involved an experimental setup. The findings show a preference for traditional houses over contemporary houses in terms of thermal comfort

Keywords: Climate responsive; Thermal comfort; Vernacular architecture; Havelis; Bikaner; India.

Introduction

The natural and passive systems in buildings use non-mechanical methods to maintain a comfortable indoor temperature and are a key factor in mitigating the impact of buildings on the environment. The traditional architecture of the past is the best pointer in this regard and constitutes outstanding evidence of being climate-responsive and energy conscious. They display years of embodied experience built on the relationship between building and climate, implying a logical analysis, the consideration of appropriate principles, and rational use of resources (Kamal, 2007). The climate-sensitive nature of sustainable design, as well as its awareness of regional environmental and material concerns, demand a fresh look at the issue of traditional architecture as it pertains to the practice of sustainable building. The inherent and timeless knowledge of traditional architecture remains key to the future of responsible design and planning, providing an important foundation of design initiatives that will inspire eco-technological advancements that might one day alleviate our reliance upon energy abusive mechanical systems that have become dangerously universal. These buildings, therefore, can be studied as models of environmentally responsive and sustainable architecture.

The Research Background

Vernacular Architecture

Vernacular architecture is defined as a "building that belongs to a place that expresses the local or regional dialect" (Bonner, 2006). The origin of the word '*vernacular*' finds its roots in the Latin word '*vernaculus*' the meaning of which is native, domestic, indigenous, or that which is indigenous of the local people. Vernacular can be said as the indigenous manifestation of the local climate, geography, materials, customs and traditions of the people. It is the architecture of the people, by the people and for the people (Bonner, 2006). Rapoport (1969) gave the idea that vernacular architecture is like the folk tradition '*direct and unself-conscious translation into the physical form of a culture, its need and values – as well as the desires, dreams and passions of the people.*' He categorizes this folk tradition into pre-industrial vernacular and modern/post-industrial vernacular. "Architecture concerned with domestic & functional rather than public or monumental buildings" (Rappoport, 1969). Vernacular architecture responds to the region and the social structure of the place. The rich architecture of the natives is like an open book. which gives us clues on the rich culture, customs and traditions, philosophy of the local people, the occupation and the socio-economic standing. As we study the various vernacular styles of the world, we see the distinct variations based on the location, need and climate of the place. Vernacular Architecture in India is vibrant in terms of variety, as we have seen across the length and breadth of the country. The concepts of space planning are very well adapted to people's needs and the climate. Continuity of tradition needs government patronage, guidelines for planning, regulating the modification and codes to safeguard the interest, regardless of whether the technology is new or traditional (Saleh & Al-Alkhalaf, 1999).

Havelis as a Paradigm of Vernacular Architecture in India

Havelis have always fascinated the urban dwellers, the scale of the structure, the majestic architecture, the reflection of the local and the socio-economic and the cultural standing of the owner. Havelis have been a part of north Indian tradition. The desert state of Rajasthan is typically blessed with a wide variety of Haveli structures. Many Indian and foreign researchers have studied native vernacular architecture. An important study has been carried out by Prasad, Kulbhushan Jain on the Havelis of India (Prasad, 1997). The courtyard typology can be observed in many parts of the world Asia, the Middle East, or the Mediterranean and the courtyard provides the natural light and ventilation to the living quarters around it. The courtyard also acts as the central hub for all the religious and cultural activities of the household. The typology has endured centuries of developmental transformation because of the contextual and behavioral changes in society (Parmar, 2005). Parmar proposes the idea that the urban courtyard form developed from the rural village house. The haveli typology was a product of the prevalent condition of the society and also became a status symbol for its owner. It could be a single-storied to a double or even a four-storied structure. The purpose was purely residential for the haveli, but in most cases, it was observed that some had an office or the merchant's place of work and interaction also. The similarities in the spatial layout of the haveli typology as observed in various regions like the one in Gujrat, Rajasthan, Lucknow, Delhi and Pakistan also suggest that the similarity is influenced by culture and the social setup. The Havelis in India date from as early as the 1600s to the early 20th century (Prasad, 1997). Jain has exhaustively studied the Havelis of Rajasthan and in her attempt to define the haveli form based solely on the physical features and how there is a deviation from the basic core structure (Shikha, 2004).

Vernacular Architecture and Climatic Design

In vernacular architecture, an effort is made towards the utilization of natural resources as much as possible. As the ancient structures are designed in such a way that there is no need for AC or cooler or fan for creating a thermally comfortable environment. They have an inbuilt feature for providing thermal comfort. In many traditional buildings, both primitive and vernacular, some ingenious solutions to the architectural problems of resisting extremes of weather and maintaining a comfortable indoor climate can be seen (Sangkertadi et al., 2008). The familiar elements of regional architectural styles i.e. verandahs, balconies, courtyards, air shafts, thick walls, high ceilings, etc. are created to use the sun for warmth and light and to create shade and breeze for cooling. In vernacular architecture, building mass distribution is in a way that in addition to taking full advantage of sunlight, airflow out of the building is reduced to a minimum. Also in the summer, while minimizing thermal conduction, radiation is used to cool the building. In the winter, the building takes the most advantage of sunlight so it minimizes the thermal conductivity. Also during the summer, while causing a delay in the thermal conductivity, proper ventilation is created (Pourdeihimi, 1999). Climatic design lessons can be learned and inspirations can be sought by the observation of the long tradition of traditional architecture (Maria, 2009). The principles of good thermal design used in traditional buildings are still valid today and it would still be possible for modern designers and architects to incorporate these design principles in buildings, which are suitable for modern-day living to conserve energy and provide better thermal comfort (Kamal, 2006). The vernacular havelis of the Bikaner region are typical examples of buildings adapted to the hot and dry climate. The vernacular architecture is in a developmental process intended to reclaim the architectural values of protection against the severities of the exterior climate following the objective of minimal consumption. During these times of environmental crisis and accelerated urban development, it seems logical for architects to practice sustainable ecological design (Bay, 2010).

Bikaner: The Study Context

Bikaner district is situated 27°11’ to 29°3’ North latitudes and 71°54 to 74°12’ East longitudes in the north-west region of the state of Rajasthan. It was established by Rao Bikaji in the year 1465 and is in the state of Rajasthan (Fig. 1), in India with a geographical area of 30382.15 sq km. After the advent of the Ganga canal in 1927, the town saw major growth and development The urban form within the walled city of Bikaner comprises of havelis which have a carved stone facade, intricately ornamental stone-carved The street form is even more striking through the characteristics of narrow shaded lanes, verandahs for resting, balconies of varied designs supporting jaali and refined wood-worked doors.

Fig. 1. Map of India, showing the location of Bikaner
(Source: Author)

The Climate of Bikaner

The climate of Bikaner is typical of a hot desert region. The two seasons predominate, summer and winter. The summer temperature is very hot and the daytime temperature can reach up to 50°C and may go down to 25°C at night. Similarly, in winter, the temperatures vary between 5°C-25°C. The diurnal range of temperatures is between 15°C and 20°C. Since the region is arid, there is very low relative humidity, especially during hot seasons. The relative humidity in summer can be less than 10% in the day. The average annual precipitation is less than 180mm which is during the monsoon months. However, in some years, there could be no rainfall at all. During the summer months of May, June, and July, the town is subjected to severe sand storms. The sky is mostly clear and solar radiation is intense throughout the year. The average solar radiation on a horizontal surface in June is 22.2 MJ/m^2/day. The solar radiation is direct and strong during the day, but the absence of clouds permits the easy release of heat stored during the daytime in the form of longwave radiation towards the night sky. Wind velocity is usually high and there are severe dust storms during May and June.

Research Methodology

Since the research is case study-based, the following methods will be involved to carry out the research:

- Physical Survey of the study area to identify the contextual issues and setting. The survey of the case study of vernacular architecture of Bikaner i.e. Havelis and the old houses to understand the typology, architectural style, construction techniques and materials.
- The temperature, relative humidity, Mean Radiant Temperature (MRT), Air velocity, were measured outside the building and in different indoor spaces for every three hours for the climatic extremes i.e. 21st June 21and 22nd December and Thermal Comfort Analysis for each of the vernacular haveli and the contemporary house has been done.

PMV and PPD Calculation

The predicted mean vote (PMV) is a model given by Fanger and the on this model the ISO7730 standard is also based. This model is employed for understanding the thermal comfort of the occupants (Van, 2008). PMV is an index to forecast the mean thermal sensation vote for a group of individuals in a defined space based on a pre-defined scale. The excel sheet for the calculation of PMV and PPD is developed by Angelo Farina. This sheet is a very useful application for the calculation of the PMV and PPD for any given space. The sheet is available on the following link http://www.angelofarina.it/Public/Fisica-Tecnica-Ambientale-2015/Lez-04-05/. When the air temperature, mean radiant temperature wind velocity, relative humidity, clothing insulation and the metabolic rate is known then the calculation can be done using the excel sheet. (Farina, 2015)

Case Studies

The case study approach is selected for the research as this will provide a detailed description of the cases and their users in the right context. The detailed study will help in structuring a systematic analysis process resulting in detailed answers to the research aim.

Case Study 1: Vernacular haveli – VH1

The Haveli VH1 is about 250 years old and is located in a dense urban setting, with adjoining Havelis next to one another. The haveli is perpendicular to the street, which is north-south aligned. The front façade of the haveli opens to the street on the Eastern face. The built-up area is 203 m^2 on the ground floor (Fig. 3). It has a central courtyard which is the source of light and ventilation for the interior rooms. The front facade of the Haveli has many openings, which help in getting the sunlight and also facilitate natural ventilation (Fig. 5). The position of the data logger is marked in the ground floor plan in yellow dots. The data logger is positioned in the spaces where the occupancy is the maximum and for the maximum duration too. The first space is the living room “Baithak”. The second location is the courtyard, and the third is the bedroom. The narrow staircase and the steep risers make it difficult for occupants to go to the first and the second floors (Fig. 4). The second-floor rooms are used for storage. The courtyard is very small and measures 2.9 x 2.9 meters. The courtyard is shaded on the second-floor terrace level with a projecting sunshade.

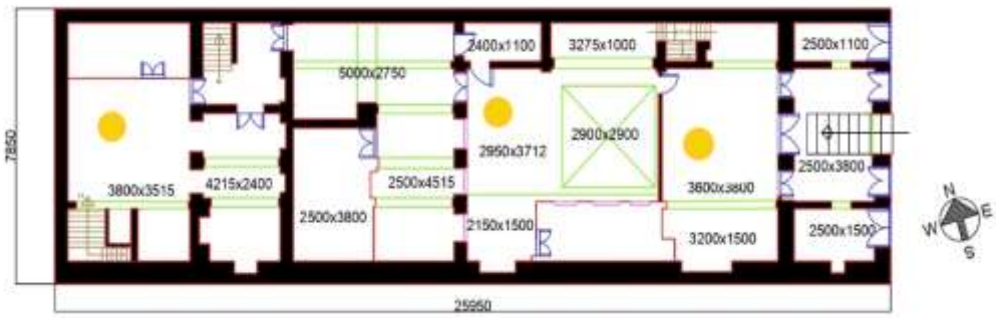

Fig. 2: First Floor Plan of Vernacular Haveli VH1
Source: Author

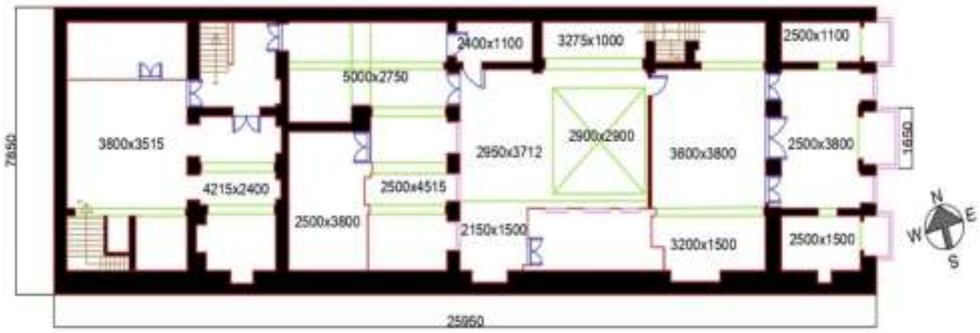

Fig. 3: Ground Plan of Vernacular Haveli VH1
Source: Author

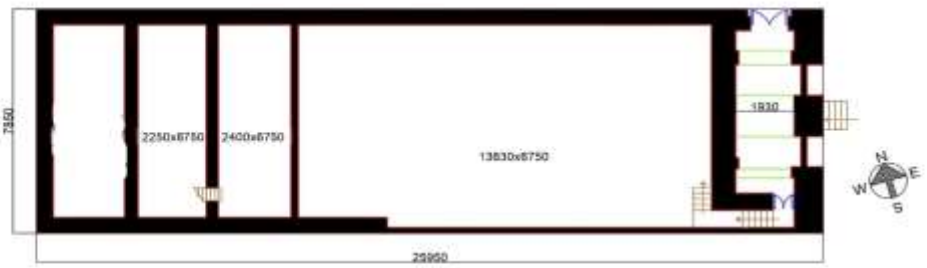

Fig. 4: Basement Floor Plan of Vernacular Haveli VH1
Source: Author

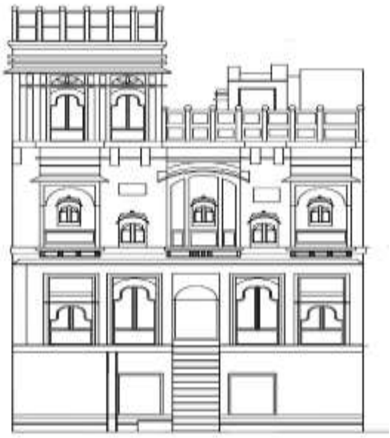

Fig. 5: Elevation of Vernacular Haveli VH1
Source: Author

Case Study 2: Contemporary House 1-CH1

The Contemporary House CH1 has been re-constructed 6 years ago by the owners after they sold off their share in the ancestral haveli. The neighborhood has many new houses constructed by the members of the same family. The house is constructed facing West and is surrounded by three adjoining houses on its three sides (Fig. 6). The built-up area on the ground floor is 150 m^2 (Fig. 7). The house has an upper floor too (Fig. 8). The spaces are compact. This house does not have a central courtyard as seen in many of the vernacular houses. There are two open sides; a front yard and a small open space in the rear. The position of the data logger is marked in the ground floor plan by the yellow dots.

Fig. 6: Front View of the Contemporary House CH1
Source: Author

Fig. 7: First Floor Plan of Contemporary House CH1
Source: Author

Fig. 8: Ground Plan of Contemporary House CH1
(Source: Author)

Thermal Comfort Analysis

Thermal Comfort Analysis of Vernacular Haveli 1 (VH1) in Summer

Analysis of the interior spaces of the case study Vernacular Haveli 1 (VH1) shows the temperature pattern of the habitable spaces mostly in use; the central hub of the haveli is the courtyard, the living room and the bedroom. As compared to the outside temperature for June, which varies from 45°C to 25°C for the outside. The courtyard temperature recorded a maximum of 43°C and a minimum of 26°C, the living room temperature range is between 32°C to 23°C and for the bedroom, the temperature range was 30°C to 25°C. The outside temperatures are maximum at around 15.00 hours and the 5 hours from 13 hours to 1700 hours in the evening see the maximum temperature outside. As observed, the internal temperature of the bedroom is maximum at 1800 hours, and the living room observed maximum indoor temperature at 17:00 hours (Fig 9). This shows that there is a time lag due to the heavy mass construction; the thickness of the walls is 700mm. The outside temperature dips to its minimum of 25°C near midnight corresponding to which the temperature indoor reaches its minimum of 22°C at around 6:00 hours in the morning.

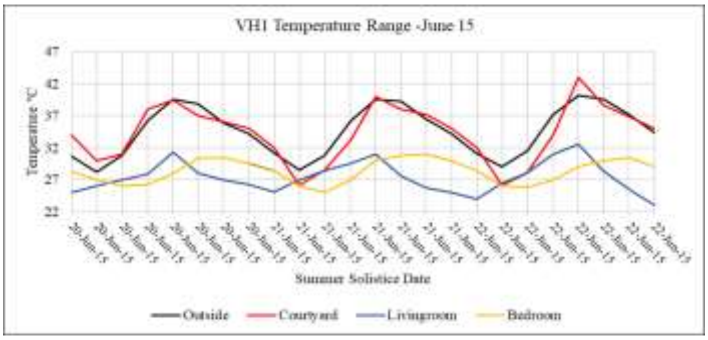

Fig. 9: Summer Temperature Profile of Vernacular Haveli VH1
(Source: Author)

The relative humidity range for the outside for June is between 70% to 25%. It is clear from the temperature vs relative humidity chart that relative humidity is inversely proportional to the ambient air temperature. The indoor range for relative humidity (RH) was between 65% to 30%. The courtyard RH was in the range of 65% to 25%. The outdoor RH varied almost 45%, whereas the enclosed spaces varied 35%. The variation of RH is directly related to the temperature variation of the respective spaces as in Fig.10. During the peak noon, when the temperature is the highest, the relative humidity is the lowest, causing the air to be very dry and making the heat unbearable.

The variation of wind velocity outside is high in comparison to the courtyard and the interior spaces, namely the living room and the bedroom (Fig. 11). The wind is channelized and controlled by the built mass of the structure. From the outside, warm winds are controlled, and limited airflow is allowed into the built spaces. The narrow streets help break the wind flow. The courtyard is also small and deep and as such is the only ventilation avenue for the interior spaces.

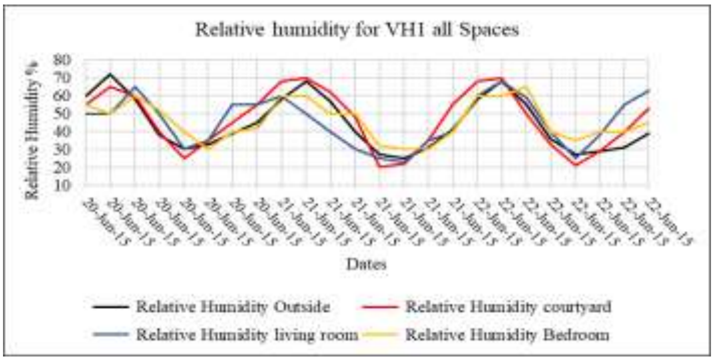

Fig. 10: Relative Humidity Profile of all spaces of Vernacular Haveli VH1 in summer (Source: Author)

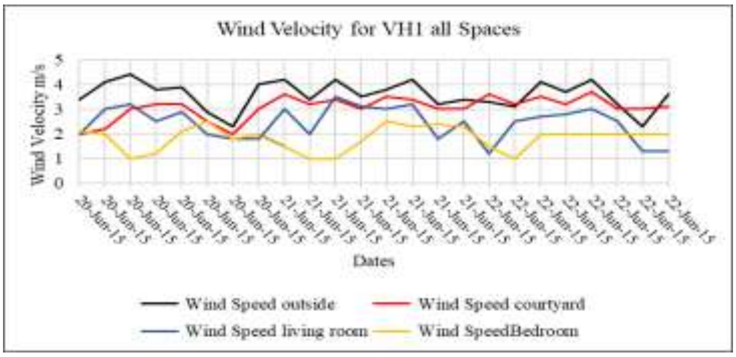

Fig. 11: Wind velocity in different spaces in Vernacular Haveli VH1 (Author) (Source: Author)

The Tropical summer Index (TSI) gives the comfort range as 25°C to 30°C, which can vary in the range of 5°C from the given limits in extreme conditions. When the outside temperature condition is either too cold or extremely hot, the temperature range for TSI extends from 19°C to 35°C (Sharma & Ali, 1986).

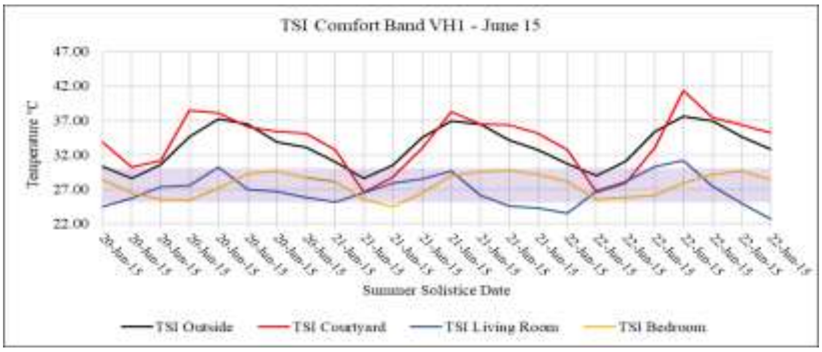

Fig. 12: TSI comfort band of Vernacular Haveli VH1 in summer (Source: Author)

The tropical summer index is calculated for the outside, courtyard; living room and bedroom for the case study VH1- Vernacular Haveli 1. The grey band in the graph shows the comfort temperature range as prescribed by TSI. The outside temperature is in the comfort range, and the inside is also in the comfort range (Fig. 12). The high thermal mass, small openings, mutual shading provided by the neighboring haveli also contributes to lowering the heat gain by the interior spaces. When the outside temperature reaches the lowest point of around 28°C, the inside temperature is at 25°C and is within the comfort range. To understand the performance of the case study VH1, a detailed analysis of the performance of the house is undertaken using DUHOI. Applying the formula of DUHOI for the case study VH1, the difference between the TSI_O and the TSI_i is calculated. The calculation for the selected three days for June for the case study house VH1 gives the DUHOI value of 5.16. This value will help to compare the performance of architectural design for the selected case study for the walled city of Bikaner, which falls under the hot and dry region.

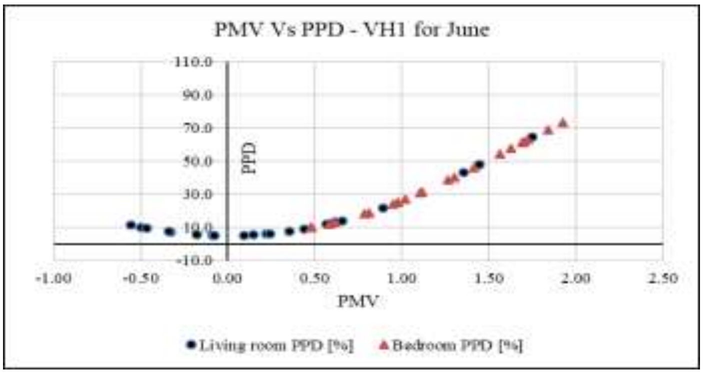

Fig. 13: PMV Vs PPD of Vernacular Haveli VH1 in summer for Clo value 1
(Source: Author)

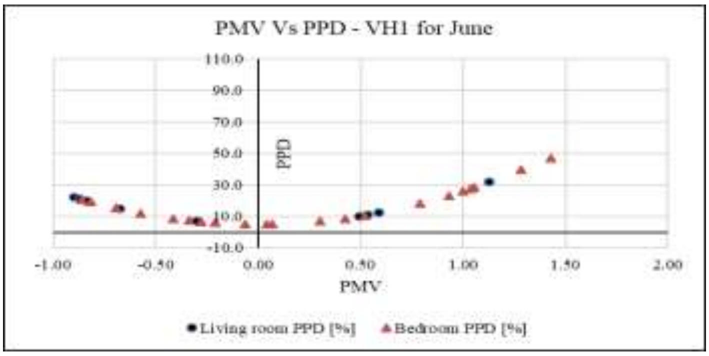

Fig. 14: PMV Vs PPD of Vernacular Haveli VH1 in summer for Clo value 0.5
(Source: Author)

Fig. 13 shows the PMV Vs PPD calculated for the case study VH1 for June. The PMV/PPD is based on the Fangers model. As for the calculation, the clothing factor is Clo considered as 1 and also the metabolic activity is kept at 1. The people use light cotton clothes, and the clothing layers are reduced. The wind flows into the interior is controlled by the louvered window shutters. Fig. 14 shows the PMV Vs PPD behavior for a Clo value of 0.5. With the Clo value of 1, the graph moves to the warmer side and the thermal vote is for warm. it does not provide thermal neutrality to the inhabitants. When the appropriate summer clothing is used, the PPD is in the range of -1 to 1.25, which is within the range of slightly cool to slightly warm.

Thermal Comfort Analysis of Contemporary House 1 (CH1) in summer

Analysis of the interior space in the case study of contemporary house 1 (CH1) shows the temperature pattern for the habitable spaces, which are mostly in use, the living room and the bedroom. As compared to the outside temperature for June, which varies from 45 to 25°C for the outside, the living room temperature range is between 36 to 28°C. For the bedroom, the temperature range is 33 to 27°C. The outside temperatures are maximum at noon and the 7-hour period from 12 noon to 6.00 pm sees the maximum temperature outside. The maximum temperature outside is at 3.00 pm and as observed, the internal temperature of the living room is also maximum at 3.00 pm. This is the case of the bedroom observed in Fig. 15.

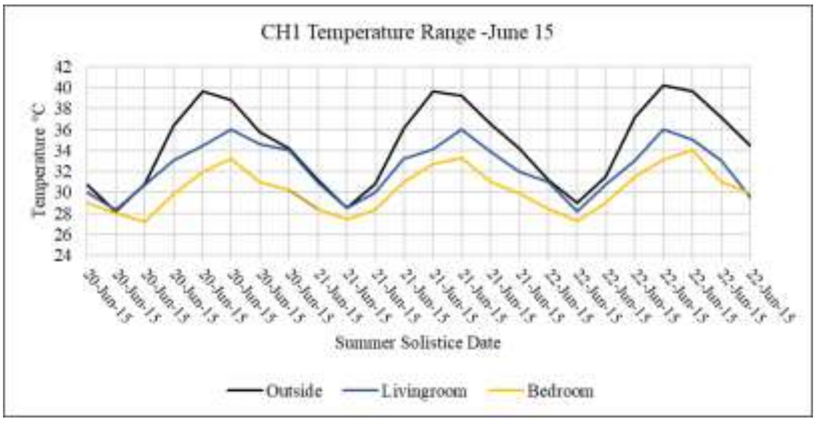

Fig. 15: Summer Temperature Profile of Contemporary House CH1
(Source: Author)

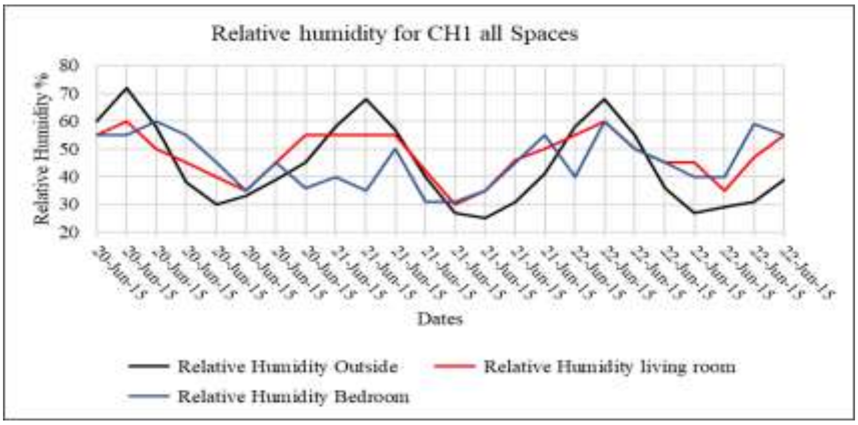

Fig. 16: Relative Humidity Profile of Contemporary House CH1 in summer
(Source: Author)

The relative humidity range for the outside for June is between 70% to 30%. The indoor range for relative humidity (RH) was between 60% to 30%. The variation of RH is directly related to the temperature variation of the respective spaces, as observed in Fig. 16.

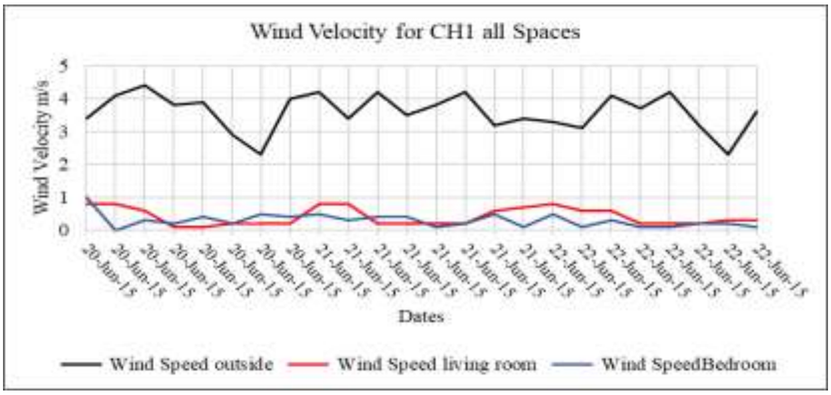

Fig. 17: Wind velocity in all spaces of Contemporary House CH1
(Source: Author)

In Fig. 17, the variation of wind velocity outside for June is shown in comparison with the interior spaces, namely the living room and the bedroom. As observed in the graph, the case study house CH1 lacks cross ventilation and hence the wind velocity indoors is negligible. The heat accumulated indoors cannot be released outside. The tropical summer index is well suited to the hot and dry region, and hence the comfort analysis for the case studies is done based on the comfort band defined by the tropical summer index. Tropical summer index was calculated for the outside, living room and bedroom for the case study CH1- Contemporary house 1. The outside TSI is in the comfort range i:e between 25°C to 30°C for about 3 hours very early in the morning. The grey band in the graph shows the comfort range as prescribed by TSI (Fig. 18). The interior space behaves in conjunction with the outside condition. The design does not provide effective thermal control due to the following reasons:

- Poor thermal resistance provided by the exposed external walls of the contemporary house allows for heat gain indoors. The heat infiltration through the windows and other cracks, and vents heat the space.
- The outside temperature reaches the lowest point of 28°C, the inside temperature is also at its lowest of 26°C, which is in the comfort range.

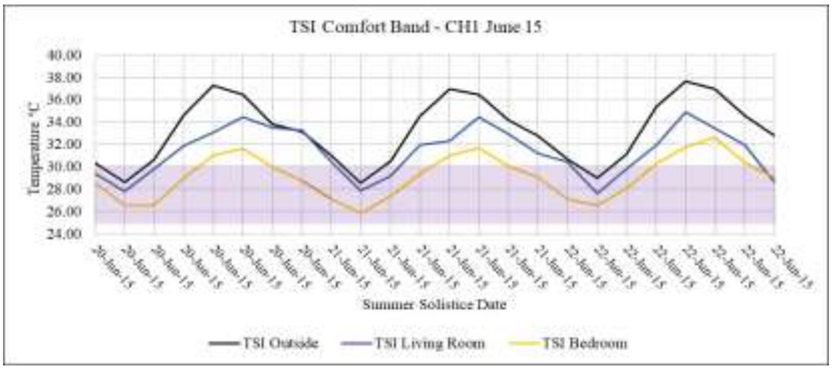

Fig. 18: TSI Comfort band in Contemporary House CH1 in summer
(Source: Author)

The calculation for the selected three days for June for the case study house CH1 gives the DUHOI value of 2.76. Fig. 19 shows the PMV Vs PPD of Contemporary House 1-CH1for June having Clo value 1. Fig. 20 shows the PMV Vs PPD of Contemporary House 1-CH1for June having a Clo value of 0.5. The living room has more discomfort hours as compared to the bedroom. The discomfort is due to the feeling of hotness during the afternoon periods. As the external face of the living room is also exposed to solar radiation and gets heated up. The sensation of warmth is experienced throughout the day as the value ranges from 1 to 4 on the

PMV axis, which means it is extremely hot. This is when the calculation with the standard Clo value of 1 is used for calculation. When the behavioral and adaptive approach is practiced, and the Clo value is taken as 0.5, there is not much change in the PMV Vs PPD graph.

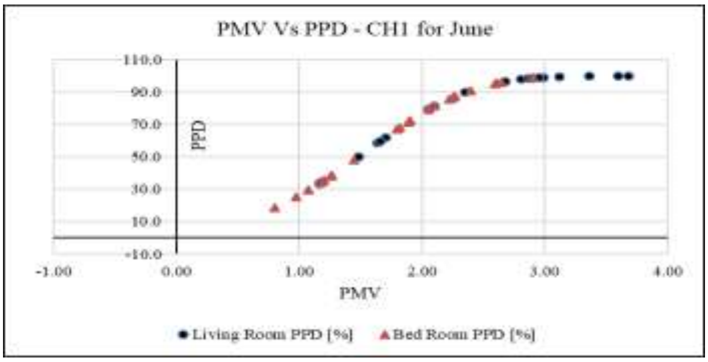

Fig. 19: PMV Vs PPD in Contemporary House CH1 in summer for Clo value 1
(Source: Author)

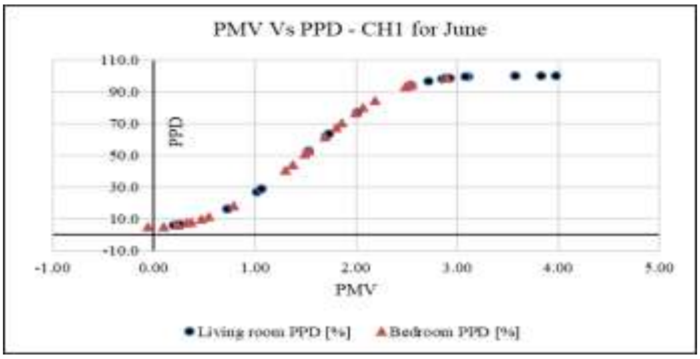

Fig. 20: PMV Vs PPD in Contemporary House CH1 in summer for Clo value 0.5
(Source: Author)

Thermal Comfort Analysis of Vernacular Haveli 1- VH1 in winter

Analysis of the interior space in the case study Vernacular Haveli 1 (VH1) namely the courtyard which is the central hub of daily activities, the bedroom used for sleeping during the night and the living room used almost throughout the day are taken for study. The recordings of indoor dry bulb temperature, relative humidity, wind velocity and global temperature are taken to understand the behavior of the spaces in comparison to the extreme climatic condition outdoors. The observation of the data recorded for the three indoor spaces is as in Fig. 21.

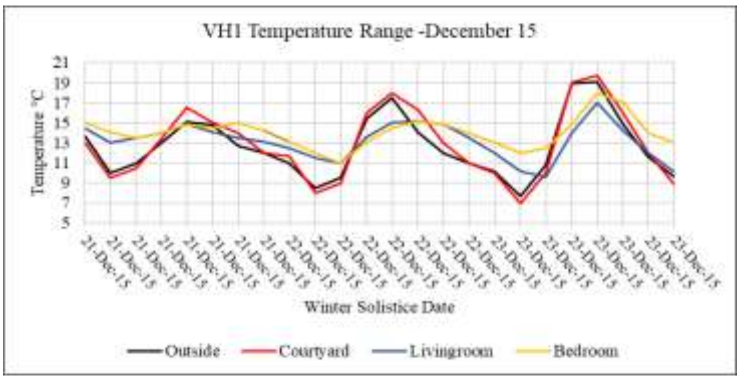

Fig. 21: Winter Temperature Profile of Vernacular Haveli VH1
(Source: Author)

As compared to the outside temperature for December which varies from 20°C to 3°C, the courtyard temperature recorded a maximum of 16°C and a minimum of 7°C. The living room temperature range is between 19°C to 8°C and for the bedroom, it was 16°C to 11°C. Observations show that the outside temperature is maximum at around 15: 00 hours and the 3-hour duration till evening 18:00 hour. The thick building envelops locks the heat indoors and the inside experiences. The temperature is in a constant band. When the outside temperature dips to its minimum of 3°C in the early morning hours, the temperature indoor reaches its minimum of 8°C at around 9:00 in the morning.

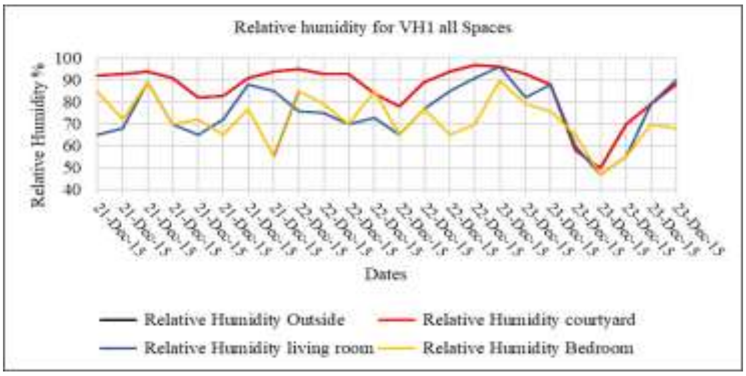

Fig. 22: Relative Humidity in different spaces of Vernacular Haveli VH1 in winters
(Source: Author)

The relative humidity range for December is between 90% to 50%. It is clear from the temperature vs relative humidity chart that relative humidity is inversely proportional to ambient air temperature. The high relative humidity, along with the low temperature, keeps the feeling of coldness in the environment. The indoor range for relative humidity (RH) was between 90% to 50% for the courtyard, which brings the cold chill indoors by ventilation. The living room was 90% to 65%, and for the bedroom, it was 85% to 50% (Fig. 22). The wind velocity is a max of 1.8m/s to a minimum of zero wind draft. The windows are closed to stop airflow, which may cause discomfort in terms of adding the sensation of coldness (Fig. 23).

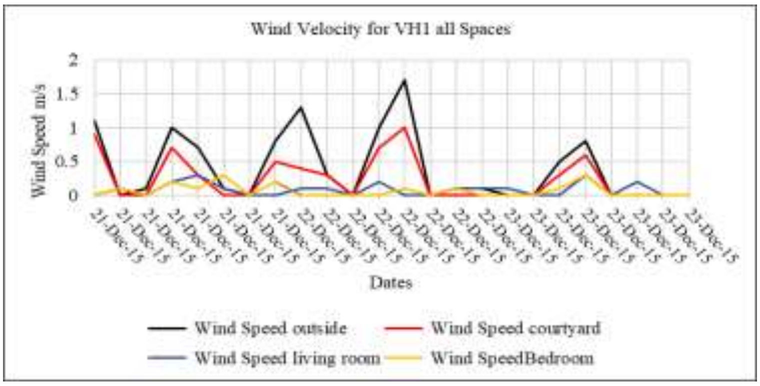

Fig. 23: Wind velocity in different spaces of Vernacular Haveli VH1 in winters
(Source: Author)

The tropical summer Index (TSI) gives the comfort range as 25- 30°C, which can vary in the range of 5°C from the given limits in extreme conditions. When the outside temperature condition is either too cold or extremely hot, the temperature range for TSI is from 19 to 35°C (Sharma & Ali, 1986).

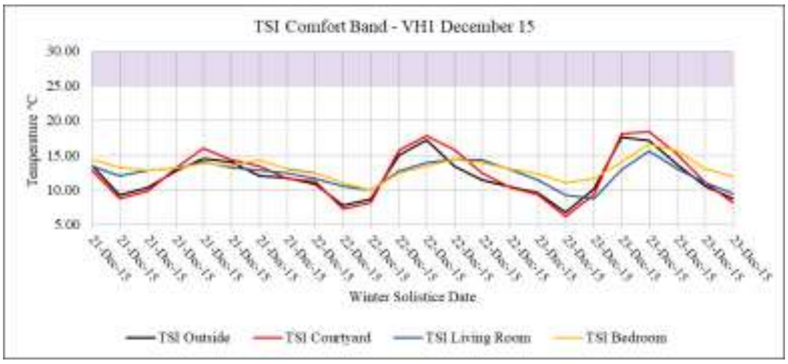

Fig. 24: TSI comfort band in Vernacular Haveli VH1 in winters
(Source: Author)

Tropical summer index (TSI) was calculated for the outside, courtyard, living room and bedroom for VH1- Vernacular Haveli 1 for December. The outside temperature is never in comfort range i.e. between 25°C to 30°C for December. The grey band in the graph shows the comfort temperature range as prescribed by TSI. The outside and inside temperatures both are outside the comfort band (Fig. 24). Also, when the outside reaches its maximum temperature of 17°C and the min of 6°C, the indoor room temperature maintains a range of 16 to 10°C. The variation of 6°C with a controlled airflow creates a condition of uniformity. The process of behavioral changes and adaptation kicks in to keep the inhabitants warm during this cold spell. The indoor temperature remains in the comfort zone because the high mass construction of the haveli provides sufficient thermal resistance, and this results in controlling the temperature fluctuation observed outdoors. The architectural design successfully provides thermal comfort for the interior space for the given outside condition. The reason for this is that when outside temperature reaches the lowest point of around 3°C to 5°C and the relative humidity is the highest at about 90%, the observed indoor minimum temperature is in the range of 9°C to 10°C.

To understand the performance of the building envelop or the architectural design of VH1, a detailed analysis of the performance of the house is done based on the concept of understanding the Difference in Uncomfortable Hours Outside Vs Inside (DUHOI). Applying the formula of DUHOI for the case study VH1, the difference between the Tropical Summer Index outside (TSI_O) and the Tropical Summer Index inside (TSI_i) is calculated for the habitable spaces. The calculation for the selected three days for the December solstice for the case study house VH1 gives the DUHOI value of -0.67. This value will help to compare the performance of architectural design for the selected case study for the walled city of Bikaner, which falls under the hot and dry region. Fig. 25 shows the PMV Vs PPD for Vernacular Haveli 1-VH1 for winter having a Clo value of 1 and Fig. 25 shows the PMV Vs PPD for Vernacular Haveli 1-VH1 for the winter having a Clo value of 2. The clothing factor Clo is 1 and the metabolic activity is at 1. The PMV range is between cool (-1.5) to extremely cold (-3.5). The living room and the bedroom are both in an uncomfortable zone.

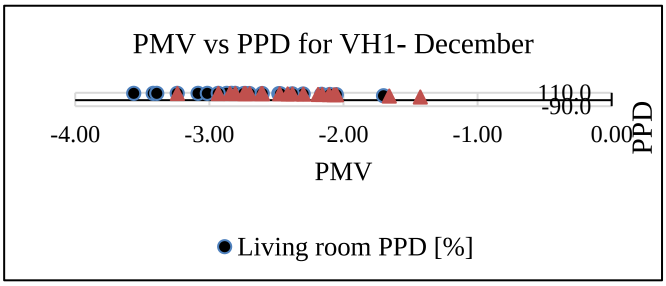

Fig. 25: PMV Vs PPD for Vernacular Haveli VH1 in winters for Clo value 1
(Source: Author)

Considering the adaptation in clothing patterns by the people, the Clo value is considered as 2 for the calculation as compared to the previously taken Clo value as 1. The change in the PMV Vs PPD graph is shown below in Fig. 26. The thermal sensation has now moved towards thermal neutrality. The observed PMV for the living room and the bedroom is between slightly cool (-1) to a feeling of thermal neutrality at 0.

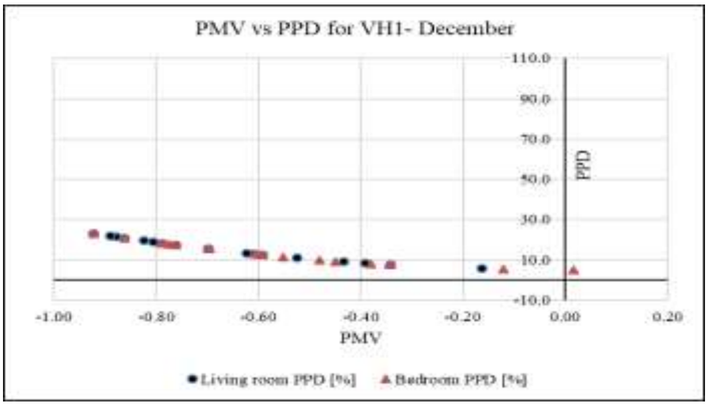

Fig. 26: PMV Vs PPD for Vernacular Haveli VH1 in winters for Clo value 2
Source: Author

Thermal Comfort Analysis of the Contemporary House 1 - CH1 in winter

The analysis of the interior spaces in the case study Contemporary House 1(CH1) namely the living room which is the central hub of daily activities and the bedroom which is used for sleeping during the night are studied. The recording of indoor dry bulb temperature, relative humidity, wind velocity and the globe temperature was recorded to understand the behavior of the spaces in comparison to the extreme climatic conditions outdoors. The observation of the data recorded for the two indoor spaces is plotted in the graph. As compared to the outside temperature for December, which varies from 20°C to 3°C, the living room temperature range is between 17°C to 9°C and for the bedroom, the temperature range was 17°C to 9°C. Observation shows that the outside temperature is maximum at around 15:00 hours, and the 3 hours till evening 18:00 hour sees the maximum temperature outside. The inside temperature also follows the outside temperature trend. Synchronous behavior of inside and outside temperature shows that there is no temperature lag provided by the light construction of the building envelope, and the interior space gets altered as per the external conditions. When the outside temperature dips to its minimum of 8°C early morning, the temperature indoor reaches its minimum of 10°C at 9:00 hours in the morning (Fig. 27).

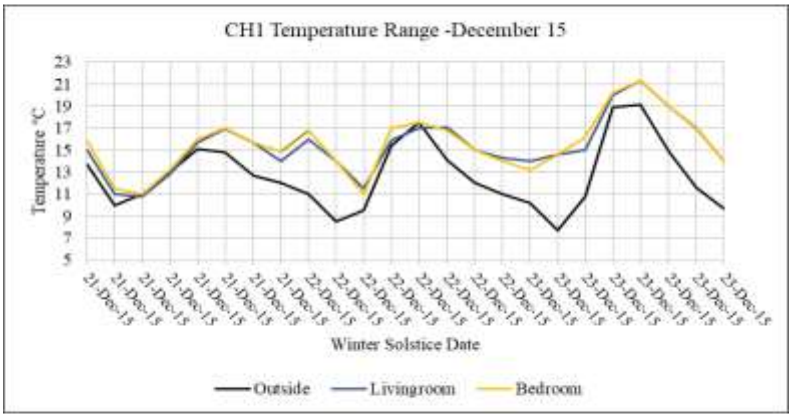

Fig. 27: Winter Temperature Profile for Contemporary House CH1
Source: Author

The relative humidity range for December is between 90% to 50%. It is clear from the temperature versus relative humidity chart that relative humidity is inversely proportional to ambient air temperature. The high relative humidity, along with the low temperature, increases the feeling of coldness in the environment. The indoor range for relative humidity (RH) was between 80% to 60% for the living room, and for the bedroom, it was also 80% to 60% (Fig. 28).

In Fig. 29, the variation of wind velocity outdoors in comparison to the interior spaces, namely the living room and the bedroom for December for the case study CH1 are presented in the graph. The wind velocity is maximum at 1.8 m/s to a minimum of zero wind. To regulate the internal thermal conditions, the windows are closed during the winter season.

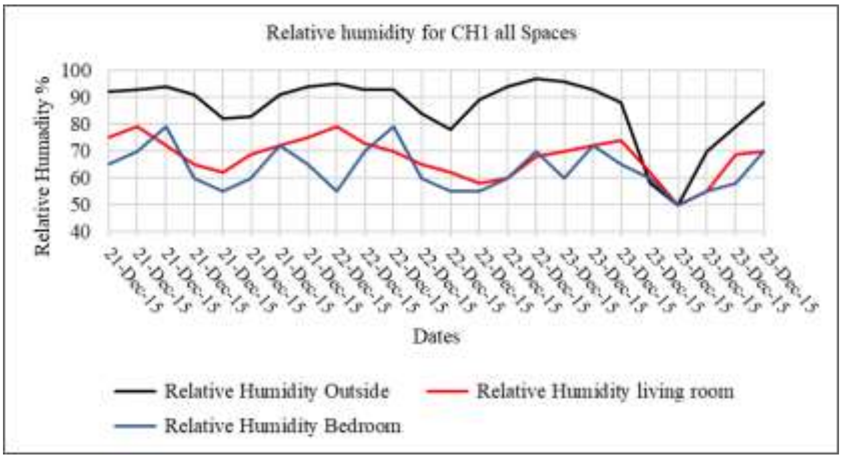

Fig. 28: Relative Humidity in different spaces for Contemporary House CH1
Source: Author

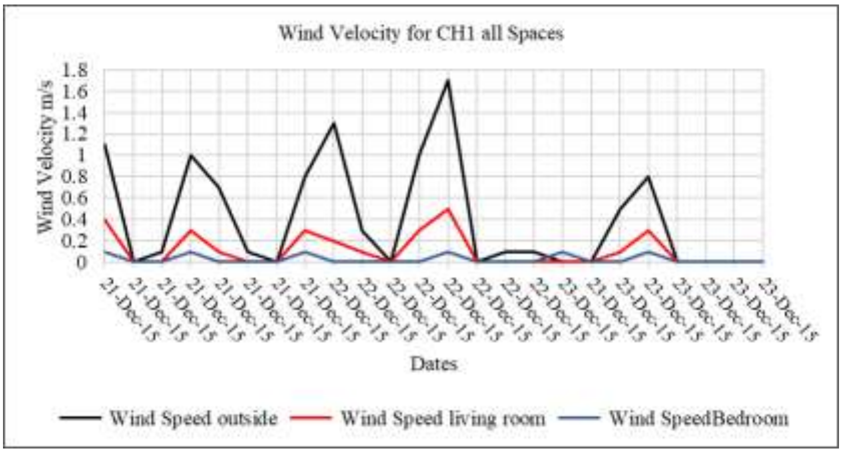

Fig. 29: Wind velocity in different spaces for Contemporary House CH1
Source: Author

Tropical summer Index (TSI) gives the comfort range as 25°C - 30°C, which can vary in the range of 5°C from the given limits in extreme conditions. When the outside temperature condition is either too cold or extremely hot, the temperature range for TSI is 19°C to 35°C (Sharma & Ali, 1986).

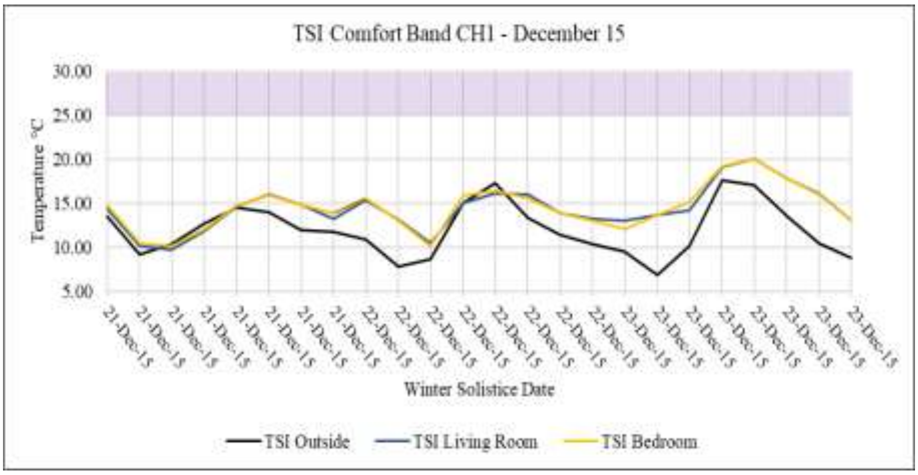

Fig. 30: TSI Comfort band in different spaces for Contemporary House CH1 in winters
Source: Author

TSI is calculated for the outside, the living room and the bedroom for the case study CH1- Contemporary House 1 for December. The outside temperature is never in comfort range i:e between 25°C to 30°C for December. The grey band in the graph shows the comfort temperature range as prescribed by TSI. Observation is that outside, and inside temperature, both are outside the comfort band. The built envelop should alter the interior conditions to provide thermal comfort to the inhabitants. When the outside reaches its maximum temperature of 17°C and the min of 6°C the indoor room temperature maintains a range of 16°C to 10°C as of 22nd Dec. 2015. The variation of 6°C with a controlled airflow creates a condition of uniformity indoors. The temperature indoor is stable in the range of 16 to 10°C. When outside temperature reaches the lowest point of around 3°C to 5°C and the relative humidity is the highest at about 90%, the observed indoor min. temperature is in the range of 6°C to 7°C. The envelope provides little comfort for the inhabitants in terms of thermal comfort.

A detailed analysis of the performance of the house is done based on the concept of understanding the Difference between Uncomfortable Hours Outside Vs Inside (DUHOI). Applying the formula of DUHOI for the case study CH1, the difference between the Tropical Summer Index outside (TSI_O) and the Tropical Summer Index inside (TSI_i) is calculated for the habitable spaces. The calculation for the selected three days for the December solstice for the case study house CH1 gives the DUHOI, a value of 2.41. This value will help to compare the performance of architectural design for the selected case study against the other selected case examples for the walled city of Bikaner, which falls under the hot and dry region. Fig.31 shows the PMV/PPD, based on the Fangers model, as derived. As for the calculation, the clothing factor Clo is 1 and the metabolic activity value is 1. The PMV range is between slightly cool (-0.5) to extremely cold (-3). The living room and bedroom both are in an uncomfortable zone. The living room has more discomfort hours as compared to the bedroom in terms of occupancy hours. The graph shows the percentage of discomfort is very high, almost 90% in the discomfort range.

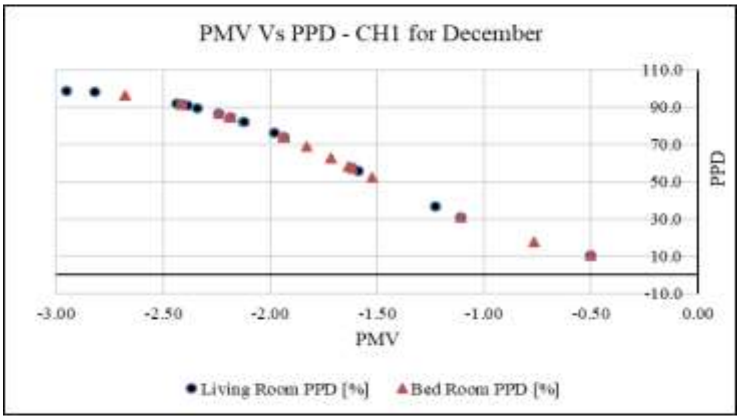

Fig. 31 PMV Vs PPD for Contemporary House CH1 in winters for Clo value 1
Source: Author

Considering the adaptation in clothing pattern by the people, the Clo value is considered as 2 for the calculation as compared to previously taken at Clo value 1. The change in the PMV Vs PPD graph is shown below in Fig. 32. Thermal sensation has now moved towards thermal neutrality. The observed PMV for the living room and the bedroom is between slightly warm (0.8) to slightly cool (-0.8).

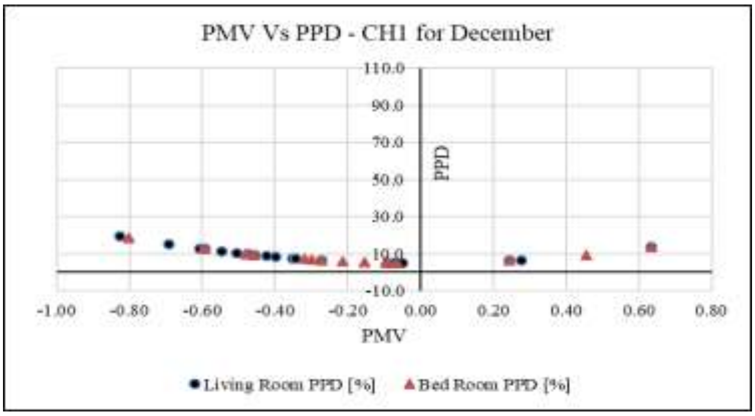

Fig. 32: PMV Vs PPD for Contemporary House VH1 in winters for Clo value 2
Source: Author

Table 1: Analysis summary for Vernacular Haveli and Contemporary House
Source: Author

S. No.	Typology	Vernacular Haveli	Contemporary House
1	Material Used	High thermal mass material for walls and roof.	Low thermal mass material for walls and roofs.
2	Fenestration and Shading	Multi control windows can be 100% closed, louvers, open and min glazing use colored glass. Shading by way of a sunshade, Overhanging Balcony, Decorative molding for self-shading. The stacking of the plan provides the terraces to be self-shaded, and mutual shading from the adjoining Havelis.	Large glazed windows, having the option to be opened or closed allowing for the solar radiation to penetrate indoors through the glass. The repetitive plan leaves the terrace fully exposed to solar radiation, and some mutual shading is available from the adjoining houses.

3	Natural Ventilation	The courtyard is the main ventilation driver. Small windows and openings draw air from the street and the courtyard. The temperature difference causes a continuous airflow into the interior spaces.	The scope for natural ventilation is only from the front windows and the rear windows. The windows are private to the rooms, and these do not create any uniform air current in the house.
4	Thermal Performance (Summer)	During the extreme summer, the haveli provides sufficient protection from heat. The summer is long extending from April to September.	During extreme summer, the architectural design envelope cannot create a thermally comfortable indoor space. During the extreme noontime, it fails to create ambient condition.
5	Thermal Performance (Winter)	During the extreme winter, the haveli provides sufficient protection from the cold. The winters are of the brief duration of December and January. The interior spaces are in a thermally neutral condition.	During the extreme winter, the architectural design envelope cannot create a thermally comfortable indoor space. During the night and early morning, it fails to create an ambient condition.
6	Overall Thermal Performance	In the extremely hot condition of Bikaner, the Haveli design envelope provides comfort to its users.	The house falls short of providing a comfort condition when the external conditions are in extremely hot conditions or extremely cold.

Conclusions

The analysis of the thermal measurements for the vernacular haveli and the contemporary house for the extreme summer and winter was carried out for the research. The results of the performance measurements based on the Difference in the uncomfortable hours outside Vs inside (DUHOI) are done for two case studies: Vernacular Haveli 1 and the Contemporary House 1. It is seen that the Vernacular Haveli 1 (VH1) performs best among the two case studies in the summer month. The contemporary house performance is very low in comparison. The reason for the superior performance of the vernacular haveli is the heavy construction, which provides a time lag of almost 10 hours. In comparison, the contemporary house has a time lag of 0 to 2 hours. The contemporary house does not provide a comfortable indoor environment when the weather is extreme be it summer or winter. When the weather is not extreme, the house maintains a reasonable level of comfort indoors. The vernacular haveli performance is better in comparison to the contemporary house for the whole year and it provides comfort conditions indoors in the extreme summer and winters.

The ventilation is continuous in the vernacular haveli. Air movement is good because the courtyard and the temperature difference between the outdoors and the indoors create good air circulation. The contemporary house has poor air circulation as there is no avenue for cross ventilation. During the extreme summer, the TSI for the contemporary house is outside the comfort band during the daytime for almost 12 hours. This renders the interior space very uncomfortable. The uncomfortable duration is minimal in the vernacular house. The significant temperature difference observed in the indoor space of the vernacular house, and the outside conditions are because of the thermal resistance demonstrated by the heavy construction of the building envelope of the vernacular haveli.

As per the Fanger's comfort model for Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) was calculated for the extreme summer and winters. The results favored the vernacular haveli as 90% satisfaction was at the given conditions for June. The PMV was between -1 (slightly cool) to 1.5 (slightly warm) which worked best for the summer months with minor clothing and activity modifications. During winters, the vernacular haveli comfort as recorded in the PMV is between -1 (Slightly cool) to 0 (neutral) which is comfortable as an individual can exercise adaptive control in terms of clothing adjustment and activity.

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