

Thermal performance design criteria for bio-climatic architecture in Himachal Pradesh

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Native architecture of any settlement is characterized by design and construction methods developed by the wisdom of local people to achieve indoor thermal comfort amidst outdoor uncomfortable climatic conditions. Modern construction practices adopt standardized building materials and construction methods that dominate the Indian market at present. The present article attempts to suggest appropriate architectural design criteria for present day buildings located in lower Himachal Pradesh through quantitative and qualitative comparison of thermal performances of traditional and modern residential buildings through field-survey. Results highlight the need for symbiosis of traditional wisdom with modern construction methods for sustainable built environment.

Keywords: Himachal Pradesh, native and modern building, passive architectural design guidelines, thermal comfort.

Introduction

INDIGENOUS and traditional buildings were constructed to create comfortable indoor living conditions for the inhabitants from the time immemorial and they were responsive to their local climate. In a traditional settlement, masons and builders use locally available recyclable resources to achieve maximum indoor thermal comfort conditions and climate was the major determinant for shelter form and design. Design and construction of building according to local micro-climatic condition is termed as bio-climatic architecture. The term 'bioclimatic' was used for the first time by Victor Olgyay¹ in 1962. Among other achievements in bioclimatology, he developed a 'bio-climatic chart', which relates climatic data to thermal comfort limits, to identify design strategies. Passive architectural design guidelines have been proposed using bio-climatic design tools like bio-climatic charts^{1,2}, Mahoney tables³ and computer-aided climate analysis tools⁴ for different geo-climatic zones in India⁵⁻⁷. It is heartening to find that the 'bioclimatism' is inherently present in the native traditional settlements which have shown their sustainability through the ages. Various

studies from other countries with cold climates have highlighted the climate-sensitive passive design and other adaptive features of traditional architecture and construction methods in response to their local geo-climatic conditions⁸⁻¹⁶. In India, quantitative and qualitative studies of native settlements have been reported from the coastal humid climate^{17,18}, hot-dry climate¹⁹, composite climate of central India²⁰, north-east regions²¹ and western Himalayan regions²²⁻²⁵ to bring out and understand the passive architectural design features and construction techniques of these buildings. The findings from these studies have been used to formulate passive design guidelines for present day buildings in countries with tropical climate like India^{26,27}. Also, the energy crisis of 1970s has made everybody aware of the fact that all the development works should be carried out in the spirit of maintaining environmental, social and economic sustainability and designing and construction of buildings according to local climatic condition should be the key for their sustenance in terms of energy consumption to maintain thermal comfort of the occupants inside the buildings.

However, in recent years, construction practices have been changed because of the availability of modern standardized building materials and methods that dominate the market in the country. The influence of market economy and electronic media along with a change in socio-cultural outlook, people have accepted the gradual change in the design of architecture even in remote, rural or semi-rural places. The modern construction practices, which can create comfortable indoor living conditions, are often carried out without giving due considerations to the local geo-climatic and cultural conditions which may have implications on energy consumption to maintain comfortable living conditions inside the houses. The inherent logic of the conventional practices can be revealed through a comparative study between native and present day constructions^{14,28,29}.

Buildings consume considerable energy both during their construction and operation. As such, the buildings are a great source of CO₂ emissions to the atmosphere. The energy consumption in the building sector is expected to increase further due to the improvements in the living standards and increase in world population³⁰. In India, the building sector consumes about 33% of electricity with commercial sector and residential sector accounting

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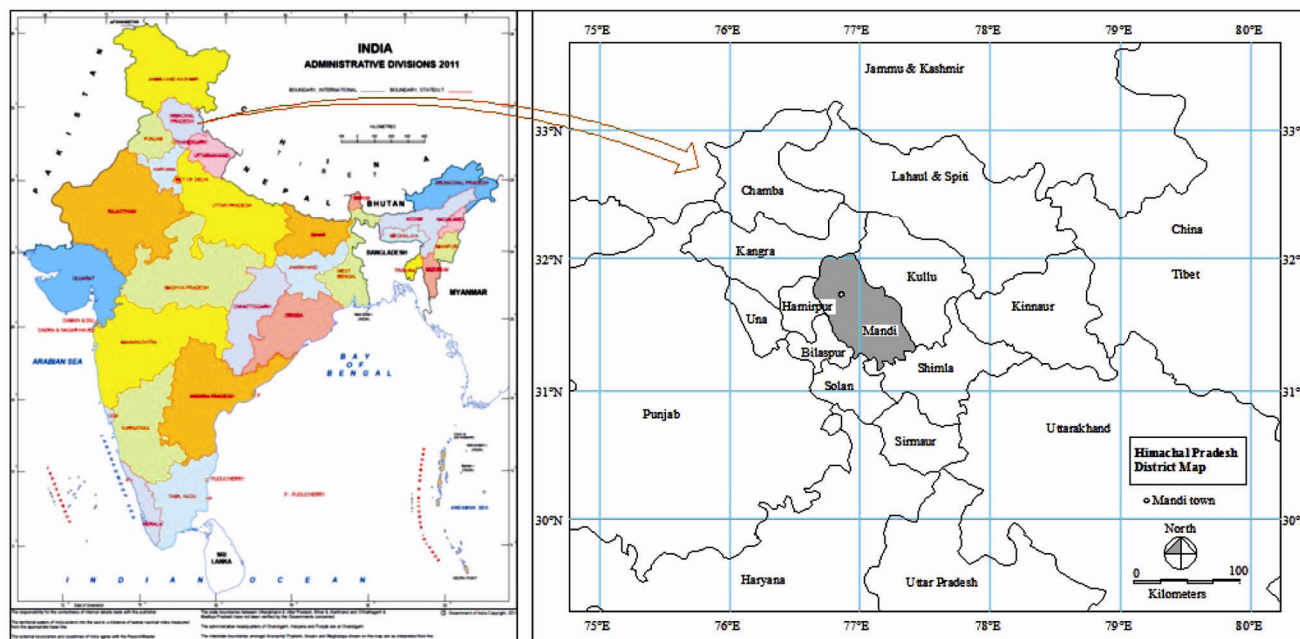


Figure 1. Location of Mandi town in Himachal Pradesh, India. Source: ref. 44.

for 8% and 25% respectively³¹. Understanding the implication of this situation on energy resources of India, the Government of India has introduced the Energy Conservation Building Code (ECBC) in 2007 and made further addition in the ECBC in 2008 to provide minimum requirements for energy-efficient design and construction of buildings and their systems³⁰. It is estimated that the nationwide mandatory enforcement of the ECBC will yield annual savings of approximately 1.7 billion kWh (ref. 31). Raising awareness of cost-benefits of the ECBC is expected to benefit the individual household by encouraging and empowering them to strive for a better architectural design of their buildings for thermal comfort and energy-efficiency in rural and semi-urban places along with major urban areas.

This article attempts to suggest appropriate architectural design criteria and material properties for present day residential buildings in the study-region of Himachal Pradesh in India through quantitative and qualitative comparison of thermal performances of traditional and modern buildings. The study consists of field survey for data collection and analysis of those data to arrive at the recommendations.

Study area

The state of Himachal Pradesh (HP) is located from 30.38° to 33.2°N lat. and 75.77° to 79.07°E long., in the western Himalayas, covering a geographical area of 55,673 sq. km. The state is divided into 12 districts surrounded by Jammu and Kashmir in the North, Tibet in the

Northeast, Uttarakhand in East/Southeast, Haryana in South and Punjab in Southwest/West³².

The study area (Figure 1) is located in the Mandi district of Himachal Pradesh, in and around Mandi town (31.32°N lat., 76.53°E long.). Average altitude of the area is 850 m amsl.

Mandi town has 'subtropical' climate with warm summers and cold winters and receives average annual rainfall of 135 cm. Table 1 shows the monthly average climatic data for Sundernagar, near Mandi town.

Research methodology

The aim of this study is to evaluate the architectural design features, construction materials and building forms used in the traditional houses and present day houses with respect to their thermal performance during winter months, in terms of maintaining indoor thermal comfort conditions for their occupants. A comparative study of thermal performance during summer months will be presented in future work.

ASHRAE Standard 55-2004 Class II protocols to conduct field-survey of indoor thermal environment have been followed to collect data³³. Twenty case-study buildings with type characteristics of traditional buildings and modern naturally ventilated buildings have been studied. Measurements of indoor air temperature, mean radiant temperature or globe temperature, relative humidity, air velocity and lighting level were recorded for 10 days during winter months from December 2012 to February 2013. Hand-held calibrated digital instruments were used and

Table 1. Climatic data for Sundernagar in Mandi, Himachal Pradesh: monthly averages

Month	Air temperature (°C)	Relative humidity (%)	Daily solar radiation – horizontal (kWh/m ² /d)	Atmospheric pressure (kPa)	Wind speed (m/s)
January	9	75	3.57	93.8	3.1
February	11	76	4.61	93.6	3.3
March	14	65	5.71	93.3	3.4
April	20	52	6.81	93.0	3.6
May	25	42	7.42	92.6	4.0
June	26	58	7.12	92.3	4.2
July	25	85	5.89	92.4	3.5
August	24	83	5.46	92.6	3.0
September	23	83	5.62	93.0	3.0
October	19	64	5.29	93.4	2.8
November	13	65	4.32	93.7	2.8
December	9	69	3.45	93.9	3.0
Annual	18.2	68	5.44	93.1	3.3

Source: refs 32, 34.

Table 2. ASHRAE scales for thermal sensation, thermal preference, and thermal acceptance

	ASHRAE scales						
	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
Thermal sensation	3	2	1	0	-1	-2	-3
Thermal preference	A bit cooler		No change		A bit warmer		
	1		0		-1		
Thermal acceptance	Yes		No				
	1		0				

Source: ref. 33.

placed on a table in the centre of the living areas to take the measurements of indoor thermal environmental variables. The outdoor climatic data were collected from the state meteorological department and other secondary sources³⁴.

Building occupants can act as measuring meter of their surrounding environment. Therefore, a thermal comfort survey was conducted with 100 occupants of both traditional and modern houses to collect data about their subjective thermal comfort responses, measured on ASHRAE’s 7-point thermal sensation (TS) scale, along with their thermal preferences (TP), measured on ASHRAE’s 3-point scale and their acceptance of the thermal environment (TA), measured on ASHRAE’s 2-point scale, during winter months. The scales are shown in Table 2. The data on clothing and activity level of the occupants of the building were recorded during the field-survey. The total clothing insulation value (in ‘clo’) and activity level (metabolic heat output in Watt/m²) is calculated according to the charts given in ASHRAE Standard 55-2004 (ref. 33). The questionnaire for the thermal comfort field-survey was prepared according to ASHRAE Standard 55-2004 ‘Informative Appendix E – Thermal Environment Survey’. First, occupants of the residential buildings, who participated in the thermal comfort

survey, were informed about conducting this survey to collect data for thermal comfort performance evaluation of their houses. They were also told that the result from this survey will help in identifying good and bad thermal performance aspects of the buildings and will give important feedback about improving the indoor thermal environment of present day buildings. The thermal comfort survey questionnaire includes questions covering the following aspects:

1. Personal information about the participant like name, age, sex, height, weight and years of stay
2. Position of the occupants with respect to the floor plan
3. Occupants’ thermal sensation, thermal preference and acceptance of the thermal environment
4. Occupants’ feeling about natural air movement, humidity and natural lighting level
5. Occupants’ feeling about the indoor air quality
6. Occupants’ activity in last 15 minutes
7. Occupants’ clothing
8. Occupants’ action during under-heating in winter months
9. Occupants’ use of environmental controls like door, window, curtains, etc.

Table 3. Thermal comfort condition for buildings according to National Building Code of India, 2005

Season	For air-conditioned buildings			For non-air-conditioned buildings		
	Air temp. (°C)	RH (%)	Air velocity (m/s)	Air temp. (°C)	RH (%)	Air velocity (m/s)
Winter	21.0–24.0	50	nil	18.0–22.0	50	nil
Summer	23.0–26.0	50	0.15–0.18	25.0–30.0	50	nil

Source: ref. 35.

10. Occupants' willingness to adopt energy conservation measures
11. Building level data about the design parameters.

The same questionnaire was also prepared in local language for smooth conduction of the thermal comfort survey between 7.00 am and 7.00 pm. It took 15–20 min to conduct the survey with an occupant. Recording of indoor environmental data was carried out simultaneously to corroborate with the questionnaire survey for analysis. Data was also collected about the socio-cultural acceptance of present day house construction methods from the occupants.

The data from the thermal-comfort field-survey are analysed and compared with the existing thermal comfort standards for naturally ventilated buildings according to the National Building Code of India (NBC) – 2005 (ref. 35). The findings are used to suggest suitable passive architectural design features for present day house construction in the geo-climatic study area which should optimize the energy consumption while providing thermal comfort to the occupants, during winter months.

Indoor thermal comfort condition

According to ASHRAE Standard 55-2004, thermal comfort is defined as 'the condition of mind that expresses satisfaction with the thermal environment'. Comfort may also be defined as the sensation of complete physical and mental well-being of a person within a built environment³⁶. The comfort conditions of the individuals depend on various physiological and environmental parameters. Study of thermal comfort standards suggests that most people are comfortable in the temperature range between 18°C and 30°C, with air-velocity 0–2 m/sec and relative humidity conditions between 30% and 70%, mentioned as 'comfort zone' on the psychrometric charts. Other factors which affect the human thermal comfort conditions include environmental variables like mean radiant temperature and rate of air-flow, and physiological variables like clothing and activity level (metabolic rate). Also, age, sex, state of health, cultural conditioning and expectations of different people affects the 'comfort limit' by influencing their tolerances to discomforts.

The range of thermal comfort conditions for humans in air-conditioned and non-air-conditioned buildings in

India is given in Table 3, according to the National Building Code of India 2005: Part 8, Section 1. The thermal comfort conditions given in NBC for naturally ventilated non-air conditioned buildings are based on the study of 'Tropical Summer Index (TSI)³⁷. The NBC has mentioned indoor air temperature range of 18–22°C for thermal comfort in winter months with 50% RH and still air. The minimum acceptable comfort temperature for winter months is given as 15°C.

Description of selected traditional house

Traditionally, houses are placed around a courtyard, connected by narrow roads and alleys, in such a manner that the courtyard can receive sun-shine during winter months, where many activities such as cooking, washing, outdoor sitting, drying of clothes can take place during day-time and also can be used for sleeping during hot summer nights. Courtyards are also used for drying of crops/grains and for some other occupational activities such as cattle farming, animal husbandry, etc. Toilets are also placed separately around courtyard in most of the houses. Sufficient spacing is given between the clusters so that all houses can have access to sun-light and air. Figure 2 shows details of the selected representative traditional house along with the courtyard.

The selected traditional house is more than 50 years old. The orientation is towards east. It is constructed with 0.5 m thick adobe and stone wall with mud plaster. Living rooms are provided on the ground floor and kitchen is provided in the top floor. The flooring is of wood planks supported on timber joists and finished with mud flooring. The height of the ground floor is 2.2 m and top floor is 2.1 m. The doors are of size 0.75 × 1.8 m. The windows are of 0.75 × 1.6 m. Openings are provided on the front side (east-facing) only. The smoke from the kitchen exhausts outside through roof by natural convection.

Description of selected modern house

Details of the selected modern house and present day housing condition are shown in Figure 3. The present day construction uses 23 cm thick burnt brick external wall, 11.5 cm thick internal wall in burnt clay bricks and 10–15 cm thick reinforced cement concrete roof. The floor

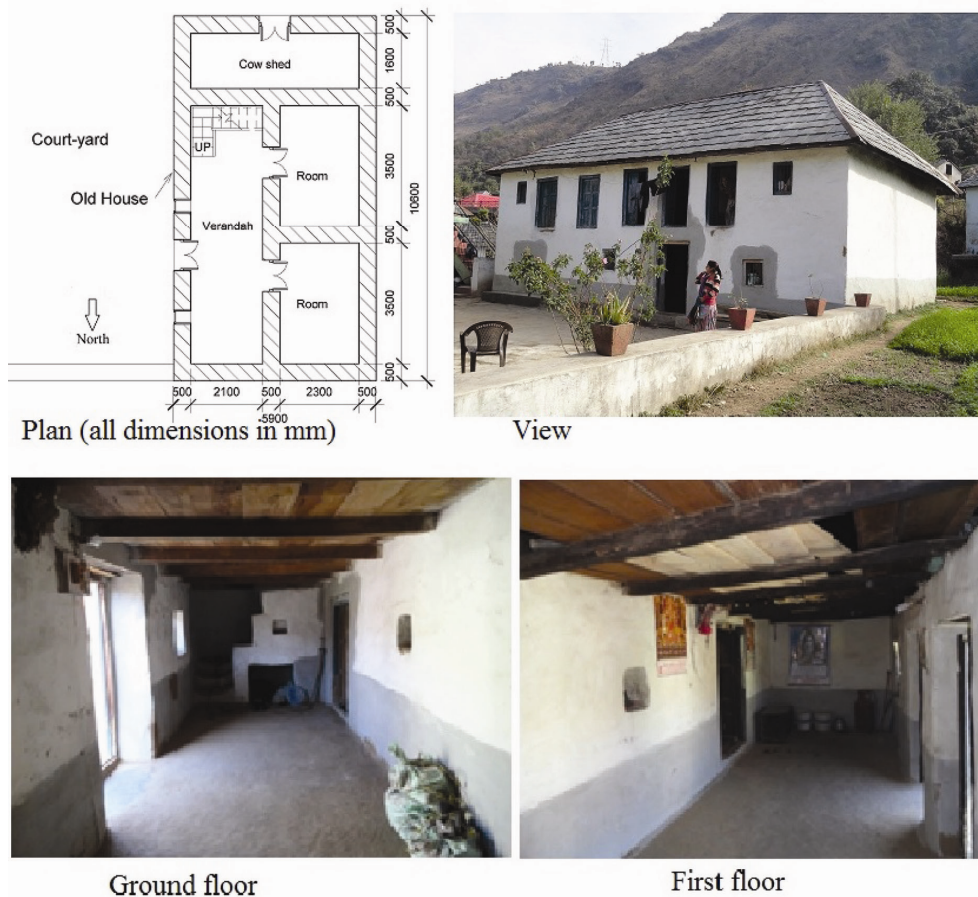


Figure 2. Details of selected traditional house at Mandi, Himachal Pradesh.

height is 3 m and the sizes of windows are 1.5×1.5 m distributed on all sides. The longer axis is along east-west direction but the front façade and main-entrance face towards east, due to prevailing cultural consideration.

Modern residential buildings in Mandi are constructed in a linear pattern with orientation towards south/south-east to allow the winter sun-light in the out-door areas and living areas during winter months when sun's position is low on the horizon, which is a positive beneficial follow up of the traditional way of arranging habitable rooms.

Results and discussion

Architectural passive design features

After the physical on-site survey of traditional houses in the hill settlement of Mandi town, the aspect ratios of the houses are found to be near 1 : 1.6, which equals the 'golden proportion'. This is achieved by linear arrangement of two rows of rooms, front row being a deep enclosed verandah, which allows the sunshine to fall inside the houses during winter months and cool breeze to flow inside by shaded verandah during hot-humid summer

months. The shaded verandah and the thick walls also keep the interior cooler and comfortable in hot months by cutting off the hot summer sun. The houses were of 2 storeys with height of each floor not more than 2.2 m with an attic floor below the pitched roof. The exposed surface area to volume ratio of the selected traditional house is calculated to be 0.6, which signifies the compactness achieved in these traditional houses by the local builders by providing low floor-height in the construction. The lower surface-to-volume ratio also helped the traditional construction to achieve less heat loss in winter months to clear night sky and less heat gain in hot summer days. The area of openings is kept less than 5% of the floor area, which prevents heat loss during cool winter months. However, the indoor day-lighting condition is found to be poor (illumination level less than 50 lux), because of least amount of openings. The orientation is found due east, due to cultural consideration; therefore, does not exploit the benefits of south orientation. However, the main drawback in the traditional construction is that it provides very less carpet area, only 65% of the plinth area, because they were constructed with thick external and internal walls, which consumes around 35% of plinth area. This is not acceptable to the occupants in present day context.

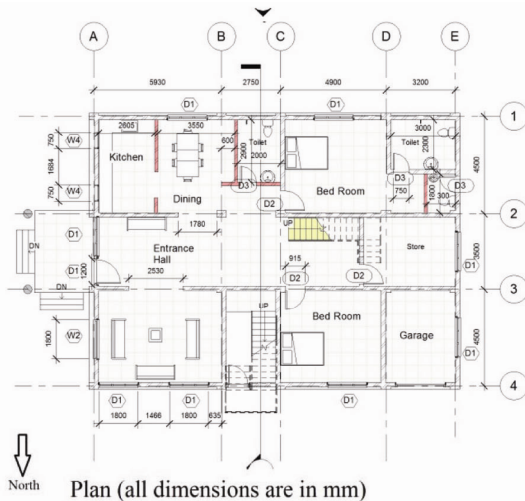


Figure 3. Details of selected modern house and present day housing pattern at Mandi, Himachal Pradesh.

In modern houses, architectural design has been done to orient the maximum living rooms towards east and south to allow day-time heating of the habitable rooms during winter months. The aspect ratio of the selected modern house is 1 : 1.3, less linear. The exposed surface area-to-volume ratio of the selected modern house is calculated to be 1.4, which is compact enough and good for this type of climate. This also demonstrates that when the present day buildings are designed with due consideration to local geo-climatic condition, they can achieve the compactness as required for the local climate. The area of openings is kept at about 20% of the floor area. The larger openings allow more day-light in the interior of the rooms and also contributes to more heat loss, resulting in

cooler interiors after sunset during cold winter months. Indoor illumination level is found to be more than 100 lux in the southern rooms during day-time of winter months when the sky is clear. Balconies and terraces provision towards south and east are beneficial for direct solar heat gain during winter days, but may require protection against heat loss during cool winter nights.

Thermal properties of construction materials

Table 4 shows the thermal properties of the materials used for construction of traditional houses and modern houses in Mandi town. It can be seen that the materials

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Table 4. Comparing thermal properties of construction materials used in traditional and modern houses in Mandi, Himachal Pradesh

Function	Overall thickness (m)	U-value (W/m ² k)	Thermal capacity (kJ/m ³ k)	Thermal time-lag (h)
Brick wall (external)	0.25	2.6	1529	8
Stone wall with mud plaster (external)	0.5	1.47	1700	11
RCC roof	0.2	3.3	2013	4.5
Slate roof with attic	1.0	2.11	1604	10

U-value is the thermal transmission through unit area of given building unit divided by the temperature difference between the air or other fluid on either side of the building unit in 'steady state' condition.

Time-lag is the time difference between the occurrences of the temperature maximum at the outside and inside when subjected to periodic conditions of heat flow.

Source: ref. 3.

Table 5. Comparison of indoor air temperatures of selected traditional and modern houses at Mandi, Himachal Pradesh, India

Month	Outdoor air temperature (°C)		Indoor air temperature in traditional house (°C)		Indoor air temperature in modern house (°C)		Indoor min. comfort air temperature as per NBC, 2005 (°C)
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	
December	16	2	16.5	14.5	15.6	12.9	15.0
January	16	2	16.2	14.4	15.1	11.9	15.0
February	18	4	16.8	14.6	15.9	13.2	15.0

and methods used in wall and roof construction of traditional houses, provide good thermal heat storing capabilities and higher time-lag of heat-transfer which can prevent excessive heat-loss during winters and heat-gain in summers as well. The present day construction methods are benefited from direct solar gain through larger windows on south during day-time insolation in winter months, which increases indoor temperature quickly. However, the interiors of modern houses tend to become cooler after sunset in winters, since rate of heat-loss increases because of the comparatively lower thermal time-lag of the construction materials. This may increase more dependence on mechanical means like heater to maintain indoor condition comfortable during winters.

Indoor thermal comfort condition

The field survey of the traditional and modern houses was carried out in winter months of December 2012 to February 2013. It was found that December and January are the coolest months when average outdoor ambient temperature varies from minimum 2°C to maximum 16°C. Table 5 presents indoor air temperature data in the selected traditional and modern houses at Mandi during winter months. It is found that the indoor air temperature of the traditional houses is 2–3°C higher than in the modern houses during winter months. Indoor relative humidity is found to be within the range of 60–70% in both the traditional and modern houses, which is within comfort range. Figure 4 shows comparison of the daily indoor air-temperature condition found in the selected traditional and modern houses during winter months. It can be seen

from Figure 4 that almost for 12 hours in a day of January, the indoor temperature in traditional house remains above 15°C, minimum comfort temperature in winters mentioned in the NBC, whereas the duration of indoor temperature above 15°C in the modern house is found to be 5 hours during the same winter day.

Indoor thermal comfort sensation, thermal preference and thermal acceptance

During thermal-comfort field survey subjective thermal comfort vote was recorded on ASHRAE TS scale from 100 occupants of the residential building along with measuring indoor environmental data: air-temperature, globe temperature (measurement of mean radiant temperature), relative humidity, air velocity and illumination level. Among 100 participants, 56 were male and 44 were female, aged between 18 and 50 years. Half of the participants are staying in the traditional houses and the other half is staying in the modern houses for more than five years, so that they are fully acclimatized with local climate.

The field-studies by several authors^{38–42} have established the dynamic 'adaptive thermal comfort model', which shows that wider range of comfort temperature is accepted by the occupants of naturally ventilated buildings, mainly because of physiological (acclimatization), psychological (expectation of the season) and behavioural adaptation (activity, clothing and use of environmental controls) of the occupants. The adaptive comfort model is most suitable for free-running naturally ventilated buildings where mechanical cooling and heating are

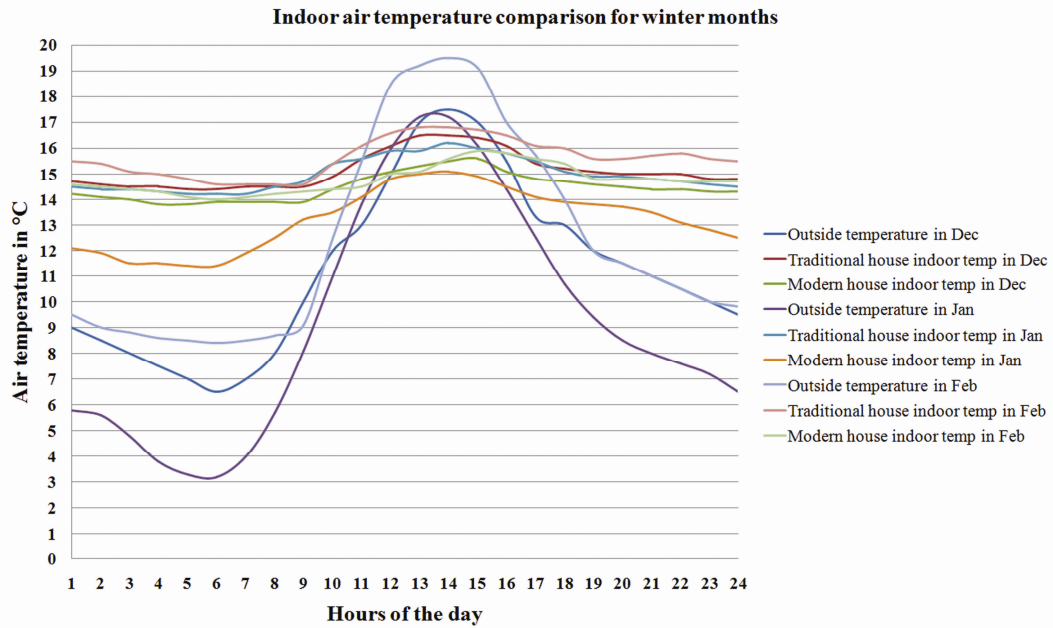


Figure 4. Comparison of indoor air temperature between the selected traditional and modern houses at Mandi, Himachal Pradesh in winter months.

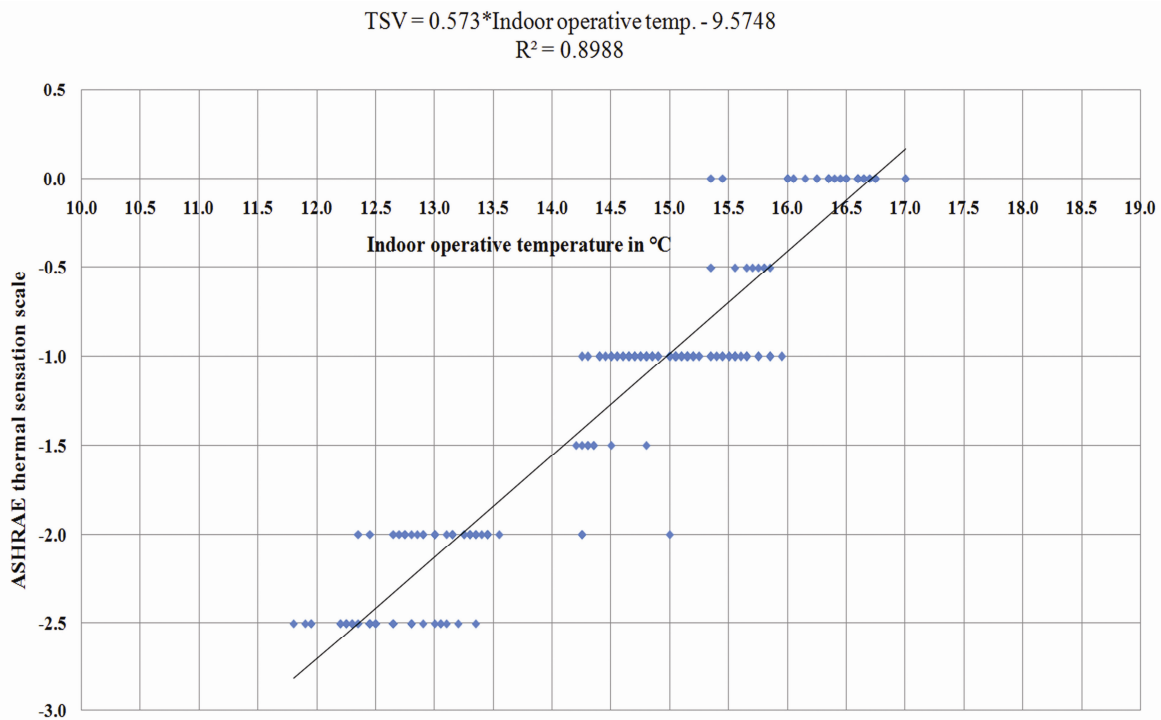


Figure 5. Indoor thermal comfort temperatures for the residential buildings at Mandi, Himachal Pradesh during winter months.

not present and occupants have total control on the operable windows. This model relates the indoor comfort temperature to outdoor air temperature. Hence in this study, the indoor comfort temperature for the naturally ventilated residential buildings at Mandi is calculated by linear regression analysis between subjective thermal

sensation vote (TSV) with indoor operative temperature (T_{op}), which is average of indoor air temperature (T_a) and globe temperature (T_g), since difference between them is less than 1°C with indoor air velocity less than 0.15 m/s (ASHRAE Standard 55-2004), and shown in Figure 5. Air-motion inside the houses is reduced to still air by

keeping the windows and doors closed. The relationship found through regression analysis is

$$TSV = 0.573 * T_{op} - 9.5748 \quad (R^2 = 0.8988, \text{ correlation coefficient } R = 0.95, P < 0.0001). \quad (1)$$

The value of gradient in eq. (1) is almost identical as the relationship proposed by Humphreys³⁸ in the equation

$$T_c = 11.9 + 0.534 T_0; \quad 10^\circ\text{C} \leq T_0 \leq 33^\circ\text{C}, \quad (2)$$

where T_c is comfort temperature and T_0 is monthly mean of outdoor air temperature.

The indoor comfort optimum operative temperature in winter months for naturally ventilated residential buildings in Mandi is found to be 16.8°C (corresponding to '0' vote on ASHRAE TS scale). The thermal comfort range is calculated as 15.5°C–17.0°C (corresponding to '±0.5' vote on ASHRAE TS scale) and minimum acceptable operative temperature (corresponding to '–1.0' vote on ASHRAE TS scale) is found to be 15°C from the linear regression analysis. The results are in close agreement with the thermal comfort temperatures mentioned in the NBC, 2005. The result of subjective thermal comfort vote from the study area shows that thermal sensation changes from 'neutral' to 'cool' for 2–3°C change in temperature, which is the difference in indoor temperatures observed in traditional and modern houses.

During the thermal-comfort survey in the study area, 80% of the occupants of modern houses have preferred higher indoor temperature than at present, while 20% of the occupants have preferred no change in indoor temperature. In contrast, 25% of the occupants of native houses have preferred higher indoor temperature. Also, 70% of occupants of traditional houses and 60% of occupants of modern houses have expressed their acceptance of indoor thermal environment during winter months.

Behavioural adaptation of the occupants

User's behavioural adaptation is crucial to achieve indoor thermal comfort in naturally ventilated buildings⁴⁰. In the present study also, it was observed that the occupants of the houses actively carry out various adaptation measures to maintain indoor thermal comfort in a sustainable manner. Some of these behavioural adaptations are: (1) clothing adaptation – the occupants wear heavy garments, inner thermals, cotton full sleeve shirts, heavy trousers, sweaters, jackets, woollen socks and shoes (total clothing insulation is calculated to be 1.62 clo according to the ASHRAE clothing insulation chart) during the thermal comfort-survey in winter months to keep themselves warm; (2) doors and window-shutters are kept closed in winters; (3) carry out activity in the sunny outdoor areas in winter days; (4) stay near heat sources during cold

winter nights; (5) adaptive synchronization of the activities with temporal environmental conditions – like carrying out heavy work in the well-lit outdoors in winter months and the same work is carried out in shade at slow pace during hot summer months; and (6) use of heaters. The design of traditional houses and distribution of its rooms shows a great degree of connectivity between indoor–outdoor spaces, which evolved by the activity pattern of the inhabitants over a period of time by adaptively responding to the geo-climatic condition of the place for holistic sustainability. Similar observation has been reported by Rijal and Yoshida¹¹.

During the study, the inhabitants informed that they felt more comfortable in the traditional houses, but still they were constructing new houses using comparatively lighter materials, because of the following reasons: (1) less carpet area available in the traditional houses; (2) overcoming maintenance problem from termites, etc.; (3) change in life-style; (4) easy availability of recent construction materials; (5) maintaining social status; (6) non-availability of artisans who can practice traditional method of construction. Similar trends were also observed by other researchers¹¹. Because of less demand, the art of traditional construction method is slowly vanishing. During the thermal comfort field-survey, the participants expressed their willingness to adopt energy-efficient passive architectural design features in their modern houses if they are proven to be cost-effective in providing thermal comfort along with satisfying other needs and if those materials and technology are readily available in the market.

Modern RCC framed structure can possess good resilience against adverse outdoor environmental conditions if designed and constructed in harmony with local geo-climatic conditions. With the advancement in building science, the design and construction of buildings should be in greater harmony with the surrounding nature, and important answers are available in the traditional structures with proven climate responsive architecture and sustainable construction methods. Modern buildings must also be designed to provide comfortable indoor conditions to inhabitants without using costly mechanical means wherever possible, by adopting proven climate-sensitive, economical and less energy consuming construction methods with the materials which are suitable for the geo-climatic location and also easily available locally without any negative impact on nature for long-term holistic sustainability of built environment.

Conclusions

The comparative study of traditional and modern houses in Mandi, Himachal Pradesh has shown that the architecture and construction methods adopted in traditional houses evolved over generations provide greater thermal

comfort and is more responsive to local climatic condition. The high thermal mass of the traditional construction methods and materials have made it possible for the indoor environment to remain comfortable during winters without using any mechanical means like heater, by damping the large daily and annual variation in temperature range. The study has also revealed that modern RCC construction has been widely adopted because of the flexibility in space-design, easy availability, utilizing more carpet area, durability, rigidity, finishing quality and availability of more day-light inside the houses. Houses are constructed to function like an 'organism', giving third level of protection to their inhabitants, whose skin and clothing serve as first and second level of protection against environmental extremities. Acknowledging the need to support the continuity of tradition in building design and construction, the HP Government has introduced amended building bye-laws⁴³, making it mandatory to design public office buildings with passive design features, suitable for the local geo-climatic location. The results of the present study will enrich knowledge on the topic and enable architects, planners, urban designers and administrators to establish a fine balance and synergy between traditional wisdom and modernization, to design sustainable buildings under the present scenario of energy-supply, global warming and climate change by empowering all the stake-holders with necessary support. Further studies to evaluate the indoor thermal conditions of houses in summers are in progress.

From the comparative analysis of the traditional and modern houses together with the results of bio-climatic analysis of local climatic data using Mahoney's tables³, the following passive design criteria are recommended in the present day building design and construction in the geo-climatic location of Mandi, Himachal Pradesh: (1) Buildings should be oriented due south, so as to utilize direct solar heat gain during winter months; (2) The aspect ratios of the houses should be kept near to 1 : 1.6 and the exposed surface-area to volume ratio of the building mass should be less than 1.4; (3) External and internal walls should have more than 8 hour time-lag of heat-transfer between outside and inside; (4) Roofs and floor should be constructed with materials of more than 8 hour time-lag of heat-transfer; (5) Area of openings should be 15–20% of the floor area and maximum of such openings should be on southern wall; (6) Shading of openings should not obstruct sun-light from entering into habitable rooms during winter months; (7) External front open space/balcony/terraces on southern side should be utilized for outdoor activity during day-time of winter months.

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doi: 10.18520/v109/i9/1590-1600
