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The Effect of Natural Materials-Based Climate Adaptation Techniques on Thermal Comfort in the Vernacular Architecture of Sistan, Iran

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Abstract

Adjusting indoor environment so as to provide thermal comfort is a matter of utmost importance in architecture. Despite the remarkable achievements so far made, the main challenge is to provide thermal comfort in buildings through minimum use of fossil fuels. In hot and dry climates, this is especially important during the hot period of the year. As the people in Sistan, a region in southeastern Iran characterized by a hot and dry climate, are from low-income families unable to afford any modern building materials and techniques, they resort to natural materials and adaptive techniques to achieve thermal comfort. This fact justifies inquiring into the effect of the local vernacular architecture, which relies on natural materials and indigenous climate adaptation techniques, on thermal comfort and energy saving. Accordingly, this study aimed at analyzing natural materials and adaptive techniques and their roles in providing summer thermal comfort in indoor spaces of the region. To this end, a typical building was selected while identifying the dominant types of vernacular architecture in Sistan. Quantitative analysis was then conducted to analyze the roles and effects of natural materials-based adaptive techniques like *Dorche, Kolak* and *Khaarkhaneh*[1] , which help provide thermal comfort in specific situations. In light of the obtained results, indoor environmental parameters of the regional vernacular architecture fail to meet the thermal comfort zone in very hot days. However, adaptive techniques hinging on natural materials and ventilation has the potential to make indoor thermal parameters tolerable at different times of the day in such periods. This will result in residents' increased thermal comfort, which will in turn reduce the amount of energy consumption.

Keywords: Natural Materials, Climate Adaptation Techniques, Thermal Comfort, Energy Saving, Sistan (Iran).

Article Type: Research Article

Introduction

Providing housing for low-income households is one of the important challenges in less developed regions. In addition, the excessively high costs of thermal comfort resulting from air-conditioning systems are unaffordable for such residents. Therefore, it is necessary to apply low-cost techniques to moderate temperature in indoor environment and provide thermal comfort for residents in such areas. On the other hand, the large number of high-consumption contemporary buildings and undeniable consequences of the current trend in energy consumption such as reduced fossil resources and global warming (Xu *et al.* 2016: 306) as well as the considerable share of modern building construction in the total consumption of fossil fuels and greenhouse gas emissions (Nguyen *et al*. 2011:2088) have turned thermal comfort provision into a complicated challenge in the contemporary architecture.

In addition to thermal comfort provision for occupants, vernacular architecture play a significant role in reduced consumption of fossil fuels (Rubio-Bellido *et al*. 2016; Xu *et al*. 2016; Nguyen *et al.*2011; Hatamipour *et al*. 2007). Moreover, this type of climate-compatible architecture is rooted in hundreds of years of vernacular residence and gives many lessons in the field of climatic responsive design (Philokyprou *et al*. 2017; Rubio-Bellido *et al*. 2016; Foruzanmehr and Vellinga 2011).

[1]Three climate adaptation techniques of vernacular architecture in Sistan

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Numerous studies have shown that thermal comfort provision is among the advantages of vernacular architecture in different climates and areas (Dili *et al*. 2010b; Nguyen *et al*. 2011; Rubio-Bellido *et al*. 2016; Victoria *et al*. 2017; Tahbaz and Jalilian 2011, 2016). Nevertheless, the literature on vernacular architecture indicates the considerable importance of this subject due to the lack of comprehensive assessment of environmental functions of vernacular buildings (Huang *et al*. 2017: 1317), the necessity for discovering, documenting and analyzing design principles and vernacular architectural components (Oikonomou and Bougiatioti 2011:669), and the absolute lack or paucity of quantitative studies on the effectiveness of different climatic building strategies on energy efficiency (Fernandes *et al*. 2015; Xu *et al*. 2016; Bodach *et al*. 2014; Du *et al*. 2014).

The discovery of the effects of climate traditional techniques on the indoor thermal quality can result in energy efficiency improvement (Holmes and Hacker 2007: 805), better control of building's indoor environment (Kim 2006; Baran *et al*. 2011), and protection of environmental and historical values of vernacular buildings (Alev *et al*. 2014: 58). Therefore, it is necessary to identify these methods and determine their roles and effectiveness in improving the indoor thermal quality and energy saving.

There are climate adaptation techniques based on natural materials in the vernacular architecture of Sistan. These techniques consist of natural materials and architectural strategies that, although embedded in the main body of the vernacular buildings, can be manually activated and used to the desired degree at the discretion of the residents. These adaptive techniques have a key role in improving the indoor thermal conditions in the region's hot summers.

A review of the available literature on the architecture and habitation of the Sistan region shows that certain studies have addressed and qualitatively described the effevtiveness of the climate adaptive techniques such as *Dorche*, *Kolak* and *Khaarkhaneh* (Molanaei and Soleimani 2016). Others have investigated these techniques mainly focusing on the role of the wind in them using the CFD software (Heidari *et al*. 2017a; Memarian *et al*. 2017). Another research has examined the role of vegetation on the microclimate of the Sistan region (Davtalab *et al*. 2016). Investigating the thermal behaviour of an innovative structure in the outdoor environment with indigenous materials was the subject of other works in the Sistan region (Davtalab and Heidari 2021, 2020; Heidari and Davtalab 2019). Accordingly, the present paper sets to identify the effects of them on the indoor environment of vernacular architecture in the hot summer. Hence, the research questions are as follows: 1) What climate adaptation techniques affect the indoor thermal quality and thermal comfort in the vernacular architecture of the Sistan region in the hot period of the year? And 2) How do these techniques affect the indoor environmental parameters and energy saving?

Previous studies have used different methods for measuring the impact of climate responsive strategies on the environmental parameters of the indoor spaces. The classification of these methods is described in (Nguyen *et al*. 2011; Manu *et al*. 2018).

The methodology chosen for this study is a quantitative one relying on field studies. To this end, through the physical presence in a certain building, different aspects of climate adaptation methods and their impact on the thermal quality of the indoor environment are analyzed. In a quantitative research, the building is evaluated through the field measurement of different indoor and outdoor climatic parameters to extract results pertaining to the thermal performance of buildings (Oikonomou and Bougiatioti 2011: 669). The operational model of the research is summarized in Table 1.

Table. 1: *The operational model proposed and applied in this research*

Step	Method	Materials
1	Collecting data	Topography and Climate of the Area/ Vernacular architecture/ Building materials/ Climate adaptation techniques
2	In-situ measurement	Full scaled measurement of micro climate (3 days quantitative evaluation)
3	Systematic analysis	Investigation the effect of climate adaptation techniques on Air temperature, Relative humidity and energy saving
4	Conclusion	Concluding remarks

Material and Methods

Topography of the Region

Occupying the northern part of Sistan and Baluchestan Province, the Sistan region makes up the easternmost point of Iran. With an approximate total area of 15179 km2, it is situated at longitude 59° 55′–61° 50′ east, latitude 30° 5′–31° 29′ north, marking the borderline with Afghanistan and Pakistan (Figure. 1).



Figure. 1: *Map of Iran showing the location of Sistan and Baluchestan Province (After:www.google.com/maps; www.amar.org.ir)*

Climate of the Region

Sistan is dominated by a hot and dry climate (Saligeh *et al*. 2008: 108). Table 2 shows the regional statistics for the air temperature, relative humidity, and wind speed.

As clearly seen, the highest mean maximum air temperature of 41.7 °C was recorded in July, while January registered the lowest mean minimum air temperature at 1.8 °C. As regards the maximum absolute air temperature, the highest record at 51 °C was credited to August, and the lowest, -12 °C, for January. The mean annual minimum and maximum air temperatures were 14.7 °C and 29.7 °C, respectively. In total, the mean annual air temperature is 22.7 °C at Zabol Meteorological Station.

According to the statistical analysis of relative humidity, the mean maximum relative humidity ranged from 30 to 74%, whereas the mean minimum

Table .2: *Summary of climate parameters of Sistan at Zabol meteorological Station (1962-2010) (After:IRIMO 2018)*

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	ANNUAL
Mean min. temp (°C)	1.8	4.4	9.5	15.7	21.1	25.4	27.8	26.1	20.6	13.9	7.2	2.7	14.7
Mean max. temp (°C)	15.2	18.5	24.6	31.7	36.6	40.5	41.7	40	36.1	30.5	23.4	17.2	29.7
Min. absolute temp (°C)	-12	-9	-2.2	3	7.2	14	19	12	6	0	-4	-10	-12
Max. absolute temp (°C)	29	32.8	38.4	43	48	49.6	49	51	46.8	42	36	29	51
Mean Max. RH (%)	74	70	65	57	43	34	31	30	34	46	61	71	51
Mean Min. RH (%)	44	39	33	27	21	18	18	17	16	21	28	38	27
Wind Direction (Prevailing)	315	360	360	315	315	315	315	315	315	315	315	315	315
Wind Speed (M/S)	2.6	3.2	3.5	4	5.9	8.9	10	9.7	7.6	4.7	2.8	2.2	5.3

relative humidity ranged from 16 to 44%. The highest and lowest relative humidity were recorded in January and August, respectively.

A study of the wind statistics shows that the direction of wind in the Sistan region is north to south during February and March and northwest to southeast during the rest of the year. The wind speed was highest in July (10 m/s) and then August (9.7 m/s) and June (8.9 m/s). The lowest wind speed was 2.2 m/s in December.

Vernacular Architecture of Sistan

Sistan is characterized by a significant vernacular architecture with a long history of residence. The recovered remains from the civilisation of Shahr-e Sukhteh in Sistan point to a history of over 5000 years. However, due to the inherent weakness of clay and mud materials (Zomorshidi 2005: 153), the age of the remnants of vernacular architecture in the region does not exceed 200 years. Epitomizing the regional people and architects' experiences over several centuries, this type of architecture was meant to provide suitable living conditions proportionate to the wealth and subsistence system of the local population.

The vernacular architecture of Sistan includes two dominant types, i.e. linear and central yard types (Oveisi Keykha and Ansari 2013). The linear-type buildings are oriented to the south and to the west. This elongation is in the form of a nearly 30° angle to the east in such a way that the building inclines towards the east. The results of studies on building orientation show that the best building orientation in the hot and dry climate is mostly north and south with a slight eastward slant (at 15–30 degrees). (Pathirana *et al*. 2019; Mahar *et al.* 2019; Sansaniwal *et al*. 2020)

The yard is one of the inseparable components of this architecture. From a climatic viewpoint, the yard plays an important role in creating natural ventilation (Soflaei *et al*. 2016a, 2016b) and lighting for living spaces. Although the severe water shortage in this hot and dry region makes it almost impossible for the residents to construct water pools and garden in their yards, sprinkling some water over the yard area in evenings and at nights during the hot period of the year will create a favorable microclimate (Zamani *et al*. 2018; Khalili and Amindeldar 2014) for spending some time, and the effects of this will be seen on the indoor thermal conditions as well.

Observation of the vernacular architecture reveals the use of smallest number of openings in the minimum possible sizes on account of the intense sunlight and heat in the summer and also the harsh cold of some winters. Most of the considered buildings contained a 1 ×2 m doorway. In very rare cases, there was also a 0.5 ×0.5 m window. This helps increase the thermal capacity of the outer building walls, maximizing energy efficiency. Yet, this low opening area will result in minimized solar gain (Gou *et al*. 2015), which is a drawback in hot climates. Windows play nearly no role in providing natural ventilation for indoor spaces. Natural ventilation in indoor spaces is achieved by other climate adaptation techniques specific to the region, and in some cases also through doors kept open.

Materials of Vernacular Architecture of Sistan

Inspired by the regional desert terrain, the main materials of vernacular architecture consist of clay and mud for footings, walls and ceilings. Rare cases of using tamarisk wood is also attested in roof coverings. Plaster and soil or solely plaster is used for final coating and fixing works on internal walls and ceilings. Clay and lime mortars are commonly used to make indoor and outdoor flooring. Exterior walls made of clay measure 65–80 cm thick. This increases their thermal capacity and prevents rapid conductive heat transfer between indoor spaces and the surrounding outdoor environments (Bhamare *et al.* 2019). Therefore, heat transfer between outdoor environments and indoor spaces occurs with a significant delay. Accordingly, in cold days, the heat gain from solar radiation through building's envelope balances the temperature of indoor spaces during the night, while the heat loss overnight makes the temperature of indoor environments desirable in the early hours of the day in warmer seasons. Analyses show that this is often a desirable scenario throughout the year, except during the nights of the hot period in the Sistan region. In these times, the thermal resistance of building' envelope prevents heat loss through conduction, and thus using indoor spaces becomes challenging. Yet, the vernacular architecture of the region has devised special solutions for this problem which will be discussed in the next section.

Climate Adaptation Techniques

Based on the field survey in the present study, *Dorche*, *Kolak* and *Khaarkhaneh* as typical openings are the three main adaptive techniques controlling

the indoor environment in summer. These techniques, seen in most of the local buildings and deemed regular forms of the region's fabric, serve two main functions. The first is creating natural ventilation for indoor spaces. Due to the high speed of winds (up to 10 m/s) in the hot period, vernacular wind-catcher, locally known as *Kolak* and built in a relatively small dimensions of about 0.35 x 0.50 m, transfer air from the roof into indoor spaces (Figure . 2).

The second function of the adaptive techniques during the hot seasons is providing the much-required humidity for indoor spaces. Pads made of thorns and sprinkled with water are placed behind *Dorches* to form a mechanism called *Khaarkhaneh* (Figure.4). Apart from its contribution to ventilation, this mechanism furnishes the required humidity for providing thermal comfort. The yard plays a crucial role in the successful operation of all the cited techniques and in the realisation of natural ventilation in indoor spaces.



Figure. 2: *Section (left), front view (centre) and interior view (right) of a Kolak*

Dorche is another architectural element used for creating ventilation in indoor spaces. Each *Dorche* usually has four holes or openings with an area of about 0.05 m2 which allow the wind to pass through. These holes transfer the wind from the north-facing side of a room into its indoor space (Figure. 3)

Observation of the wind behaviour in Kolak and Dorche by Memarian *et al*. (2017) using CFD software demonstrated that the wind produced by the Kolak technique enters the room at high speeds (between 4-8 m/s), creating airflow up to 4 m/s in the path between inlet and outlet (Figure. 5a). While

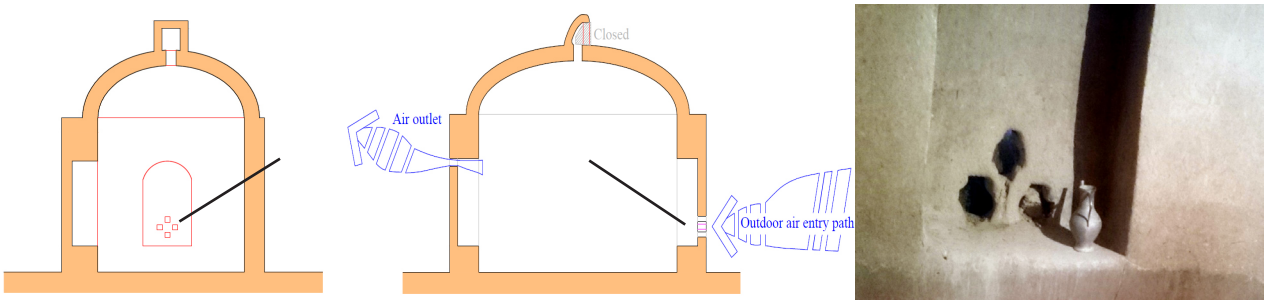


Figure. 3: *Front view (left), section (centre) and interior view (right) of Dorche*

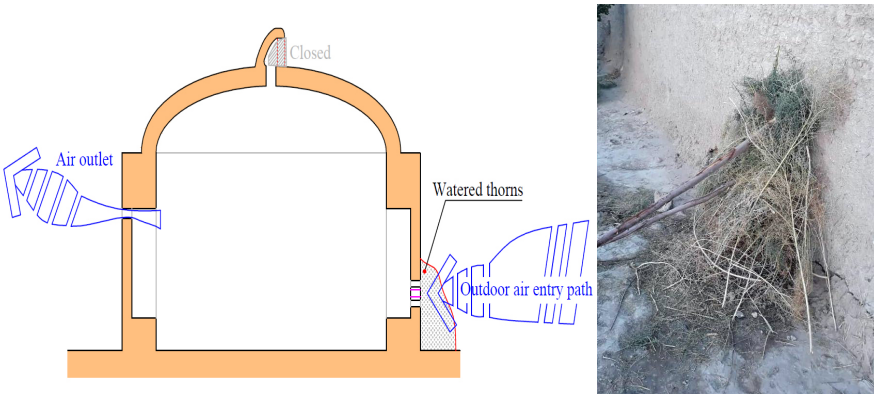


Figure. 4: *Section (left) and outdoor view (right) of Khaarkhaneh*

operating in a similar way, the Dorche technique results in still higher wind speeds at low elevations (Memarian *et al*. 2017) (Figure. 5b)

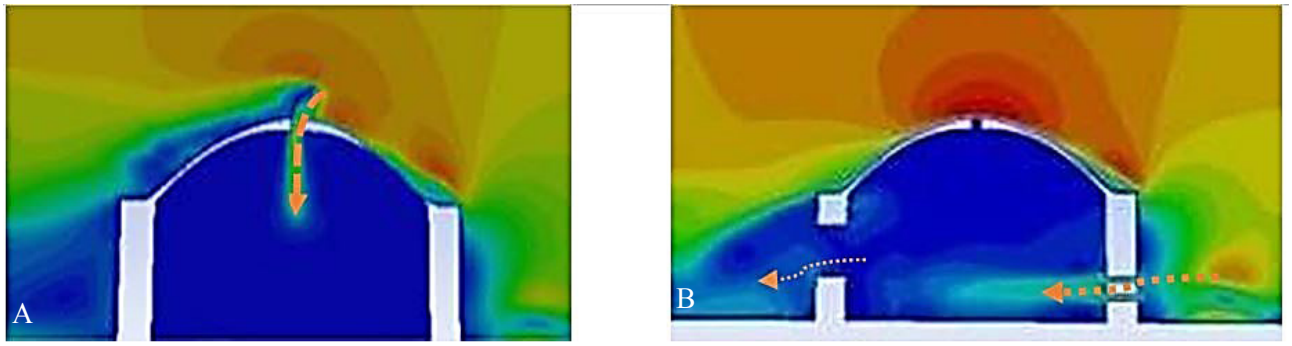


Figure. 5: *A: Air circulation in the Kolak and Dorche B: techniques based on the CFD software (After: Memarian et al. 2017)*

For further details on the wind behaviour and circulation in these techniques obtained through the CFD software, the reader is referred to Memarian *et al*. 2017 and Heidari *et al*. 2017.

However, each of the described techniques has its own limitations and drawbacks. A case in point is the ineffectual function the *Dorche* and *Kolak* techniques during storms when dust may enter indoor spaces through these contraptions. This inefficiency is less problematic in the case of Khaarkhaneh because of the thorn pad; however, keeping the pads moist by the household members becomes tedious, and is practically impossible during sleeping hours. Another disadvantage of this technique is the adverse effect of moisture on the wall adjacent to the pad.

Methodology

In this study, precise measurement tools were employed in a field study conducted on a specific building to analyze the effects of natural materials and adaptive techniques on indoor environment and thermal comfort.

Parameters Definition

There are four ways to exchange heat flux in a room (Verbeke & Audenaert 2018):
1) Internal gain: the heat obtained from artificial lighting, work and office equipment and human body.
2) Solar radiation: receiving direct heat through transparent parts of the building's envelop such as windows and skylights.
3) Conduction: heat transferred through opaque walls of the room. Thermal mass as a passive design feature plays a significant role in this sector. High thermal mass is proposed in climates with high diurnal temperature fluctuations, and when the average daily outdoor temperature is in the comfort range brings the average indoor air temperature within the comfort range. This feature makes outdoor fluctuations have less impact on the indoor space (Bhamare *et al*. 2019).

The most important criteria for determining the thermal capacity of materials (thermal mass) are the time lag and decrement factor (Becerra-Santacruz and Lawrence 2016). The time lag is the time when the maximum (or minimum) temperature of the outdoor environment increases (or decreases) the temperature of the indoor space to the maximum (or minimum) possible degree (Verbeke and Audenaert 2018). A higher thermal capacity in building materials means higher time lag (Becerra-Santacruz and Lawrence 2016) and can be calculated from formula (1) :

$$TL_{max} = t(Tin_{max}) - t(Tout_{max}) \quad (1)$$

where TL_{max} is "Time lag" for maximum air temperature, t(Tinmax) is time of maximum indoor air temperature, and $t(Tout_{max})$ is time of maximum outdoor air temperature.

The second criterion, namely the decrement factor, is a change in the sine curve of heat transfer when passing through a building material (Verbeke & Audenaert 2018). The value can be calculated with DF formula (2) (Becerra-Santacruz & Lawrence 2016):

$$DF = (Tin_{max} - Tin_{min}) / (Tout_{max} - Tout_{min}) \quad (2)$$

where (DF) is the "Decrement Factor", Tin_{max} and Tinmin are respectively maximum and minimum indoor air temperatures, and $Tout_{max}$ and Toutmin are maximum and minimum outdoor air temperatures, respectively. The smaller the coefficient is, the higher the thermal capacity of the materials would be (Becerra-Santacruz & Lawrence 2016). The values

of DF <0.2 can be considered as a good standard, and LT values higher than 6 hours are sufficient for thermal inertia of envelope materials in hot climate buildings (Barrios *et al*. 2012; Becerra-Santacruz and Lawrence 2016; Gagliano *et al.* 2014).

4) Convection: heat exchange through the movement of air between the inside and outside of the room. Also, if there is a temperature difference between the outside and the inside air of the room or different parts of the room, the air is transferred from the hot side to the cold side (Yang *et al*. 2019). From this view of point, natural ventilation is one of the main factors in changing the environmental parameters of a room and thus thermal comfort range.

Building Description

The building selected for this study is located at the Dehno Pirran village of Nimrooz County in northern Sistan. As with other regional traditional structures, this about 100-year old building is made of clay and mud in three sections, i.e. living spaces, service areas, and livestock and poultry spaces. The building roughly measures 18 ×20 m. Its northern quarter is dedicated to living spaces for the occupants, while the southern side contains service areas and spaces for keeping livestock and poultry. The yard is divided into two sections. All indoor spaces have direct access to the yard (Figure. 6). The main exterior walls measure 65–80 cm thick and are made of clay. As stated above, this gives the building a higher thermal capacity through excluding rapid conductive heat transfer between indoor spaces and the surrounding outdoor environment (Bhamare *et al*. 2019). During the summer, thermal comfort is provided via natural ventilation created by the *Kolaks* and *Dorches* and the humidity created by the *Khaarkhanehs*.

Details of the Fieldwork

The fieldwork used the Kestrel, WBGT and Kimo meteorological devices (Table. 3) to record the air temperature, globe temperature, relative humidity, and wind speed. The accuracy of these devices has been evaluated by the Management of Meteorological Equipment Engineering and Transport Department of Meteorological Organisation of Iran. The air temperature and wind speed were measured with the Kestrel device, the globe temperature with the WBGT device, and the relative humidity with the Kimo.

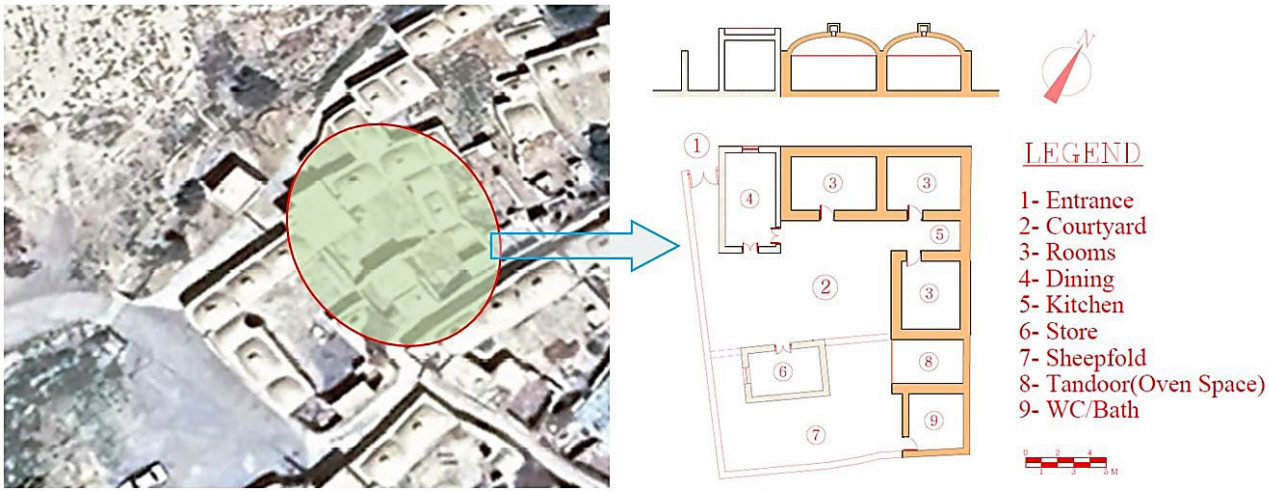


Figure. 6: *Location of the selected building at the village (left), and the plan and section of the selected building (right) (After: www.google.com/maps; Drawing by the Author)*

Table. 3: *Detailed information of instruments (After: https://kestrelmeters.com; http://www.kimocanada.com; https://www.reedinstruments.com)*

Accuracy	Range	Parameter measured	Trade name	Description
Heat Stress Tracker	Kestrel 4600/4500	Air Temperature Air velocity	-10.0 to 55.0 °C 0 to 40.0 m/s	±0.5 °C ±3% of reading
THERMO-HYGROMETER	Kimo KH50	Relative Humidity	From 0 to 100% RH	±2% RH
WBGT	Heat Index CHECKER 8778	Globe Temperature	0 to 80°C	±1.5°C

The involved instruments were installed at three points of the building (Figure. 7). Point (1) was located on the building roof to obtain the parameters of local climate (outdoor environment). Point (2) was set in a room which benefited merely from the permanent strategies to moderate the indoor space. This room was named the Instance room. Finally, Point (3) was selected in a room with specifications identical to those of Point 2. Climate adaptation techniques such as Kolak, Dorche and Khaarkhaneh were also used at Point 3. All the three devices were used at all the measurement points.

According to Table 2, the research parameters were recorded in three very hot days from July 26, 2019 to July 29, 2019. All parameters were recorded in 10-minute intervals by data loggers. The outdoor instruments were installed at a height of 1.50 m, and the indoor instruments were installed at an approximate height of 1.10 m of a seated person (Figure. 7) (ANSI/ASHRAE Standard 55, 2013).

Data Analysis

To evaluate the effect of the mentioned techniques, the need for cooling degree-hours has been calculated separately for the Instance room and indoor space with different adaptive techniques in hot period. Equation 3 has been used for this purpose:

$CDH=\sum_{i=1}^{N}(Top_average - Tupper_limit)$ (Michael *et al*. 2017) (3)

One of the components of this equation is the upper limit of indoor thermal comfort. In order for the calculation of this research to be in line with international standards, the upper limit of thermal comfort range in the ASHRAE standard (2004) (ASHRAE Standard 55 2004) have been used. Accordingly, in CDH the upper limit of summer thermal comfort is 27 ° C.

The operative temperature (Top) can be obtained by Formula (4).

Top= (Ta*(√10*Va)+Tr)/(1+*(√10*Va)) (ISO-7726 1985) (4)

where Ta is the air temperature, Va is the wind speed in m/s, and Tr is the mean radiant temperature which can be obtained by Formula (5):

$Tr=[(Tg+273)^4+2.5*108*Va^{0.6}(Tg-Ta)]^{1/4}-273$ (ISO-7726 1985) (5)

where Tg, Ta and Va are the globe temperature, air temperature and air velocity in m/s, respectively.

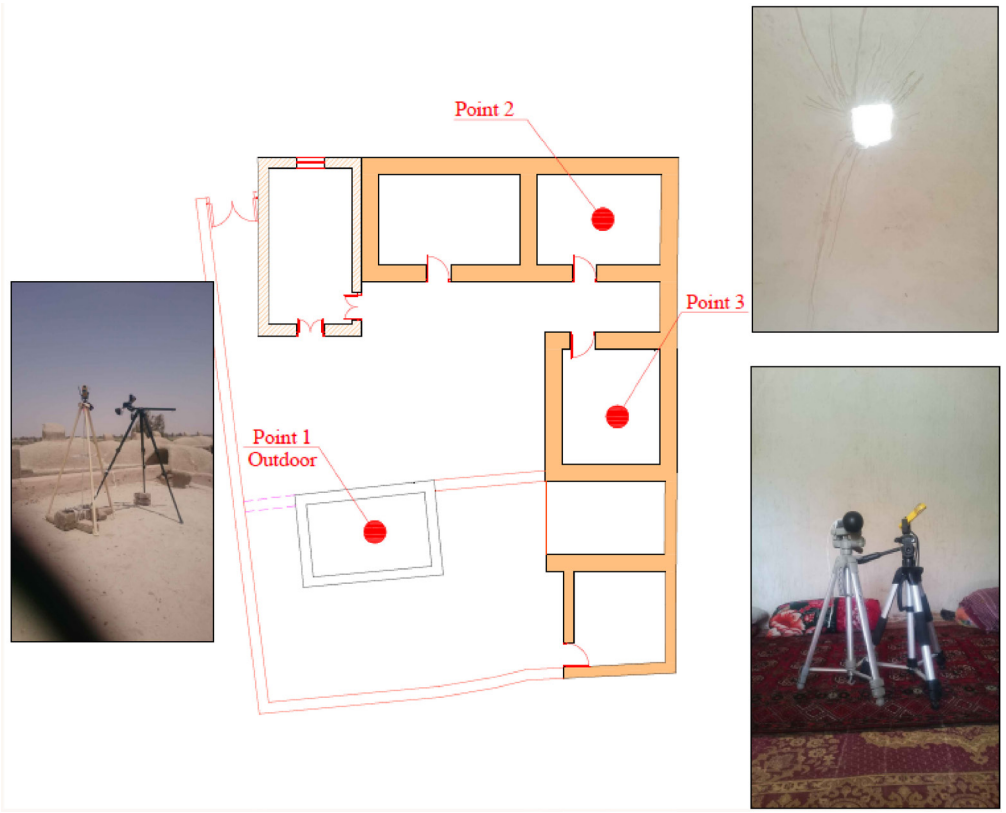


Figure. 7: *Installation of instruments at the specified points*

Results and Discussion

Air temperature, relative humidity and wind speed parameters were recorded at various points around the building during hot season, and their role was analyzed in terms of thermal comfort and energy saving in indoor spaces. In order to discover the effect of adaptive techniques, in the first 24 hours, *Dorche* technique was used. The *Kolak* and the *Khaarkhaneh* techniques were used in the second and the third 24 hours, respectively. Globe temperature of indoor environment was also recorded. However, as already stated in Humphry *et al.* 2007, the air temperature and globe temperature in indoor spaces measure closely in ordinary conditions (Humphreys *et al*. 2007: 61), which in the current example was 0.3 °C in 178 records during the summer. Therefore, there was no need for analyzing this parameter.

Results

A look at the air temperature and relative humidity in the first and second 24 hours during which the *Dorche* and *Kolak* techniques were used shows that the outdoor air temperature ranged from 31 °C to 46.7 °C and the indoor air temperature from 33.4 °C to 41.4 °C. At the same time, the Instance room air temperature varied between 35–39.2 °C (Figure. 8). Accordingly, the difference between the minimum and maximum air temperatures in the outdoor, indoor (with *Kolak*), indoor (with *Dorche*), and Instance room is 15.7 K, 8 K, 7.2 K and 4.2 K, respectively.

In the third 24 hours, another architectural technique called *Khaarkhaneh* was used in the indoor space. According to the recorded information, the minimum and maximum indoor air temperatures were respectively 31.2 °C and 37 °C when the *Khaarkhaneh* technique was applied. At the same time, the outdoor air temperature ranged from 30.7 °C to 45.3 °C, and the *Instance* room air temperature ranged from 36.4 °C to 38.7 °C (Figure. 8). It may be safe to conclude that the difference between the minimum and maximum air temperatures in the outdoor environment, indoor space with *Khaarkhaneh*, and *Instance* room are 14.6 K, 5.8 K and 2.3 K, respectively.

In terms of relative humidity, a 6% to 26.4% range was observed for the outdoor environment during the 72 hours of research. In the first 48 hours when the relative humidity of the outdoor environment fluctuated between 6% and 21.2%, the relative humidity of the *Dorche* and *Kolak* techniques ranged from 9% to 17.5%, whereas that of the Instance room ranged from 12.9% to 19.3%. In the last 24 hours, the relative humidity of the indoor space with *Khaarkhaneh* technique ranged from 18.9% to 35.5%. At the same time, the relative humidity of the outdoor environment and the Instance room respectively ranged between 9.3–26.4%, and 14.9–20.6% (Figure. 8).

In the research period, the wind speed ranged from 0 m/s to 8.1 m/s with an average of 3 m/s in the outdoor environment (Figure. 9). The speed of wind

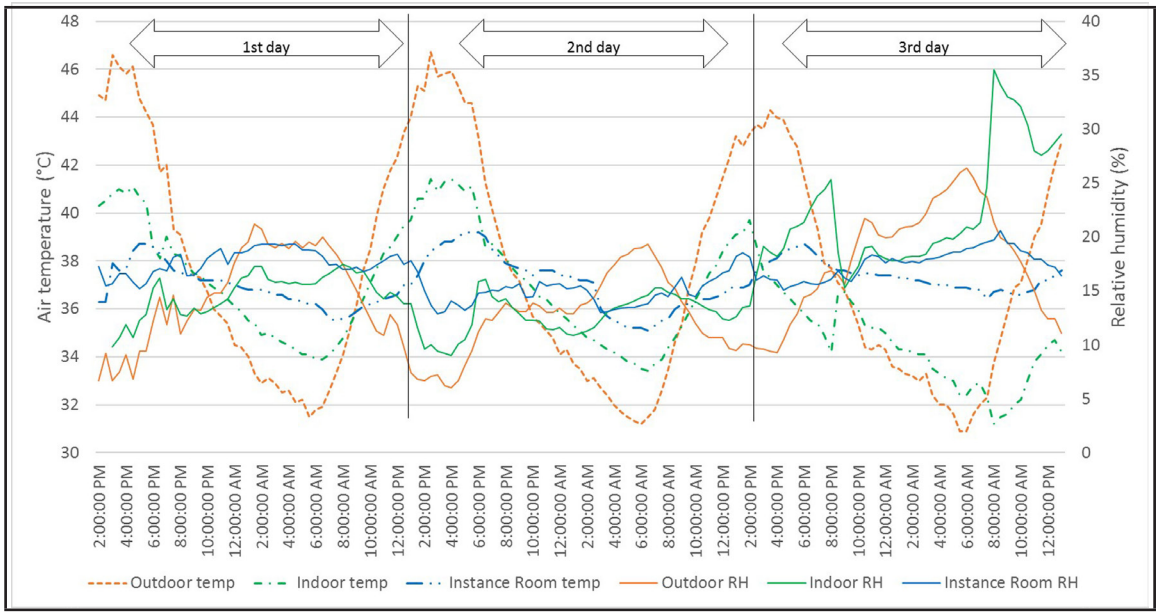


Figure. 8: *Air temperatures and relative humidity in different parts of the building during the research days in the hot period of the year (9-12 July 2019)*

in the indoor space was 0-1.1 m/s during the first and second 24 hours when the *Dorche* and *Kolak* were active, and 0-2.3 m/s in the last 24 hours when the *Khaarkhaneh* system was working (Figure .9). In terms of how air enters the indoor space in different techniques, when wind flow hits a *Kolak,* it enters the room with a 90-degree rotation from the roof level (Figure. 2). However, in the *Dorche* (and *Khaarkhaneh*) technique, wind enters the room in a direction parallel to its flow near the ground level (Figures. 3, 4). Therefore, despite the higher maximum and average values of wind speed on the second day (*Kolak* technique) compared to the first day (*Dorche* technique) in the outdoor environment, the measurements of the wind speed in the indoor space were the same on both days. The wind speed in the Instance room without any openings was zero during the hot period.

Air Temperature

"Conductive" and "convective" were the main ways of heat flux exchange in the indoor space with *Dorche*, *Kolak* and *Khaarkhaneh* techniques (Figure .10). On the other hand, there was no heat flux exchange through convection in the *Instance* room due to the lack of opening and natural ventilation, and the main contributor to the diurnal fluctuation of the indoor air temperature was conductive heat transfer from the outdoor environment.

Figure 11 shows TL_{max} criterion to be three and a half hours in the *Instance* room during the hot period of the day. Although this is lower than the 6 hours reported in Gagliano *et al*. 2014, a review of other studies conducted in the hot climate shows that materials with 5 hours (Michael *et al*. 2017) and 4 hours (Sivitanidou and Nikolopoulou 2019)

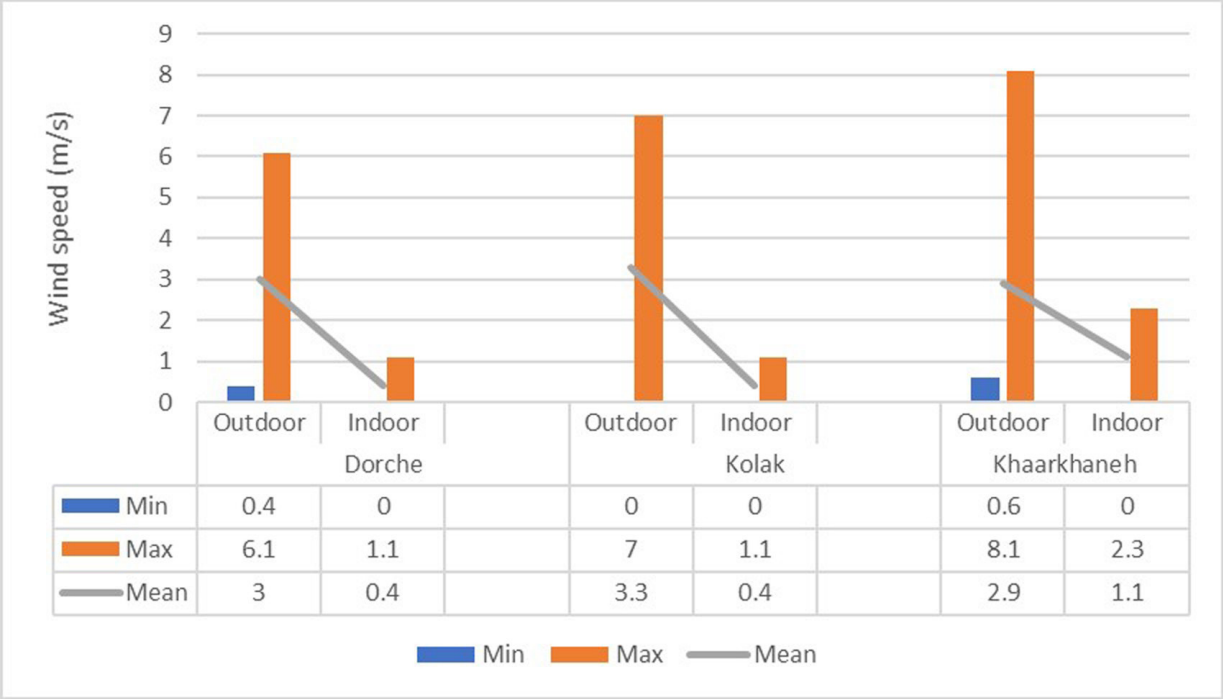


Figure. 9: *Wind speed in the indoor space and outdoor environment during the research days in the hot period of the year (9-12 July 2019)*

Results Analysis and Discussion

In a hot and dry climate, the air temperature, relative humidity and wind speed play the foremost role in thermal comfort studies of indoor environments with small openings (Humphreys *et al*. 2007). This section analyzes the results of these three parameters and evaluates the thermal comfort of the indoor space based on the different techniques used in the hot period of the year.

for TL_{max} performed well. Based on this, the time lag of the materials used in this building, viz. local materials mainly consisting of clay and mud, can be acceptable.

In addition, the DF criterion was 0.26 in this room during the study period. Similar studies show that 0.38 (Becerra-Santacruz and Lawrence 2016) and 0.28 (Dili *et al*. 2010a) had acceptable performance for DF in a hot climate. This value is

lower than these results, and also is very close to the good standard for DF (Barrios *et al*. 2012; Becerra-Santacruz and Lawrence 2016).

Analysis of the air temperature parameter for the *Instance* room shows that although high thermal capacity of the building materials and consequently a longer time lag and a lower decrement factor are considered appropriate features for a hot and dry climate (Verbeke and Audenaert 2018), the lack of openings and natural ventilation has deprived the Instance room from the low temperature and natural ventilation of nights via convection. As a result, the room's temperature was as high as 35–39.2°C.

Dorche, *Kolak* and *Khaarkhaneh* as adaptive techniques provide air ventilation in the indoor space and heat exchange takes place through convection in addition to conduction. *Dorche* and *Kolak* techniques cause the indoor temperature to be closer to that of the outdoor, and as a result, the diurnal fluctuation of indoor temperature (about 8K) is greater than the *Instance* room (4.2K). Yet, while the *Instance* room showed better value in diurnal temperature fluctuation during the research period, the *Khaarkhaneh* technique had still better results in terms of both the indoor maximum air temperatures (37 °C to 39.2 °C) and the indoor minimum air temperatures (31.2 °C to 35 °C) (Figure. 8).

the relative humidity would be, and vice versa. This phenomenon is related to the water vapor capacity. Because of the longer distance between its molecules, hot air has a higher vapor capacity and the amount of water vapor decreases compared to the overall volume. Therefore, the relative humidity decreases (Tahbaz 2013).

The relative humidity measurements for the indoor spaces show that the average relative humidity of the Instance room fluctuated in the range of 13 to 19% and between 9 and 17.5% in the *Dorche* and *Kolak* techniques. Although the *Instance* room yielded higher values than the *Dorche* and *Kolak* techniques, in all these cases, the relative humidity is lower than the minimum value (20%) proposed by ASHRAE (ASHRAE Handbook 2001) for thermal comfort.

On the other hand, analysis of the relative humidity in *Khaarkhaneh* technique shows that when the *Khaarkhaneh* mechanism was active, the relative humidity values of the indoor space were 18.9% to 35% and within the acceptable range for thermal comfort (20% to 80% according to (ASHRAE Handbook 2001))(Figure. 8).

In the research period, while the average relative humidity of the outdoor environment was often below 20%, the relative humidity of the *Instance*

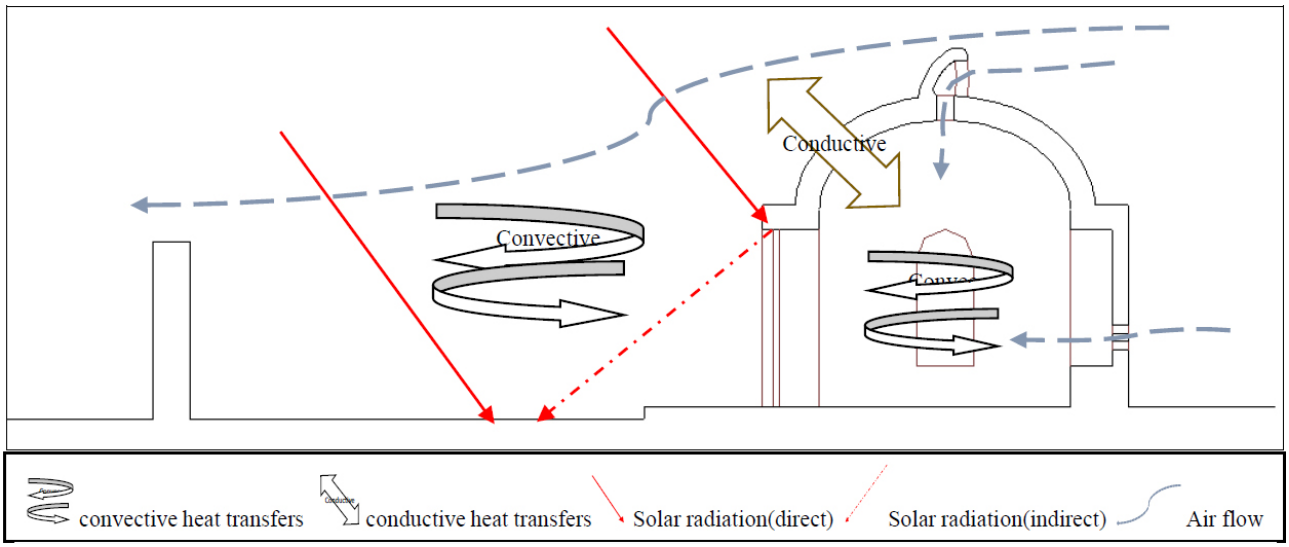


Figure. 10: *Heat exchange between different parts of the building during the hot period of the year (9-12 July 2019),*

Relative Humidity

With regard to the relative humidity values, there is an inverse relationship between air temperature and relative humidity in the outdoor environment (Figure. 8). The warmer the air is, the lower

room and the indoor space with the *Dorche* and *Kolak* was likewise below 20% and lower than the minimum values required for thermal comfort. It can be concluded that the two adaptive techniques of *Dorche* and *Kolak* do not have the ability to

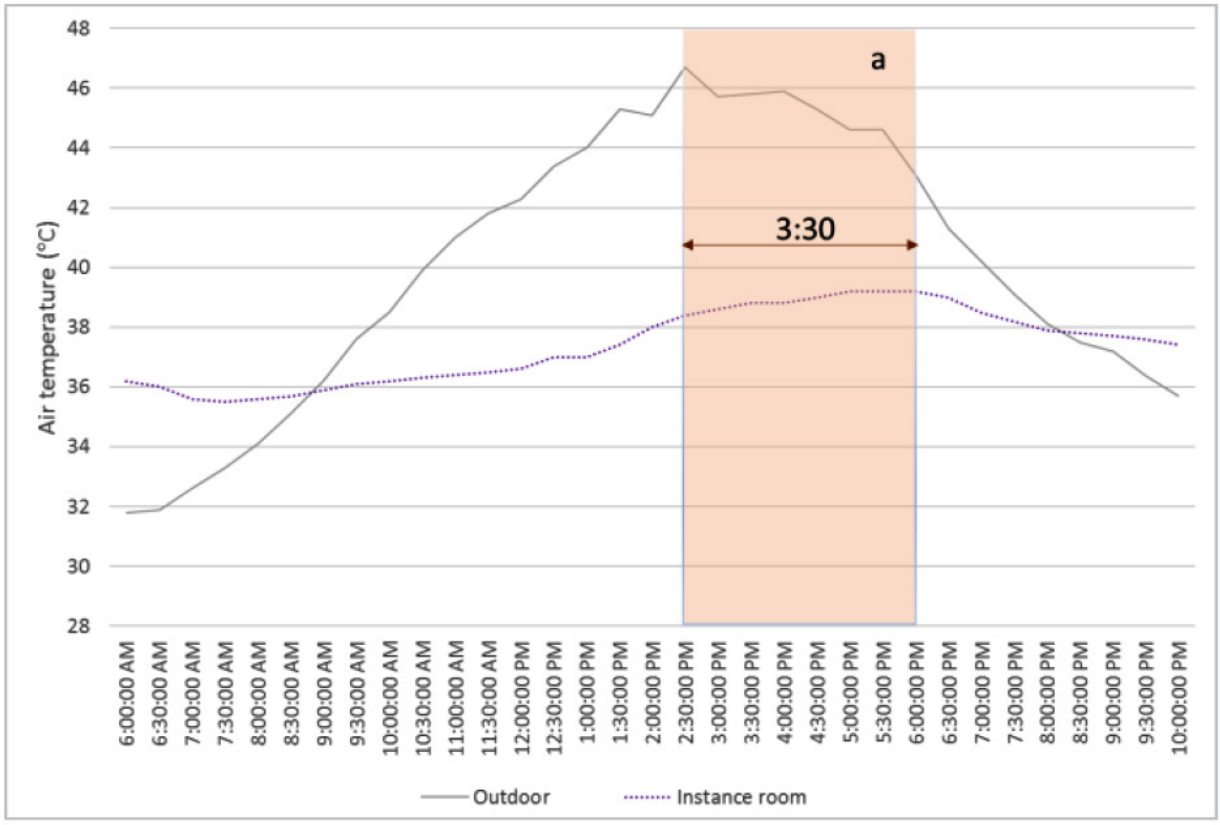


Figure. 11: *The time lag (max) of the indoor space during the hot period of the year*

increase and improve the relative humidity in the hot and dry climate of the region.

Energy Saving

The most important results of this study was the amount of energy saving achieved by each adaptive technique and the "presence mode" of the residents in different parts of the buildings. To measure these amounts, the required cooling degree hours (CDH) were calculated in the hot period of the year. Field measurements showed that the residents of the Sistan region utilize the open and closed spaces of their abodes in different ways. They sometimes use the closed spaces as they are or along with an adaptation technique (*Dorche*, *Kolak* or *Khaarkhaneh*) to achieve thermal comfort. However, when the outdoor environment (e.g., the yard) is climatically more favorable, they often use the open spaces. Therefore, the analyses performed in this section led to formation of three categories: (1) CDH-Outdoor: required cooling degree hours when the residents are in the yard and not confined within a room's walls; (2) CDH-*Instance* room: required cooling degree hours when the residents are indoors but do not use any adaptation technique, i.e., when the building walls are the only means of thermal comfort; (3) CDH-Indoor: required cooling degree hours when the residents are indoors and use an adaptation technique. In addition, due to the large difference between the daytime (08:00-20:00) and nighttime (20:00-08:00) temperatures and their different effects on each of the mentioned modes, the results of this section are presented for daytime and nighttime separately (Figure. 12a and 12b).

In the daytime interval (Figure. 12a), the outdoor CDH need was highest (160-180 cooling degree hours). The need was 121-126 cooling degree required cooling degree hours for the *Instance* room. The comparison of the *Instance* room and the outdoor environment showed that the CDH need in the former was between 21-33% lower than the latter.

The comparison between the indoor environment (*Dorche* and *Kolak* techniques), the outdoor environment and the Instance room in the same period showed that although the CDH need at the time of using *Dorche* and *Kolak* was 22% and 27% lower than that of the outdoor environment respectively, it respectively was 17% and 10% higher than that of the Instance room. Lack of any

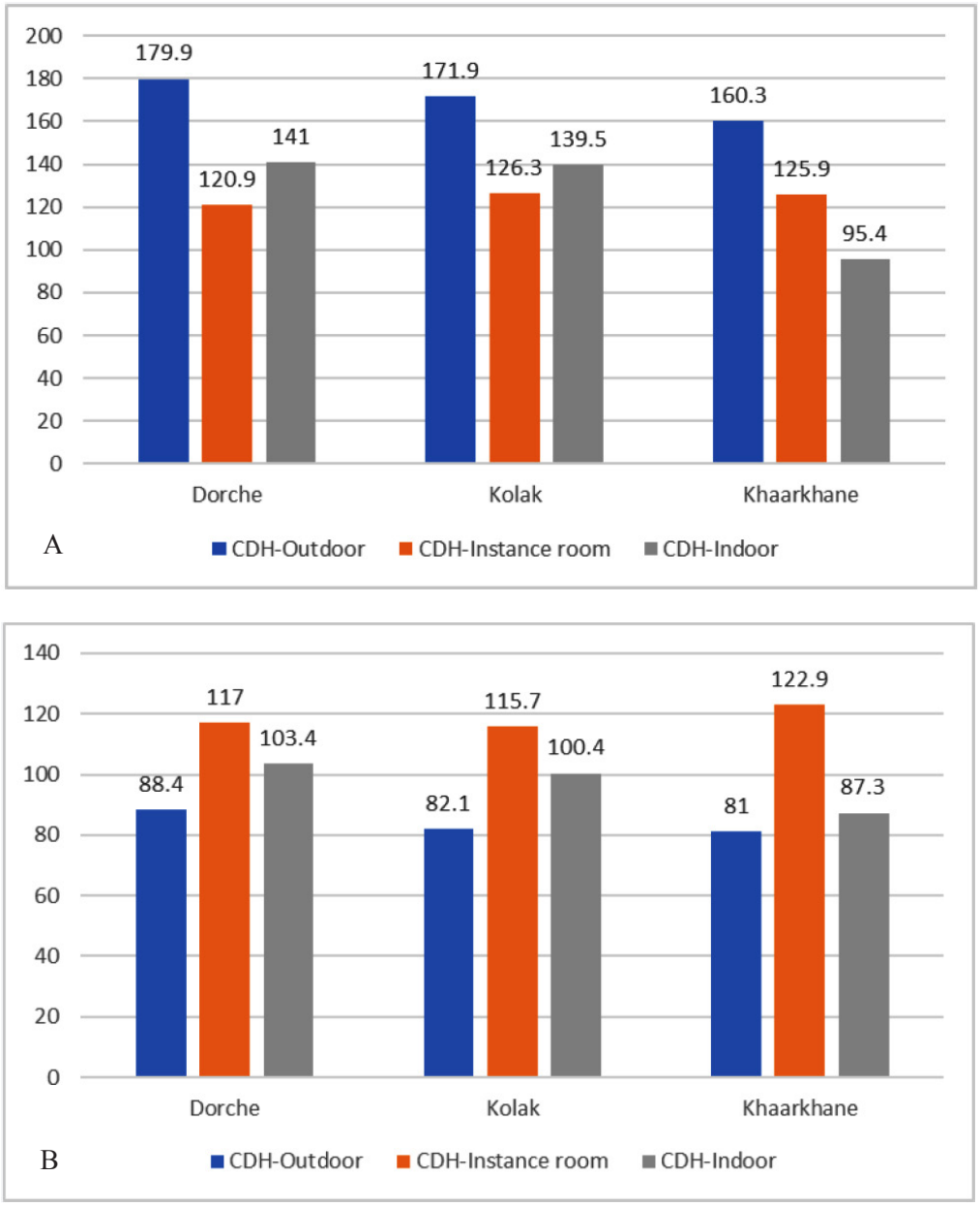


Figure. 12: *A:The CDH values of different techniques during the daytime , and B: the nighttime*

opening in the Instance room and thus prevention of ambient heat transfer to the indoor environment via convection seems to be the main reason. The comparison between the indoor environment at the time of using *Khaarkhaneh*, the outdoor environment, and the *Instance* room in the same period showed that the need for cooling in the indoor environment was 60% and 24% lower than that of the outdoor environment and the *Instance* room, respectively. It can be concluded that in the daytime period, the indoor space at the time of using *Khaarkhaneh* had the lowest need for cooling, and thus the highest amount of energy saving, followed by the *Instance* room.

During the night, the need for cooling was lowest in the outdoor environment. The local residents spend as much time as possible in their yards or on the roof of their houses overnight. As can be seen in Figure 12b, the greatest need for cooling was registered for the *Instance* room. Lack of any opening to bring the nightly cool air into the room was the main reason. The comparison between the *Instance* room and the outdoor environment shows that the CDH need in the *Instance* room was 32–52% higher than the outdoor environment.

The comparison between the indoor space at the time of using *Dorche*, *Kolak* and *Khaarkhaneh,*

the outside environment and the Instance room during nighttime indicates that although the need for cooling in the indoor space at the time of using all three techniques was more than that of the outside environment (8–22%) and less than that of the *Instance* room (12–29%), the CDH need in the indoor space at the time of using *Khaarkhaneh* was only 8% higher than that of the outdoor environment. Despite the flaccid nature of the *Khaarkhaneh* mechanism during the night, the condition created by this technique in the indoor space can be favorable for spending one's time, and ranks second after the outdoor environment. Overall, the need for cooling was lowest in the indoor space at the time of using *Khaarkhaneh* during nighttime, and consequently the highest amount of energy saving among the three techniques was achieved in this mode.

Conclusions and Suggestions

This study investigated the effect of climate-based adaptation techniques relying on natural materials on the vernacular housing of low-income residents of the Sistan region. The region has a dry climate with continuous winds during the warm period of the year. The local houses serve both residential and subsistential purposes, with special spaces for keeping livestock and performing daily activities while concomitantly fulfiling the basic needs of the residents.

The effect of these climate-based adaptation techniques on the parameters of the indoor space, the residents' thermal comfort and amount of energy saving were examined in this paper via measuring the environmental parameters of the different parts of a local house.

This research showed that the adaptive techniques in the indoor spaces are meant to provide nocturnal air ventilation and to increase the relative humidity in addition to contributing to diurnal ventilation. Mere reduction of daily air temperature fluctuation was proved to be insufficient in the considered structure, a vernacular NV building. Rather, it was found out that it is necessary to reduce the indoor air temperature by night ventilation as well as the cold air caused by wet thorns. That being the case, the time of thermal discomfort and the need for energy consumption will be reduced. This study also indicated that given the high wind speed in the Sistan region, the dimensions and shape of the adaptive techniques will result in lowered indoor wind speed. These properties, stemming from local architects' long experience, can be used in the architectural design of contemporary buildings. In addition, although similar studies in hot regions have shown that openings and natural ventilation improved the thermal quality of the indoor environment, in the Sistan region it is not effective during the day time of the hot period of the year.

In addition to providing the necessary ventilation, the *Khaarkhaneh* technique increases the relative humidity of the indoor space and bring it to the minimum relative humidity required for thermal comfort. With its definite drawbacks notwithstanding, it is still a suitable technique with minimal dependence on fossil fuels and water resources.

The findings showed that *Khaarkhaneh* provides the highest level of thermal comfort and energy saving in the vernacular houses of the region during the day. Overnight, however, the preferred option is resting in the outdoor environment, followed by the *Khaarkhaneh* technique, both of which furnish thermal comfort and reduce residents' dependence on fossil fuels.

By these techniques, the vernacular architect has the freedom of action to take advantage of the heat transfer properties through the walls and the convection exchange to provide thermal comfort in different situations. Continued application of these principles in present-day architecture contributes to the thermal comfort in NV buildings with the least dependence on fossil fuels in hot, dry and windy climates similar to that of the Sistan region, among them being eastern Iran and southwestern Afghanistan.

As the present study focused on pinning down the capabilities of this vernacular architecture and the impact of its climate adaptation techniques on the indoor thermal conditions and thermal comfort, it is recommended that interdisciplinary studies be carried out by the experts of related disciplines in the fields of architecture, mechanics and civil engineers to solve the limitation of these techniques, notable among which are the dust entering the interior spaces through *Dorche* and *Kolak*, the need for manually watering the thorn pads as well as the relatively weak structure and height limitations of these vernacular techniques. With our current architectural, mechanical and civil engineering knowledge, these problems are easily eleminatable, and it is possible to turn this type of architecture

into an economical and valuable model for use in rural residential environments and low-density urban complexes, especially for providing thermal comfort with maximum energy saving.

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