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Experimental Evaluation of Summer Thermal Comfort in Various Types of Sardab (Cellar): Underground Space in Iran Vernacular Houses

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ABSTRACT

This article aims to evaluate the effect of three types of Sardab (Cellars) on thermal comfort conditions. Two vernacular buildings in Yazd have been selected as case studies. In the Rasoulian house, a sardab with a water pond has been defined as case A and a Sardab without pond has been chosen as case B. Case C is a Sardab without pond in Mortaz house. Using experimental data, environmental parameters were analyzed for a month in two consecutive years. Using measured data, the values for Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) have been calculated. The results show a considerable reduction in the air temperature (up to 20 oC) and an increase in the relative humidity of the air (up to 50%) in case A (the Sardab with pond). The sardabs without pond (Case B and C) presented lower efficiencies. Variations in daily temperatures have been presented in three cases with ceilings elevated at different heights. While the sardab that is placed completely underground presented the lowest temperature, in two other sardabs, the average air temperature was 2-3 degrees higher. According to the results, in a hot and dry climate, application of all sardab types, either with or without a pond, elevated or underground, would improve the thermal comfort condition and the energy efficiency of buildings.

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1. Introduction

Today, one of the significant universal challenges is global warming and increasing carbon dioxide emissions. Such crises show the need to reduce fossil fuel applications and renewable energy use [1-3]. Between 20 to 40 percent of fossil fuels are consumed in the building sector in industrial countries [4]. This emphasizes the necessity to reduce the energy used to provide thermal comfort in buildings. On the other hand, vernacular architecture has always been considered as a passive climatic strategy. One of the leading passive methods for cooling is applying underground spaces using the benefits of thermal mass capacity. Underground buildings are spread worldwide in the vernacular architecture of many countries, including Japan, Tunisia, China, Turkey, Jordan, Scotland, and Iran. They are mostly located in hot and warm climates [5]. There are studies about various aspects of these buildings, including their thermal energy performance. Alkaff had examined the traditional and modern model of subsurface buildings from different points of view and divided the underground structures into three types named Atrium, Elevational, and Bermed (figure.1) [6]. Although sardab does not fit into any of the mentioned typologies, it has most of the mentioned properties.

In many countries, underground spaces were used to preserve food and wine. Obtaining and maintaining wine needs a specific temperature and humidity for long periods [5,7]. So, several studies that tried to find the optimum temperature and humidity to maintain and preserve wine quality in underground spaces and cellars [8-10]. Underground spaces are also used as a shelter with more security, especially in war times or secretly religious duties and gatherings [11-12]. Nowadays, various urban and architectural spaces are being built underground, such as parking lots, exhibitions, shopping malls, leisure, sport, and recreational centers [13-15].

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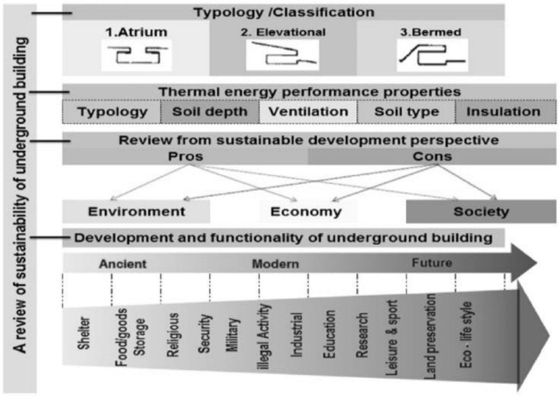


Figure 1. Model for a review of the underground building [6].

As the results of previous studies, the underground buildings have great potential for sustainable design, minimizing building energy consumption [6]. Several studies were conducted on the thermal performance of underground buildings [16]. Soil type and density affect the thermal diffusivity of the ground as its water content does. Soil depth is an essential variable in soil temperature. There are various theories to predict soil temperature at different depths, among which the Kasuda method is one of the most reliable ones [17]. Kasuda found a correlation to define the ground's temperature as a function of the time and the depth. The soil temperature fluctuations diminished, increasing the depth, and finally, the temperature equals the annual average air temperature [18]. In arid climates, where the daily change in air temperature is high, the fluctuation between day and night temperatures is less [19]. At 10 meters depth, the soil temperature is constant and equals the average air temperature [20-23].

In the vernacular architecture of Iran, there are various types of underground spaces categorized in three scales. Macroscale includes underground villages and cities like 'Nushabad' and 'Meymand'. While urban equipment such as qanat, cisterns, and yakhchal (ice-pit) are in the mesoscale group, architectural spaces are defined as microscale. Shabestan (sardab), shavadan, sunken courtyard, houzkhane, and padiav are some of the mentioned underground spaces [24]. In Figure 2, some of the mentioned spaces have been illustrated. Shavadan is an underground space 5 to 12 meters in depth. Investigation of shavadun temperature shows the average temperature of 17 °C and 23 °C while the ambient temperature is 7 °C and 47 °C in January and July, respectively. Sunken courtyard (Goudal Baghche) integrates earth-sheltered and courtyard concepts providing an effective climate control system. Al-Mumin had discussed the ability of the sunken courtyard to modify the harsh desert climate. The energy consumption and construction costs of a sunken courtyard building had been compared to above-ground structures [25]. While most of these spaces had cooling applications [26], urban structures such as cisterns [27] and ice-pits (yakhchal) [28] are also built underground to store water and ice.

Nowadays, many ancient buildings are rehabilitated to accommodate today's required functions such as restaurants, offices, museums, and warehouses. To make the proper decisions for revitalization and new function, understanding the thermal performance of the buildings is necessary. Previous studies revealed that underground spaces in the vernacular buildings could significantly affect indoor thermal comfort. However, these studies are mostly either qualitative or descriptive. Using a quantitative field study, this study investigates the thermal comfort condition of three different types of sardabs (with and without water pond) in the vernacular buildings of Yazd. However, these studies are mostly either qualitative or descriptive. The results could be helpful in making the most proper decision for buildings revitalization.

2. Sardab definition

Sardab (cellar) is the most common underground space in the vernacular architecture of Iran, always considered as one of the passive cooling systems [24]. Sardab is a space located entirely or most partially below the ground level. In most cases, the roof of the sardab is about 70 cm above the courtyard level so that windows direct natural light and wind flow into space. In warm seasons due to the reduction in internal air temperature, sardab is a suitable place to rest and store food [33]. In hot-dry climates, sardab with a central pond is usually connected to the above windcatcher. Previous studies had examined sardab mostly in terms of spatial, functional, and architectural characteristics [34].

Constructional and behavioral patterns are two significant factors that provide environmental comfort conditions for the inhabitants of traditional Iranian buildings. The first one is based on climate considerations, and the second one is the time-depended adaptations to climate, which make the lifestyles [27]. So in each season, based on weather conditions of the day, the inhabitants select which space to use. On hot-dry summer days, shaded and underground spaces like sardab and houzkhane were used. These underground spaces were much cooler than the spaces located at the ground level [26].

According to Forouzanfar and Vellinga, in vernacular houses, the only space with constant temperature is the basement or cellar [34]. They reported that even the ground-floor rooms equipped with windcatchers could not provide a comfortable condition. The average basements temperatures are continuously and substantially are lower than the mean outdoor temperature. The results of research in the basement of traditional houses in Kashan show that the basement temperature is always within the comfort zone [26]. In some houses in Yazd, there is hozekhane, which is a similar space to sardab with access to the Qanat canal. From this canal, water is purred into a pond in hozekhane. In some houses, this space had designed in combination with windcatchers.

3. Methodology

(a) (b) (c) (d)

Figure 2. (a) Sardab (Cellar) [29]; (b) Shavadan [30]; (c) Sunken courtyard (Goudal Baghche) [31]; (d) ice-pit (yakhchal) [32].

In this study, three types of sardab have been experimentally investigated for a month (July as one of the hottest months of a year) in two consecutive years. Two houses named Rasoulian and Mortaz were selected as the case studies in Yazd with hot summers and cold winters. The first two cases, A and B, are sardabs located in the Rasoulian house. Case A is an underground space with a water pond and fountain in the center and clerestory windows on the west side. Case B is a square plan space with no water pond, which is placed completely under the ground level. In case B, daylight illuminance is also measured. Similar to case A, case C is sardab without pond located in Mortaz house. Based on the measured variables, the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) are calculated. PMV index as the thermal sensitivity of the environment is calculated using Equation (1), and PPD as a percentage of dissatisfied people is calculated using Equation (2) as followed:

$$PMV = (0.303e^{-0.036M} + 0.028).\{(M-W) - 3.05 \times 10^{-3}[5733 - 6.99(M-W) - P_W - 0.42[(M-W) - 5815] - 1.7\times 10^{-5}(5867 - P_a) - 0.0014M(34 - T_a) - 3.96 \times 10^{-8}.f_{cl}[(T_{cl}+273)^4 - (T_r+273)^4] - f_{cl}h_c(T_{cl} - T_a)\} \quad (1)$$

$$PP = 100 - 95e^{-(0.03353PMV^4 + 0.2179PMV^2)} \quad (2)$$

where M is metabolic free energy production, w is external work, Pw is the water pressure, fcl is the ratio of clothed/nude surface area, Tcl is the temperature of clothing surface, hcl is convective transfer coefficient, and Tr is mean radiant temperature. According to ISO 7730 [35], the PMV values are defined in 7 scales from cold to hot, as is shown in Table 1.

Using Equation (1), the PMV values were calculated based on the measured data for air temperature, relative humidity, and mean radiant temperature. Equation (2) has been used to calculate PPD values. The metabolic rate was assumed to be 1.0 for a reading activity or seated persons. The cloths are assumed to be typical summer indoor cloths with 0.5 value according to ISO 7730 [35]. Calculations have been done using CBE Thermal Comfort Tool.

3.1. Climatic Condition

Located in the central part of Iran, Yazd is the historical city that UNESCO has recognized as a World Heritage Site. Made of sun-dried bricks, it is known as "City of Wind catchers" with precious vernacular architecture. With hot-dry summer and cold-dry winter, Yazd is defined as Bwh according to the Koppen-Geiger climate classification with 18.41 ^{o}C as the annual mean air temperature. Daily temperature variation is very high, and precipitations are low in all seasons. So, the main climatic issues are high air temperature, low relative humidity, and increased daily temperature fluctuations. Table 2 shows the average values of climatic parameters

Table 1. Thermal sensitivity values for PMV inde(ISO,2005).

PMV	Thermal	Sensitivity
-3	Cold	
-2	Cool	
-1	Slightly	cool
0	Neutral	
+1	Slightly	warm
+2	Warm	
+3	Hot	

3.2. Case studies

Two residential buildings located in the historic district of Yazd were selected (Rasoulian and Mortaz house). Rasoulian house has two types of sardab with and without a pond, and in Mortaz house, there is a sardab without a pond. Both investigated buildings have two courtyard plans and the same orientation. Elaborated facades, elegant decoration and wooden sash windows, pool and flower beds in the courtyards are the common elements of the selected buildings. In both cases, the ceiling of the sardab was constructed 70 cm above the courtyard level make it possible to use natural daylight and ventilation through small windows.

3.2.1. Rasoulian House: Case A and B

More than a century old, this house is located in the Sahl-ibn Ali district. The building is divided into two parts; both have a courtyard as the focal point. The large part consists of two floors and a basement but on different levels. The southwestern façade has a wide and large “Iwan” and is taller than the other side facades. Sardabs and their connecting spaces occupy a considerable portion of the structure. There is also a corridor that connects the sardabs. There are sardabs with various heights from the courtyard level (0, 70, 120 centimeters). In the Rasoulian house, sardab with a pond is defined as case A and sardab without a pond is case B (Fig. 3). They are located in the corner of the large courtyard at the intersection of southeast and southwest facades.

3.2.2. Mortaz House: Case C

Fig. 4 shows a Mortaz House in Yazd. Located in “Mortazioon” alley, this house has two exterior, and interior parts, and both parts have a separate entrance and courtyard. There is a large “Iwan” on the southwest side of the large courtyard, which is the tallest façade. Only a large part of the house has spaces on the underground level. The sardab in the north side of the courtyard has been defined as case C, a type of sardab with no pond with ceiling 70 centimeters above the courtyard level.

3.3. Experimental Setups

The case studies were examined for the same time, in two consecutive years. Experimental tests and data collections were conducted in July. TES1365 Data logger was used as thermometers and hygrometers, and TES-1339R_Data logger Light Meter collects daylighting data. The temperature and relative humidity sensors have an accuracy of 0.5 ºC and 3% and work in the range from − 20 ºC to +60 ºC and 10 – 95%. With 0.5 ºC of accuracy, a Testo-925 sensor is used to measure MRT. The data loggers have a detachable sensing probe and automatic time recording. Three sets of each instrument were used. The temperature and humidity sensors were installed in the different locations of sardab and outside. One was placed in the outdoor space of the courtyard, and two sets were placed in the sardab space. The three sardab (cellar) were studied in a hot and dry climates during 2013 and 2014.

Table 2. Climatic parameters of Yazd (climate consultant 6.0)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average
Dry bulb temperature (Average Monthly c)	4	7	12	19	25	30	31	30	25	19	12	7	18.41
Relative Humidity (%)	50	42	32	31	22	15	15	17	17	22	37	46	28.83
Ground Temperature (Average monthly of 2.15 m)	11	9	10	12	17	22	26	27	27	24	19	15	18.25

Figure 3. Rasoulian House (Left: case A, Right: case B)

4. Uncertainty Analysis

To estimate the uncertainty of the calculated result based on the uncertainty of the initial measurements, the calculated result of R is a definite function of the independent variables x1, x2, x3, ……, xn as R = f (x1, x2, x3 , ……, xn) is expressed. Assuming that WR is the final uncertainty and x1, x2, x3, ……, xn are the uncertainties of the independent variables, the relationship is presented as follows [36-38]:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{\frac{1}{2}} \quad (3)$$

Where w_1 is the uncertainty of the independent variables (measurement tolerance), and $\frac{\partial R}{\partial x_1}$ is sensitivity.

The measurement errors are temperature measurement, humidity ratio (W), pressure (P), and temperature surface measurement. Therefore, the Predicted Mean Vote (WPMV) uncertainty can be calculated from Equation (4). According to the calculation of uncertainty *h* and *fcl* and the measurement sensors' known error, the value related to the accuracy (error) of the WPPD measurement is determined. Based on the number of relationships and formulas used to calculate the uncertainty in this work, the Predicted Percentage of Dissatisfied (WPPD) uncertainty is calculated from Eq. 5.

$$WPMV = \left[\left(\frac{\partial PMV}{\partial M} wM \right)^2 + \left(\frac{\partial PMV}{\partial W} wW \right)^2 + \left(\frac{\partial PMV}{\partial Pw} wPw \right)^2 + \left(\frac{\partial PMV}{\partial Pa} wPa \right)^2 + \left(\frac{\partial PMV}{\partial Ta} wTa \right)^2 + \left(\frac{\partial PMV}{\partial f_{cl}} wf_{cl} \right)^2 + \left(\frac{\partial PMV}{\partial T_{cl}} wT_{cl} \right)^2 + \left(\frac{\partial PMV}{\partial T_r} wT_r \right)^2 + \left(\frac{\partial PMV}{\partial h} wh \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

$$WPPD = \left[\left(\frac{\partial PPD}{\partial PMV} wPMV \right)^2 \right]^{\frac{1}{2}} \quad (5)$$

5. Results and Discussion

The thermal energy performance of an old building is complex and, in many cases, different from conventional buildings. In the present study, the thermal performance of

Figure 4. Mortaz House, case C

sardab as an underground part of vernacular buildings has been evaluated. At other climatic conditions, the earth is a capacitor to store heat [39]. Depending on the soil's thermal properties, underground buildings benefit the earth's thermal mass to modulate interior temperatures. In hot countries, major electricity consumption is used for indoor cooling [19]. On the other hand, at 6 meters depth, the underground temperature is almost equal to the yearly average temperature. So, using underground spaces could help reduction in electricity usage in hot-dry climates.

In sardab many factors affect the air temperature including, sardab depth, ground surface temperature, outside air condition, and soil humidity. Due to the material-ground seasonal time lag, sardab is a warmer space in winter and cooler in summer compared to the on-ground space. In sardab, the cooling effect of the ground as a material with high thermal mass capacity in combination with water pond and natural ventilation results in a considerable reduction in air temperature and an increase in relative humidity. Figure 5, shows the average monthly ground temperature in Yazd with related time lag and damping at three different depths. The annual mean air temperature is 18.4 ºC. Various parameters of the case studies are defined in Table 3.

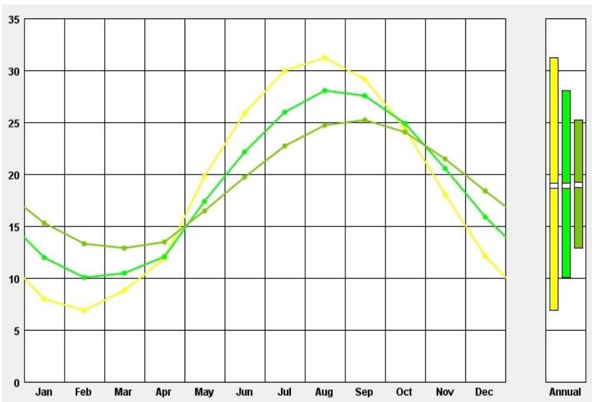


Figure 5. Ground Temperature in Yazd (depth 0.5, 2, 4 meters in yellow, light green, and dark green respectively) (Climate Consultant software)

5.1. Rasoulian House

5.1.1. Case A: sardab with a water pond

In the case of A, sardab is a space that has a water pond and fountain in the center of the place. So, the indoor air is in direct contact with water profited by the evaporative cooling effect. Fig. 7 and 8 show the variation of mean temperature and humidity in case A, sardab with water pond. The air temperature is almost 20 degrees lower than ambient temperature with a 60% difference in relative humidity. This indicates that while the relative humidity is excessively higher than the optimal value, the temperature of this cellar is 2-4 degrees lower than the comfort temperature. However, such a condition is appropriate to preserve food and wine-drinks.

5.1.2. Case B: sardab without water pond

Located in Rasoulian house, case B is similar to case A, but it has no water pond. Illustrated in Fig. 8 and Fig.9, in the two years of investigation, the temperature variation is within 9 to 17 degrees while relative humidity changes were 3 to 20 percent. The temperature in this model of the sardabs that had no direct contact with water was 17 °C lower than the outer space. The moisture of sardabs created an increase of 3-20 percent in the humidity of sardabs compared to the outside space.

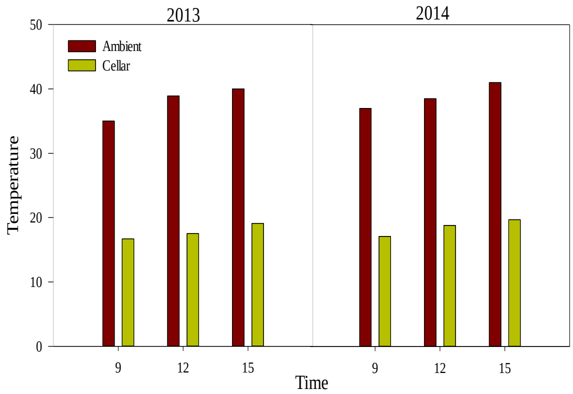


Figure 6. Temperatures variation in case A (sardab with water pond in Rasoulian house)

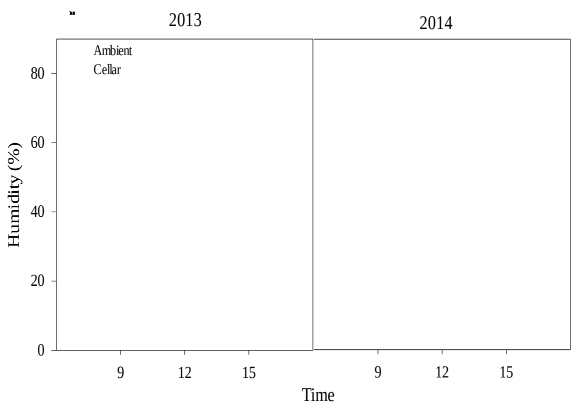


Figure 7. Humidity variations in case A (sardab with water pond in Rasoulian house)

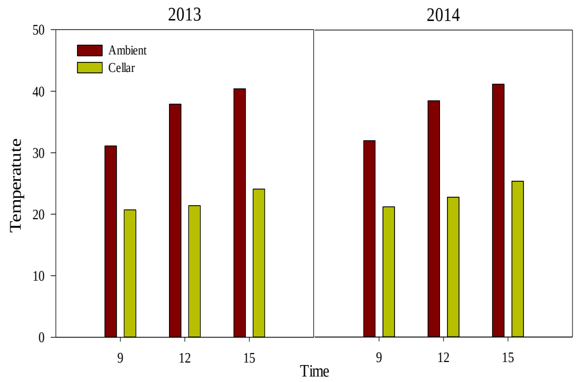


Figure 8. Temperatures variation in Case B (sardab without water pond in Rasoulian house)

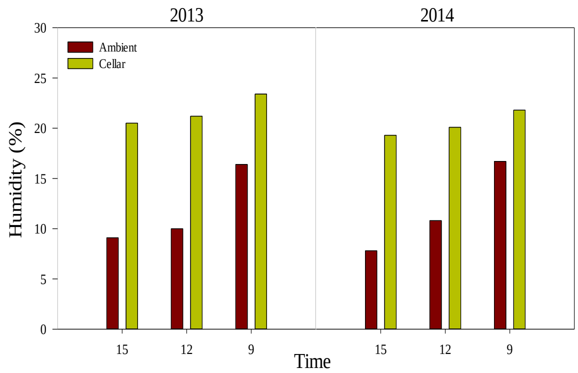


Figure 9. Humidity variations in Case B (sardab without water pond in Rasoulian house)

In the case of B, experimental setups also include light intensity measurement. Since sardab is an underground space, it does not usually provide a sufficient level of daylight. In sardabs with elevated ceilings from the ground, the light of the sardabs is supplied through the clerestory openings which look to the central courtyard. The light illuminance in cellar B, is in the range 55-86 Lux (Fig. 10). It is lower than values defined in (ASHRAE-the international standards) for residential spaces, and so the

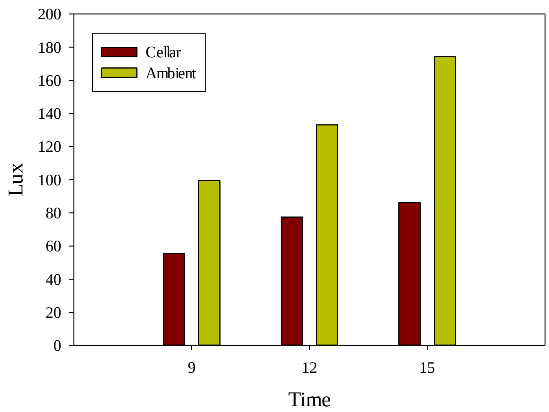
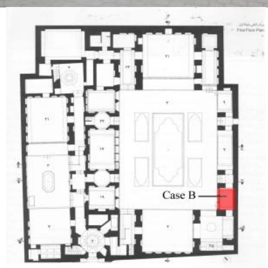
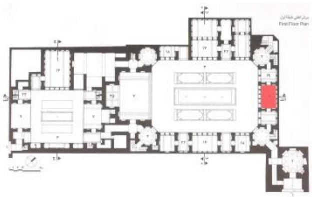


Figure 10. Light illuminance variations in Case B (sardab without water pond in Rasoulian house)

Table 3. Various parameters of the case studies.

Parameter	Case A	Case B	Case C
Location	Rasoulian house	Rasoulian house	Mortaz house
Water Pond	+	-	-
Ceiling level	Entirely under the ground level	70 cm above the ground level	70 cm above the ground level
Size	4*5 (m)	5*8.5 (m)	3.5*5 (m)
Plan shape	Hexagon	Rectangle	Rectangle
Orientation	Southeast	Southeast	Northeast
Image			
Plan			

cellar openings could not provide sufficient daylight. Meanwhile, light illuminance in the upper room is almost double within the range 99-174 Lux.

5.2. Mortaz House: Case C

Case C is a sardab in Mortaz house without a pond. In this case, the environmental variables have been measured in three different places, sardab, a room on the upper floor and, outdoor space. In Fig. 11, air temperatures in these three locations have been compared. Based on the results with outdoor temperature fluctuation from 32 to 41, the air temperature in sardab is 21 to 23 and 24 to 30 in the upper room.

According to the results, the cellar temperature is almost constant at different hours of the day. As shown in Fig. 11, from 9 a.m. to 3 p.m. (the hottest day time), the cellar temperature is 3-10 degrees lower than the air temperature in the upper room and 11-17 degrees lower than ambient temperature. At 9 a.m., air relative humidity in the cellar is about the same as in the upper room and courtyard. On the contrary, from 12 p.m. to 3 p.m. the air in the basement is much more humid, and the difference reaches 12 percent (Fig. 12).

5.3.Thermal comfort in sardab

Using measured data, the mentioned Equations, and preset assumptions, PMV, and PPD values are calculated using the CBE thermal comfort tool. Figure 13 shows the values of PMV and PPD in all three cases.

According to Figures 13-a and -b, the PMV index of the cases is not in the comfortable range of -1 to +1 most of the time. In the case of A, the PMV values vary from -0.83 to +0.59, while PMV values of the outdoor are above +1 from +2.94 to +5.04. So despite the hot sensation outdoor with 100 for PPD value, in sardab case A, the sensation is slightly cool or cool with PPD values from 12 to 67. In the case of B, the outdoor PMV values vary from +1.47 to +5.11 with the sensation of hot, slightly warm, and warm. In sardab case B, the PMV values are from -0.98 to +0.13, and the sensations are one step cooler than the outside sensing Neutral, slightly cool, and slightly warm. While the outside PPD values range from 49 to 100, they vary from 5 to 25 in sardab case B. In the case of C, the PMV values vary from -0.15 to +2.06, while PMV values of the outdoor are from +2.94 to +5.04. Despite hot, and warm sensation outdoor, in sardab case C, the sensation is slightly cool, neutral, slightly warm, and warm with PPD values from 5 to 79. So, in all cases, although the PMV values are not in the range specified by ISO7730, they are

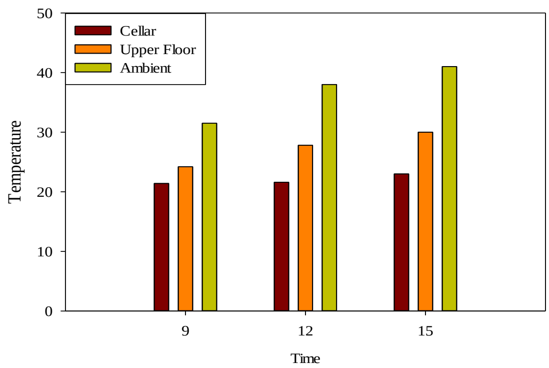


Figure 11. Temperatures variation in Case C (sardab without water pond in Mortaz House)

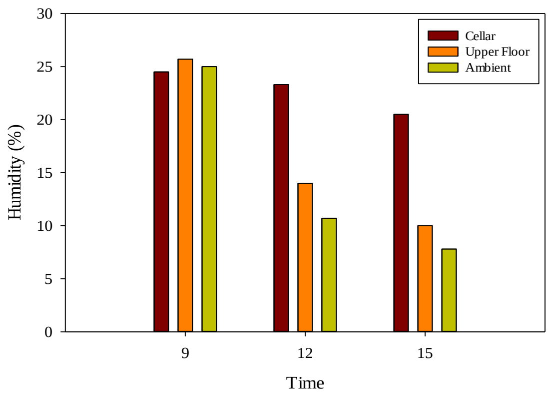


Figure 12. Humidity variation in Case C (sardab without water pond in Mortaz House)

lower than outdoor PMV values. The lowest PMV of the sardabs is in case A at 9:00, and the highest is in B at 15:00.

In figure 14, the psychometric chart of Yazd has been illustrated for adaptive thermal comfort. According to ASHRAE standard 55-2010, the adaptive thermal comfort model could be used in naturally ventilated spaces. Compared to the buildings with centralized HVAC systems, such spaces with no mechanical cooling system have a wider comfort range. Considering this, it is reasonable that the PMV values of sardabs are in different ranges and still providing thermal comfort. In figure 14, the average monthly value of measured data is also presented for two kinds of sardabs (with and without the pond). As it is shown, the values for sardab with pond are in the comfort zone. While the temperatures in sardab B (without the pond) are lower than sardab A, the humidity values are much higher, resulting in the comfort zone's thermal condition. Selecting numbers 2, 3, 4, and 5 strategies, 46 percent is comfortable in a year. The selected strategies are the ones that spaces such as sardab could provide.

The heat transfer in the underground buildings can be described using thermodynamic principles. The heat slowly soaks into the soil from the soil surface and diminishes soil temperature fluctuations at 6 m depth. In such depth, soil temperature equals the annual average air temperature. Hence the summer temperature of an underground building is lower than the above-ground building temperature and ambient temperature and vise versa for the winter temperature. In other words, the earth provides constant temperature as a heat capacitor, which absorbs heat during summer and released heat during winter. Therefore as the depth of the building increases, thermal comfort is enhanced. In the annual heat storage concept, the surrounding earth's heat capacity helps to provide the underground building more comfortable.

Contact surface area of building with the earth and the building depth into the earth play a key role in heat transfer. As the contact surface or the depth of the building increases, the indoor temperature fluctuation reduces. Other factors that affect temperature fluctuation are the soil thermal conductivity depending on the soil type,

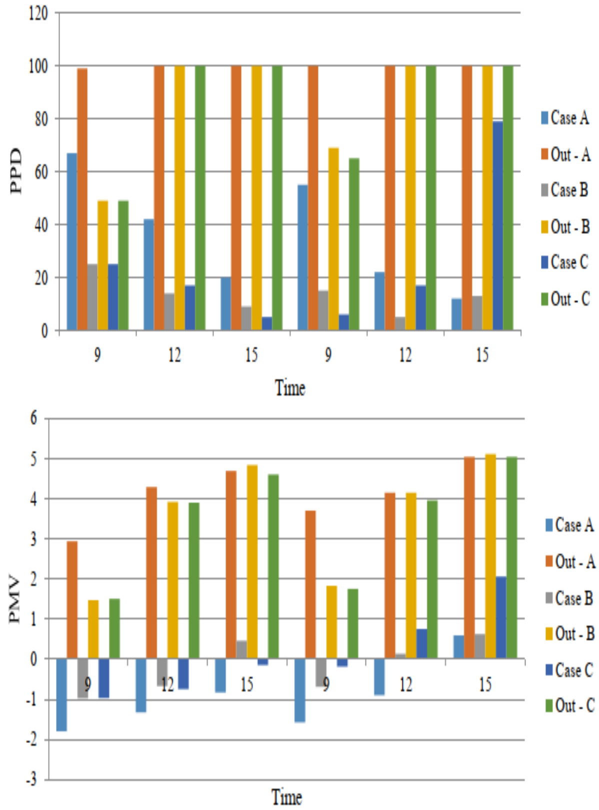


Figure 13. Thermal comfort values in case A, B, and C, (13-a): PPD, and (13-b): PMV

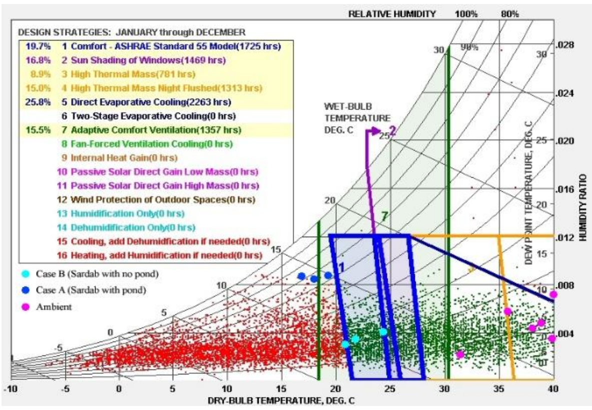


Figure 14 . Mean thermal condition of cases in psychometric chart of Yazd, case A, B in the middle up and middle and in the right corner is the ambient (climate consultant software)

thermal diffusivity, and moisture content. On the other hand, there is no exterior façade exposed to solar radiation and ambient temperature. The underground buildings or spaces such as sardab offer better indoor conditions compared to an above-ground building.

5.4. Effect of depth on thermal comfort in Sardab

As expected, the results show distinct characteristics of sardab compared to conventional above-ground buildings. Since in the vernacular architecture of Yazd, sardabs had been built with ceilings at different levels, the effect of sardab's depth on thermal comfort is also evaluated. The

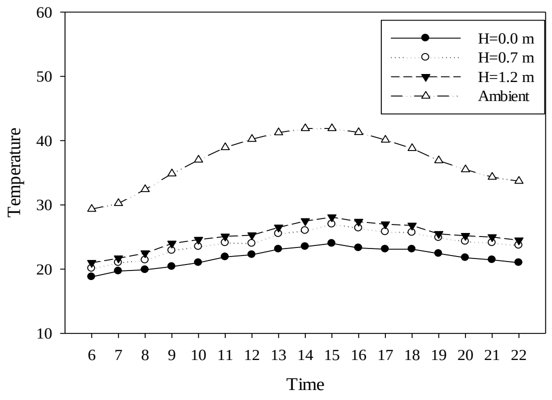


Figure 15. Diurnal temperatures in Sardabs with various heights from courtyard level (0, 70, 120 centimeters)

height of the sardab ceiling from the courtyard level makes it possible to take advantage of clerestory windows. Such windows are the only apertures to direct daylight into space. Besides, they improve indoor air quality and natural ventilation by facilitating the circulation of airflow.

Having no daylight, sardabs entirely located under the ground (H=0) were usually used to preserve foods and drinks. In the Rasoulian house, there are sardabs with different ceiling heights. To study the effect of sardab's depth on the thermal condition, case studies of sardabs are selected with three different heights (0, 70, and 120 centimeters). Figure 15, shows the daily temperature variation of the three cases chosen in July. As it is shown, the least temperature relates to *sardab* with no height. In two other sardabs the average air temperature is 2-3 degrees higher. Although the temperatures of all three sardabs are within thermal comfort boundaries, in a few hours of the day sardab with no height is slightly cool. So, considering thermal comfort zone, daylight, and natural ventilation, sardabs with elevated ceilings have a better condition, either thermal or visual.

Conclusion

As the first step to revitalize vernacular buildings, this article aims to evaluate the thermal condition in two types of sardab (cellar) in several vernacular architecture landmarks in Yazd, Iran. Based on the experimental results, in hot and dry climates where the best climatic strategies are thermal mass cooling and evaporative cooling, using sardab is a proper design solution. The experimental results show that in Case A, sardab with pond, the average air temperature is 20 degrees lower than the outside temperature in the courtyard. While the air relative humidity reaches 60 percent, it is 40-50 percent higher than the corresponding value in the courtyard. In Cases, B and C, sardabs without a pond, the average air temperature is 20 degrees lower than the courtyard temperature, and the relative humidity is almost 7 to 24 percent higher. The thermal condition was studied in sardabs with various ceiling heights (0, 70, and 120 centimeters). Based on the results, the light illuminance level in cellar B is in the range of 55-86 Lux, while it is in the range of 99-174 Lux, in the upper room. Considering thermal comfort zone, daylight, and natural ventilation, sardabs with elevated ceilings have better conditions in both thermal and visual aspects.

The average monthly value of measured data for two kinds of sardabs (with and without the pond) is presented in the psychrometric chart. The values for sardab without a pond, Case B, are within the thermal comfort zone while values for Case A are plotted in the parts with a relative humidity higher than 60 percent. Although thermal condition in both Cases is much better than the ambient, high air relative humidity in Case A is not desirable. This indicates that Case A with lower air temperatures is a better space for food storage. While Case A is more convenient for a short time, the thermal condition in Case B is preferred for long-term use. The lowest PMV of the sardabs is in Case A at 9:00, and the highest is in Case B at 15:00. Based on the results, Sardab has preferable thermal conditions compare to outdoor, which makes it a useful space as a café or restaurant while is not suitable for galleries and museums due to high air humidity and insufficient daylight illuminance. Also, in hot and dry climates, the application of both types of Sardab, either with or without a pond, would improve thermal comfort and building energy efficiency.

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