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Research paper

Assessing indoor thermal comfort of rock-cut architecture in Meymand world heritage site during winter and summer

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ABSTRACT

Rock-cut architecture is among the unique types of ancient architecture in Iran, which creates human living space by excavating the stone mass in the rocks. The rock-cut architecture benefits from utilization of the temperature of the groundmass in cold and hot weather by penetrating its heart. The World Heritage Site of rock-cut architecture in Meymand with more than 360 architectural units is considered as an evolved and appropriate example of such architecture in the semi-hot and dry foothill climate of Iran. The present study aims to determine indoor thermal comfort level of some buildings in the site as mentioned earlier to measure their fitness to climatic conditions of the area without energy consumption. To this aim, Predicted Mean Vote (PMV) index was determined for four selected buildings through the indoor bioclimatic monitoring, as well as calculating the level of the above-mentioned index during December–February and June–August. Then, the ASHRAE standard questionnaire was prepared to evaluate and compare the comfort sensation feedback of the occupants in the aforementioned buildings with indoor PMV calculation results. The results indicated that the average indoor PMV during the winter and summer equaled -2.17 and -1.07 with a cold and cool sensation, respectively, which is in line with those of the questionnaire in which most occupants reported a neutral and cold sensation during the winter and a cool one during the summer. In addition, calculation of the percentage of proximity to the comfort zone for indoor environment of the above-mentioned buildings showed they are closer to comfort by 22% and 36%, during the winter and summer, respectively Finally, the results indicated the rock-cut architectural buildings had provided conditions by applying the high thickness of their architectural layers, low heat exchange coefficient of the walls, and temperature of the groundmass, which they are in the comfort zone without energy consumption in summer and provide living conditions with minimal energy consumption in winter.

1. Introduction

A large number of studies have been conducted on energy consumption in buildings due to the obstacles created by lack of energy and an increase in demand during recent years (Santamouris and Vasilakopoulou, 2021). Examining the thermal behavior and environmental comfort in different buildings is among the research fields which can be effective in making decisions for design of passive energy buildings in the future (De Dear et al., 2013). Different types of architectural heritage include various examples of buildings with proper thermal behavior and energy consumption (Martínez-Molina et al., 2016) which can be appropriate models for studying in this field. Native architecture in any climate is among the types of architectural heritage which is formed based on the needs, available materials, and standard techniques in a specific geographical area (Widera, 2021). Different types of such architecture have evolved over time according to the climatic conditions and facilities in their place (Gil-Crespo, 2014; (John) Zhai and Previtali, 2010). Rock-cut architecture is among the types of native architecture, which is created by excavating a physical space inside a stone mass or dense soil (Mangeli et al., 2018). The rate of heat exchange in such buildings is regarded as low due to thickness of their bed mass and thermal behavior of

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the mass forming their bed (Givoni, 1981; Agan, 2011), which can be explored more as a model.

The strategies related on the aforementioned architecture to create comfortable living conditions include the use of groundmass heating, protection from sunlight and wind, and shape of entrances (Canas and Martín, 2004; Zhao et al., 2020), utilizing the experience of which, along with evaluating human and economic conditions results in achieving the standards for designing such new rock-cut and passive energy buildings (Gil-Crespo, 2014; (John) Zhai and Previtali, 2010). Applying the passive heating and cooling system through the groundmass and thermal phase of material is considered as the essential instrument of such architecture to create thermal comfort (Ghaedi, 2020; Fabbri and Pretelli, 2014), which has attracted much attention. The settlement material and selected stone for the excavation of these buildings are usually pyroclastic deposits, especially tuff and pumice which have high thermal capacity and nowadays are used as phase change materials (Sarıand Tyagi, 2020; Koçyigit et al., 2016; Ascione et al., 2019). However, investigating the indoor thermal comfort indices in the form of field analysis in rock-cut buildings has received less attention (Anselm, 2008; Yu et al., 2020). Martinez-Molina et al. (2022) reviewed the thermal comfort of religious stone buildings in a humid climate during the winter. To this aim, indices such as Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) was compared by assessing the thermal comfort data taken from inside the building and users' questionnaire, as well as measuring the relationship between thermal comfort and indoor environmental condition. Using modern thermal comfort standards such as ASHRAE (Martínez-Molina et al., 2016; Ascione et al., 2019; Anselm, 2008) is regarded as common criterion to measure the level of comfort for historical monument users (Vázquez-Torres et al., 2022). In addition, analysis instruments such as CBE provide the researchers with sufficient facilities for calculating the environmental comfort indices inside the buildings based on ASHRAE (Tartarini et al., 2020). Understanding the thermal comfort behavior of historical buildings introduces indices and instruments to reduce energy consumption, as well as playing a critical role in making decisions for their future in the process of protection and revitalization (Martinez-Molina et al., 2022). Comparing the thermal comfort indices such as PMV and TSV with each other in historical buildings can be considered as an appropriate method to judge their comfort level (Alkaff et al., 2016; Vázquez-Torres et al., 2022). Discussing the compliance of actual conditions related on thermal behavior in historical buildings with thermal comfort sensation (Li et al., 2017) leads to a more detailed knowledge of such buildings and elements involved in creating comfortable conditions (Koçyigit et al., 2016; Tartarini et al., 2020) to be utilized in future decisions for architecture and architectural protection to reduce energy consumption. Analyzing the thermal behavior and comfort of the occupants helps document and assess the historical buildings considering their long life and possibility of their changes or destruction (Xiong et al., 2021). Studies related on thermal behavior and comfort in rock-cut buildings can be divided into three categories. Most of the studies have focused on simulating the thermal performance of the above-mentioned buildings (Review, 2021), another group evaluates the architectural elements related on their climatic conditions qualitatively (Rostam et al., 2014; Xiong et al., 2021), and some others examine their thermal comfort (Alkaff et al., 2016). In addition, Zhu et al. (2020) evaluated the passive architectural strategies of the aforementioned buildings in creating environmental comfort in a combined quantitative and qualitative study on analyzing the thermal behavior of underground residential caves in China. To this aim, monitoring of temperature conditions were modeled, along with recognizing the strategies such as building orientation, constituent layers, building materials, semi-open space, and water use, as well as their annual temperature and humidity conditions, indicating that both quantitative and quantitative studies were consistent with each other. Based on the results, such strategies help create environmental comfort in such buildings and can still be applied in new ones. Further, Xiong et al. (2021) studied a 2000-year-old underground rock-cut tomb in China in computational fluid dynamics modeling they found that the rate of changes equaled 10 °C (temperature) and 20% (relative humidity) during 0.3 h when the tomb was open, while such rate was extremely low when the building was closed. The results were congruent with each other, indicating that the temperature and humidity changes during the opening of the buildings can affect the protection of their indoor works. The closure of underground buildings is regarded as a critical principle in controlling their environmental conditions. Similar cases are revealed in terms of selected subject matter by reviewing the available sources. The climate and comfort studies of earth-sheltered and underground buildings are among the closest cases to the subject. Most of the above-mentioned studies which are close to each other in terms of method, type of selected building, type of data extracted from field studies, and approach focus on the deficiencies in analyzing the thermal comfort in rock-cut and underground buildings (Koçyigit et al., 2016; Anselm, 2008). Few studies have been conducted on the thermal comfort of architectural heritage buildings during the winter (Martinez-Molina et al., 2022). Most of the studies have focused on the thermal behavior modeling and mathematical calculations of thermal performance in such buildings (Yu et al., 2020). The indoor thermal comfort of such buildings is studied by modeling the related software. However, the level of thermal comfort and satisfaction of their occupants have not been questioned in the field to check the actual compliance of their comfort conditions with the conditions extracted from thermal comfort measurement software based on real data. In other words, a study based on integrating the quantitative and qualitative methods can assess the actual conditions of satisfaction and the indoor thermal comfort in such buildings more accurately.

Thermal comfort indices are divided into two general categories including experimental and analytical (Walls et al., 2015), which are based on the energy balance between humans and environment. In fact, factors such as spatial diversity, climatic conditions, and human experiences play a critical role in this regard (Bruse, 2009). A correlation of about 89% is observed between the PMV index and perception of thermal comfort by people (Monteiro and Alucci, 2009). PMV is considered as appropriate for evaluating environments with stable conditions, whose parameters do not fluctuate significantly, and those with temperatures between 10–35 °C (Ole Fanger and Toftum, 2002). In addition, the PMV is regarded as appropriate for calculating the temperature sensation numerically, which assesses human and environmental factors together (Andersen et al., 2009; Fanger, 1986), can be measured during natural ventilation and in the condition of using the heating, ventilation, and air conditioning (HVAC) system (Enescu, 2017), and is mostly utilized to evaluate the thermal comfort of the indoor spaces (Enescu, 2017).

The PMV index is not calculated as one of the standard criteria for examining the thermal comfort level in rock-cut buildings. The PMV can be compared with the level of satisfaction among the occupants based on the ASHRAE standard after calculation in some of the aforementioned buildings and can investigate whether the data reported by the indices and models about the indoor thermal comfort conditions of earth-sheltered buildings are in line with the comfort mentality of their occupants. This study seeks to determine the indoor temperature comfort range of rock-cut architectural buildings in Meymand site during the winter

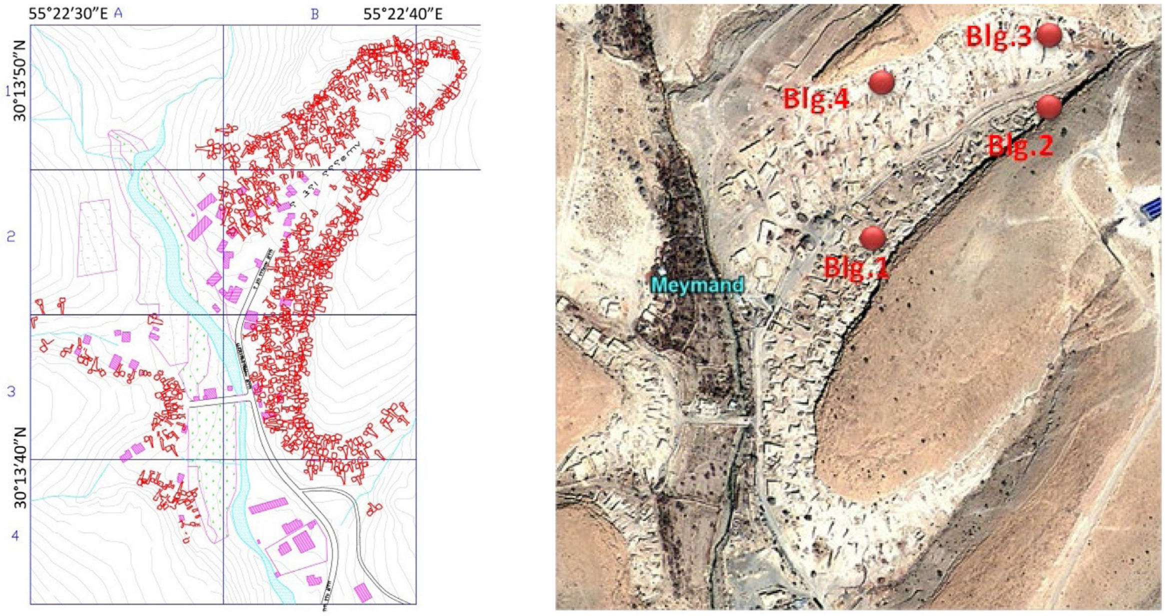

Fig. 1. Meymand general map and selected building location.

and summer applying climatic data collected from their inside to assess the PMV index and comparing the results with their occupants' opinions. To this aim, the CBE and PMV are used to calculate the indoor comfort range of the buildings and the results are acquired from their occupants' opinions regarding satisfaction with the thermal comfort conditions in Meymand buildings by utilizing a questionnaire in accordance with ASHRAE. Based on the results, the calculated thermal comfort corresponds to the satisfaction level of the occupants. The results can be applied in decision-making for restoring such architectural heritage and their protection during exploitation, resulting in formulating the criteria for selecting the installation system appropriate for their new use in order to be utilized in the future to reduce energy consumption. Few studies have been conducted in the field of thermal comfort in the case of Meymand, and those conducted were based on simulating the thermal behavior of buildings (Khaksar et al., 2022) and determining the sub-climatic patterns (Moradinasab and Khaksar, 2021). None of the above-mentioned studies compared the thermal comfort of the aforementioned buildings during the winter and summer. In addition, no study has been conducted in the above-mentioned field. Further, no study has investigated and compared the thermal comfort feedback of the occupants with existing conditions of the buildings. The present study aims to measure the PMV of the buildings with their occupants' sense of comfort applying real data obtained from field study during the winter and summer in which buildings need the most energy consumption to reach the level of thermal comfort required for human life in order to determine the appropriateness of such buildings for life without energy consumption. No study has been conducted so far through which some models can be achieved for modern sustainable architecture in the future. The design patterns related on four buildings selected for study have been used repeatedly among the 360 architectural units in Meymand and the acquired results can be generalized to their general behavior in the aforementioned architectural site. The pattern of sustainable design for new rock-cut architecture and revival of such buildings in accordance with modern life can be obtained even by further studying the components of such architecture which results from more than 2000 years of experience in this field.

2. Methodology

2.1. Case description

The rock-cut village of Meymand is considered as the largest architectural site in Iran with more than 2000 years old (Ashrafi, 2022). Meymand which was registered in the UNESCO World Cultural Heritage List during 2015 includes a collection with more than 360 rock-cut architectural units, which were excavated on the hillsides of igneous pyroclastic sediments containing tuff and pumice at an altitude of 2250 m above sea level (Kiani et al., 2022). Meymand is located at 30°15′ north and 55°22′ east near Shahre babak in Kerman province in the center of Iran (Fig. 1). The general climate of Meymand region is regarded as semi-desert foothills according to Köppen climate zoning (Kottek et al., 2006). The above-mentioned climate zone has limited vegetation, intense sunlight, and a large temperature difference between day and night due to low rainfall and relative humidity, leading to severe and biting winter colds and dry summers with high temperatures, which make living conditions difficult. The average rainfall in Meymand which experiences cold winters, as well as hot and dry summers equals 220 mm per year. All of the original buildings in the aforementioned site have been excavated with primitive instruments inside the solid masses, resulting in forming a kind of organic architecture (Taher Tolou Del et al., 2022) commensurate with the climate and living conditions of their occupants (Goudini, 2020). A traditional method of living is still observed in some of the houses in this village (Mangeli et al., 2022).

A combined approach of quantitative (analyzing the state of the thermal comfort level inside rock-cut buildings) and qualitative method (applying a questionnaire to measure the satisfaction level of thermal comfort among the occupants) was utilized. The data used in analyze the thermal comfort were collected weekly during the winter (December–February) and summer (June–August) in order to study the behavioral state in severe hot and cold conditions. The data were collected from inside the buildings while they were empty and free from heating and cooling facilities. Then, a questionnaire was prepared from

Table 1
Selected buildings properties.

Building name	Depth (m)	With (m)	Height (m)	Altitude (m)	Door area (m^2)	Outside wall thickness (m)	Inside wall thickness (m)	Roof thickness (m)	Area (m^2)	Orientation	Shading (m)
Bldg.01 *(Kicheh qasemi)*	8.5	4.3	2.1	2237.5	0.95	0.95	1.07	1.2	35.5	−50	3.3
Bldg.02 *(Kicheh zeynadini)*	11.5	6.1	2	2265	1.76	1.6	0.9	4	70.1	−10	1.1
Bldg..03 *(Kicheh bibi zeynadini)*	10.2	6	2	2267	1.4	1.2	1.3	3.5	34.2	+180	2.3
Bldg.04 *(Kicheh ebrahimi)*	5.7	4.8	1.9	2252.5	1.6	0.7	0.7	0.7	23.8	−10	0.5

people with a history of living in evaluated or similar buildings. The users of the spaces utilized the buildings for more than five years and were selected among the educated people. Finally, the information obtained from quantitative and qualitative analysis was compared.

2.2. Selected buildings

The selected buildings include four residential units in four different parts of the village on both sides of the central valley. In addition, two units are excavated in the stone wall of the vertical rock and the other two on the sloping surface of the hill. The units excavated in the vertical surface are connected to the outside directly with a shallow semi-open space, while those dug in the inclined surface have a larger semi-*open* space and are connected to the outside by trench. The trenches which are called *"Kicheh"* in the local term represent a residential unit (Table 1) (Fig. 1).

The walls of the spaces are excavated in the stone bed with high thicknesses. In addition, the minimum thickness equals at least 50 cm in the door and separator wall. The thickness of the stone mass equals more than 70 cm on average in areas such as roofs. The entrance doors, the frame of which is made of wood, are 5 cm thick with an average area of 1.04 m^2. The floors of the rooms are made of the same monolithic material as the base stone of the building, which are about 40 cm lower than the semi-open and outside space on average. All Meymand's buildings have not any cooling HVAC equipment and without energy consumption, they are in the comfort zone in summer and their heating system in the past was provided by burning charcoal in the stove of each room, which is less applied today or replaced by oil heaters with 1500–2500 (Kcal/h) heat production capacity. All of the walls and layers in the buildings, except for the entrance doors, are made of monolithic pyroclastic stone masses with a density of 650–1250 kg/m^3 and a heat transfer coefficient of 0.4–0.17 (w/m^2 k) (Koçyigit et al., 2016).

2.3. Environmental monitoring

As shown in Table 2, four temperature and humidity measuring instruments are installed in four rooms at four different buildings indicated in the previous section and the data are collected simultaneously. The instruments are installed in the last 1/3 of the rooms at a height of 110 cm from the floor at a distance of 1 m from the internal walls and 2 m from the surface walls on which the entrance is located in accordance with the ASHRAE standard (Fig. 2) (Turner et al., 2008). In addition, one instrument is installed in the open space to measure the climatic data outside the buildings. The selected buildings are uninhabited and free from cooling and heating systems during data recording to investigate the pure conditions of their thermal conditions in cold and hot seasons. The data of the above-mentioned instruments are collected at three-hour intervals, once every seven days during December 2021–February 2022 and June–August 2022 in cold and hot seasons. Wind speed data are obtained from the local meteorological station. The average air temperature and relative humidity inside and outside the rooms are indicated daily and monthly (Tables 3 and 4).

2.4. Questionnaire

In order to strengthen the results achieved from the assessment of thermal comfort conditions in Meymand buildings, a questionnaire was designed in accordance with the ASHRAE standard (Turner et al., 2008; Rupp et al., 2022). The respondents ($N = 35$) included people who lived in selected and similar buildings in Meymand for a long time with education ranging from diploma to doctorate. In addition, eight people were among the local occupants and specialists in historical monuments working in Meymand World Heritage Site. It is worth noting that the informed people who lived in Meymand for some time could not be accessed easily to collect and complete the questionnaire data due to demographic conditions and the decrease of the population living in this village, resulting in selecting only 35 people to fill the questionnaire. The population of native people residing in Meymand decreased to less than 100 people due to migration. The questions designed according to the information needed to measure PMV asked the following questions (Turner et al., 2008).

- Age, sex, height, weight, and education
- Average years of residence in the building
- Selecting the places in the buildings with the most comfort or lack of thermal comfort during the winter and summer
- Type of clothing during the winter and summer
- Predominant type of daily physical activity inside the building (lying down, sitting, sitting with little physical activity, standing with light physical activity, standing with moderate activity, high activity) to calculate the metabolic rate
- Overall satisfaction level of thermal comfort during the winter and summer based on the spectrum (extremely uncomfortable, uncomfortable, slightly uncomfortable, average and neutral, relatively comfortable, comfortable, extremely comfortable)
- Overall level of dissatisfaction with environmental comfort conditions during the winter and summer based on the spectrum (always cold, often cold, rarely cold, neutral, rarely hot, often hot, extremely hot)
- Selecting the most comfortable time during the day in cold and hot seasons (6–11 am, 11–2 pm, 2–6 pm, 6–12 pm, 24–6 am, always)

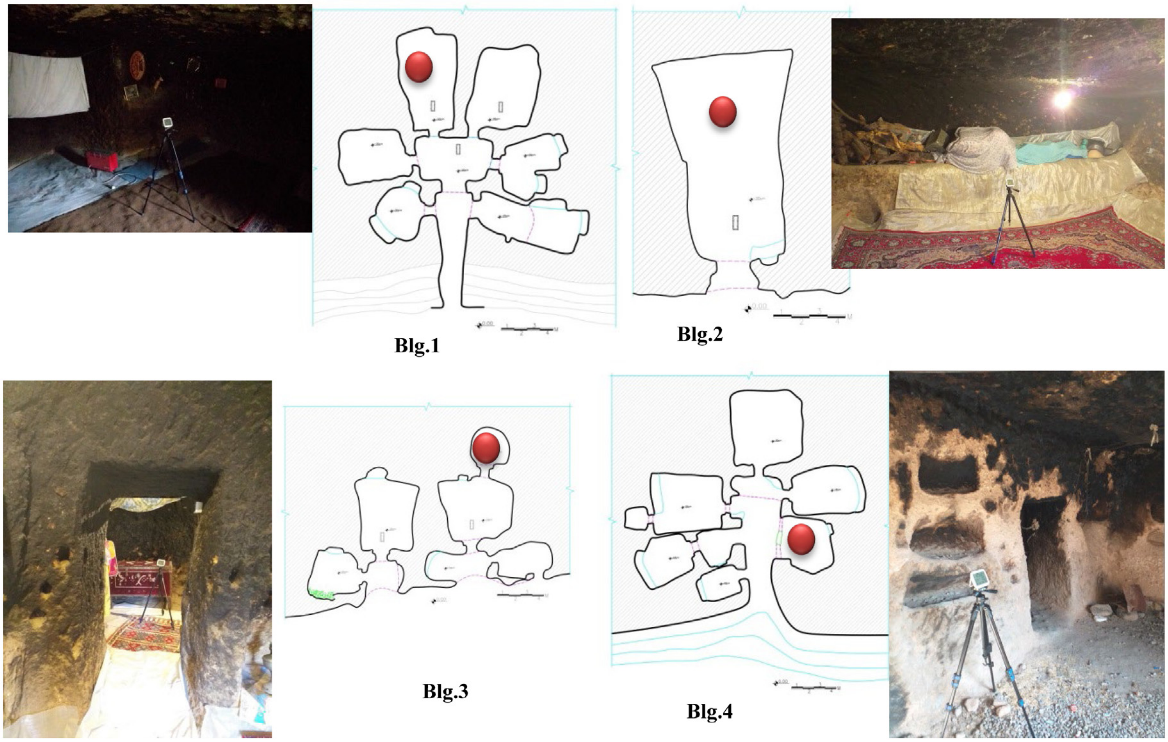

Fig. 2. Buildings plans and monitoring device installation places.

Table 2
Monitoring device product specifications.

Measured variables	Brand and model	Measuring range	Precision	Error degree
Indoor air temperature	Brisk HT33	−10° to 50 °C	±0.1 °C	±1 °C
Indoor relative humidity	Brisk HT33	10% to 99%	±1%	±5%
Outdoor air temperature	Brisk HT33	−10° to 50 °C	±0.1 °C	±1 °C
Outdoor relative humidity	Brisk HT33	10% to 99%	±1%	±5%

Table 3
The average of daily outdoor and indoor temperature in buildings.

Date	Bldg.01 (°C)	Bldg.02 (°C)	Bldg.03 (°C)	Bldg.04 (°C)	Indoor average (°C)	Outdoor average (°C)
19 Dec	11.75	11.13	17.12	10.30	12.57	0.32
26 Dec	11.35	10.50	16.75	10.02	12.10	−2.80
02 Jan	11.17	10.55	16.77	9.80	12.07	−1.62
09 Jan	11.25	10.65	17.00	9.95	12.21	−1.10
16 Jan	11.20	10.97	17.35	10.10	12.40	−2.40
26 Jan	11.55	10.47	17.00	9.92	12.23	−1.15
06 Feb	11.85	10.85	17.15	10.12	12.49	−1.22
Winter average	11.44	10.72	17.02	10.03	12.31	−1.42
27 June	17.96	21.16	20.36	27.60	21.77	30.33
05 July	18.16	22.17	20.56	28.00	22.22	31.66
12 July	18.60	21.80	21.25	27.60	22.31	33.50
19 July	17.80	22.72	20.71	28.00	22.30	35.50
26 July	17.55	23.10	20.90	27.50	22.26	32.00
01 Aug	18.10	23.30	21.50	27.50	22.60	34.00
08 Aug	17.90	23.50	21.20	28.10	22.67	34.20
Summer average	18.01	22.53	20.92	27.75	22.30	33.02

Table 4
Indoor and outdoor measured data averages in winter and summer.

Month	Indoor		Outdoor		
	Air temperature (°C)	Relative humidity (%)	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)
Dec 2021	12.36	45.83	−1.24	67.86	1.14
Jan 2022	12.23	40.24	−1.56	53.06	2.40
Feb 2022	12.49	34.81	−1.22	38.87	1.48
Jun 2022	21.77	27.61	30.33	22.85	3
Jul 2022	22.28	26.74	33.16	19.62	3.99
Aug 2022	22.63	28.72	34.10	17.96	2.39

Table 5
Respondents general info.

Sex	Age	Height (cm)	Weight (kg)	Education			
				PhD	Master	Bachelor	Diploma
Female	41.05	166.4	64.4	2	6	5	2
Male	43.26	180.53	80.8	2	5	9	4
Final	42	172.45	71.12	4	11	14	6

Table 6
Clothing rate (clo) and metabolic rate according to ASHRAE 55.

Sex	Clothing in winter (% of cases)		Clothing in summer (% of cases)		Activity (metabolic rate) (% of cases)		
	Jacket (clo = 0.96)	Coat (clo = 1)	Long sleeve shirt (clo = 0.5)	t-shirt (clo = 0.36)	Seated (met = 1)	Light activity seated (met = 1.2)	Light activity stand (met = 1.4)
Female	66.67	33.33	100	0	45	35	20
Male	75	25	53.33	46.67	26.67	60	13.33
General	71.43	28.57	80	20	37.14	45.71	17.14

- Selecting the reasons for not feeling comfortable and discomfort during the winter and summer

The average age for women and men is 41 and a little more than 43 years, respectively. The average age of the above-mentioned people is calculated to be 42 years. In addition, the overall average height and weight for the aforementioned people are 172.45 cm and 71.12 kg, respectively. The respondents' education include PhD (N = 4), MA (N = 11), BA (N = 14), and diploma (N = 6) (Table 5). The respondents mainly wear a jacket with clo = 0.96 (71.43%) and a coat with clo = 1 (28.57%) while residing in the buildings during the winter. All of the women wear long-sleeve shirts with clo = 0.5, while men wear long-sleeved shirts (53.33%) and t-shirts with clo = 0.36 (46.67%) during the summer (Table 6). In addition, all the respondents live in such buildings for more than 4 years and their main physical activity includes sitting or standing with quiet activity while residing in the buildings during the winter and summer.

The overall level of thermal comfort indicated by the respondents in terms of percentage and number during the winter is as follows. Based on the results, 40% of women (N = 8) and 53.33% of men (N = 8) report neutral temperature feeling. In addition, 20% of the respondents including women (N = 4) and men (N = 3) feel a little cool. Further, 15% of the respondents including women (N = 3) and men (N = 2) feel a little warm. Furthermore, 20 (N = 4) and 13.33% (N = 2) of men feel cold and 5% (N = 1) of women report feeling extremely cold. Finally, 30% of women (N = 6) and 20% of men (N = 3) select a neutral feeling and 70% of women (N = 14) and 80% of men (N = 12) report a slightly cool feeling during the summer (Fig. 3). The overall level of thermal satisfaction indicated by the respondents inside the buildings in terms of the percentage and number during the winter is follows. Based on the results, 60% of women (N = 12) and 73.33% of men (N = 11) feel slightly satisfied. In addition, 0% of women (N = 0) and 6.66% of men (N = 1) feel satisfied. Further, 30% of women (N = 6) and 13.33% of men (N = 2) express an average feeling. Furthermore, 10% of women (N = 2) and 6.66% of men (N = 1) express a slight feeling of dissatisfaction. Finally, 35% of women (N = 7) and 33.33% of men (N = 5) feel high satisfaction, 45% of women (N = 9) and 60% of men (N = 9) report satisfaction, and 15% of women (N = 3) and 6.6% of men (N = 1) indicate little satisfaction during the summer. Only 5% of women (N = 1) report an average feeling (Fig. 3)

2.5. CBE analysis tool for indoor PMV measurement

CBE, which is considered as a thermal comfort calculation and visualization tool developed by Berkeley University based on ASHRAE 55-2017, ISO 7730-2017, and EN 16798:1-2019 standards, is used here. The above-mentioned tool is utilized by more than 49,000 users annually in various fields. The inputs of CBE, which calculates PMV, Predicted Percentage of Dissatisfied (PPD), sensation, and set in different standards, include temperature, humidity, air flow speed, metabolic rate, and clothing type (Tartarini et al., 2020). CBE was developed to calculate the indoor thermal comfort of the buildings and this tool has been used in new studies (Martinez-Molina et al., 2022; Foroozesh et al., 2022; Chen et al., 2022; Wong et al., 2023) and was applied to analyze the PMV level inside the studied buildings using the climate data collected in the four selected buildings during the winter and summer.

2.6. Rayman analysis instrument to measure external PMV

In order to analyze thermal comfort and calculate PMV in the outdoor environment, its parameters should be studied. Calculating the parameters which are intended to check the PMV includes the Sky View Factor (SVF), apart from those related to the indoor environment including the type of activity and cloth, wind speed, temperature, and relative humidity. RayMan software was utilized to calculate SVF and PMV in the outdoor environment (Fröhlich et al., 2019; Matzarakis et al., 2007).

3. Results

3.1. General assessment of temperature and humidity

Figs. 4 and 5 show the average temperature and relative humidity of the indoor and outdoor spaces measured data during the winter and summer three-hour intervals, once every seven days during December 2021-February 2022 and June-August 2022 in cold and hot seasons. The average measured the indoor temperature in Meymand buildings during the winter is almost uniform and constant (12.29 °C) (SD = 2.82), while the outdoor one in the same time period equals −0.82 °C on average (SD = 3.77). In addition, the relative humidity inside and outside the buildings during the same season equals 40.97 (SD = 4.49) and 55.03% (SD = 15.47), respectively. Further, the average temperature and relative humidity for the indoor spaces during the summer equals 21.09 °C (SD = 3.29) and 28% (SD = 5.49), respectively. Furthermore, the average temperature and relative humidity for the outside air during the same time equals 28.11 °C (SD = 6.76) and 19.55% (SD = 5.49), respectively. A slight and almost constant fluctuation is observed in the indoor temperature of the buildings during the winter and summer, leading to an increase during the summer due to the rise in outdoor temperature. The temperature and humidity change slowly in the buildings due to the low level of their openings and high thickness of the walls and roof. In addition, the degree difference between the average

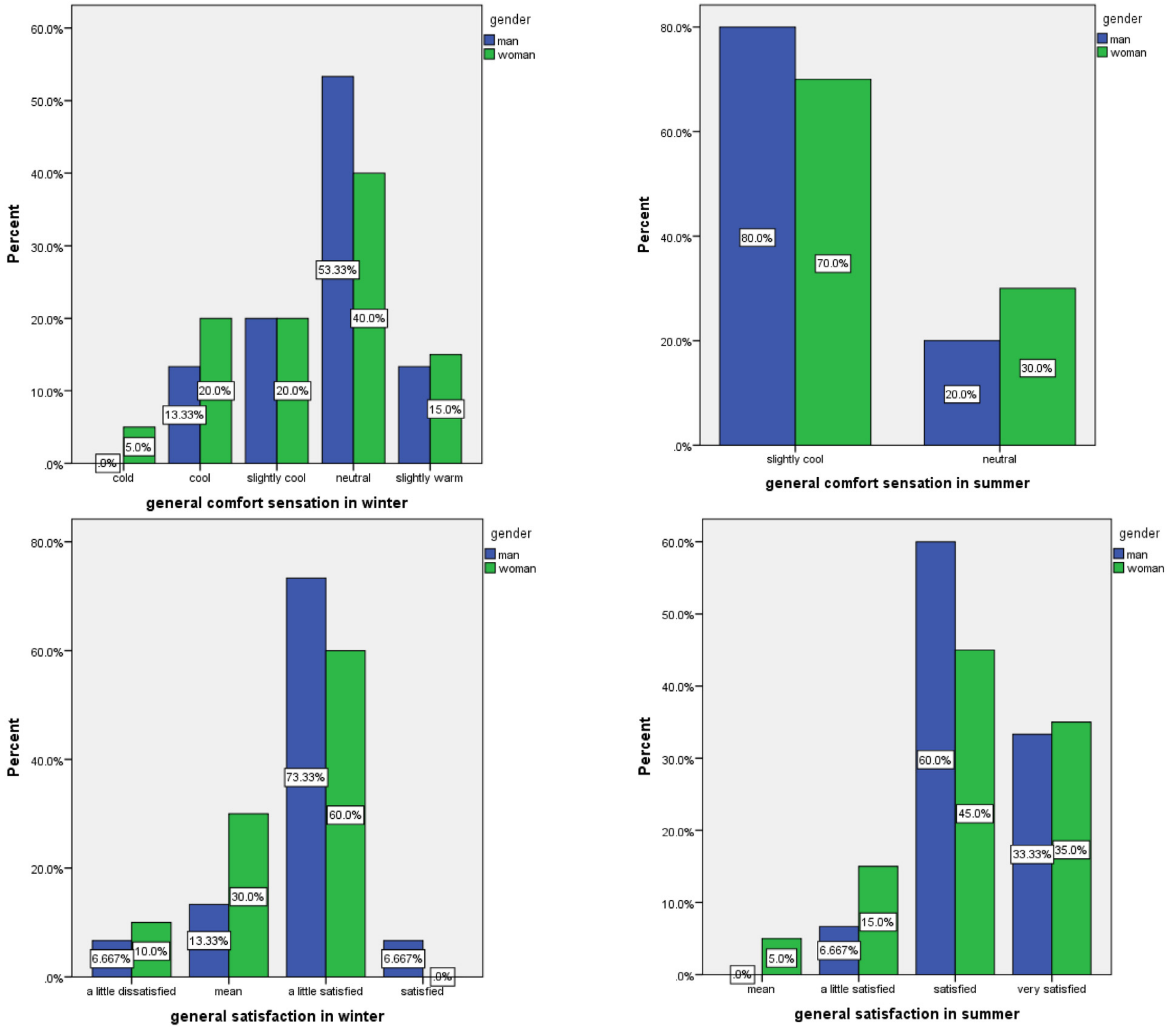

Fig. 3. Indoor general comfort and satisfaction in winter and summer based on questionary.

temperature inside and outside the buildings is greater during the winter. Based on results, the average the indoor temperature is 13.11 °C warmer and 6.21 °C cooler than the outdoor one during the winter and summer, respectively. Further, the average relative humidity inside is 14.06% less and 8.46% more than outside during the winter and summer, respectively.

3.2. General assessment of PMV

Fig. 6 illustrates the changes in the average PMV of the indoor and outdoor space of the evaluated buildings in Meymand during the winter and summer. The average PMV inside the aforementioned buildings equals -2.12 and -1.07 ($SD = 0.622$, 0.971) during the winter and summer, respectively. The above-mentioned values for outdoor space equal -5.82 and 0.658 ($SD = 0.940$, 3.12), respectively. The PMV level inside the above-mentioned buildings changes more gradually, despite the large changes in that of the outside air during the winter and summer due to the semi-arid climate of the region. In addition, the indoor PMV is observed in the cold and cool range during the winter and summer, respectively, which is consistent with the results of the questionnaire (Fig. 3) regarding the overall comfort sensation while living in the aforementioned buildings.

3.3. Comparing the indoor PMV level in the studied buildings

The data acquired from the PMV analysis applying the CBE thermal comfort instrument do not distribute normally. In addition, the non-parametric Mann–Whitney and Kruskal–Wallis tests are used to analyze the significance level of their mean difference because their variance is not regarded as homogeneous. Based on the results, a significant difference was reported between the average PMV in four evaluated buildings ($sig < 0.05$). Then, Kruskal–Wallis was utilized to determine whether a significant difference was observed between the average the indoor PMV in each of the four studied buildings during the winter and summer, respectively. As Table 7 represents, building 1 is compared with 2, 3, and 4, 2 with 3 and 4, and 3 with 4. The results indicated a significant difference in the PMV level in building 1 with 2 during the winter and summer, $sig < 0.05$, $Z = (-5.888)$, (-8.716). In addition, a significant difference in the PMV level was reported between building 1 and 3, $sig < 0.05$, $Z = (-9.046)$, (-8.699). Further, a significant difference in the PMV level was observed between buildings 1 and 4 like the previous cases, $sig < 0.05$, $Z = (-9.036)$, (-8.716). Furthermore, a significant difference in the PMV level was reported between building 2, 3, and 4, $sig < 0.05$, $Z = (-9.045)$, (-7.027), $Z = (-6.797)$, (-8.963). Finally, a significant difference in the PMV level was observed

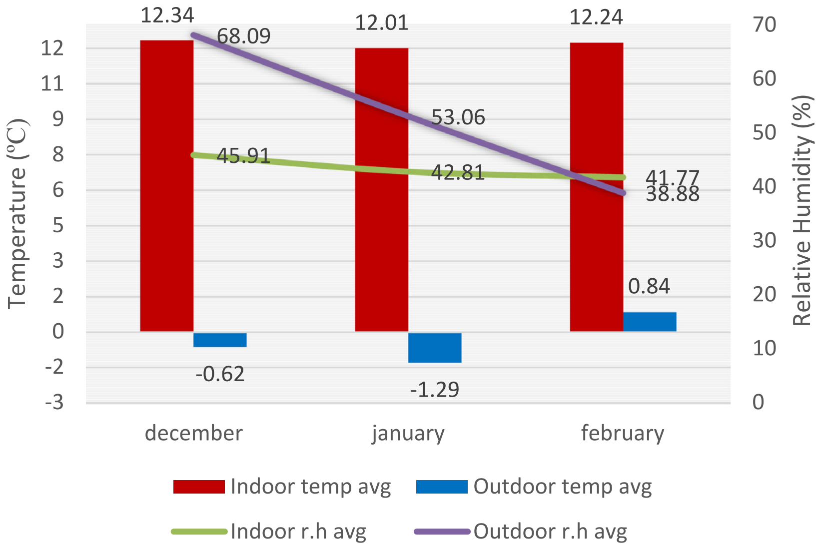

Fig. 4. Indoor and outdoor air temperature and relative humidity average during study in winter in Meymand.

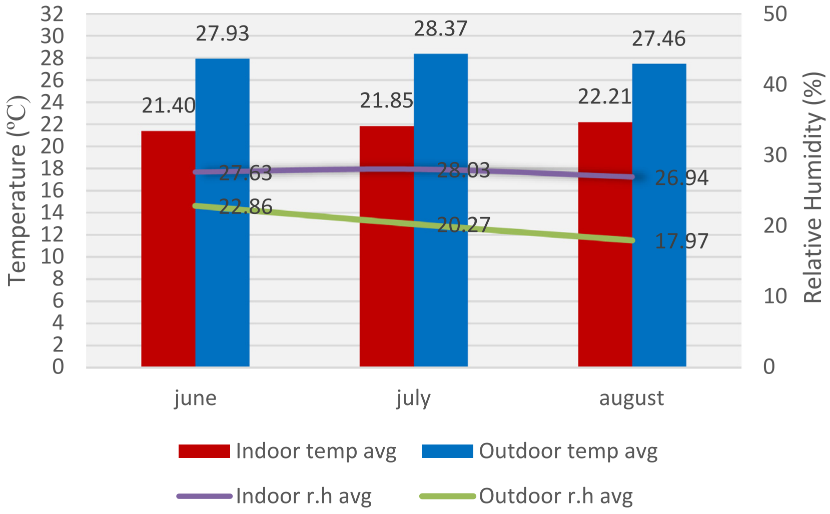

Fig. 5. Indoor and outdoor air temperature and relative humidity average during study in summer in Meymand.

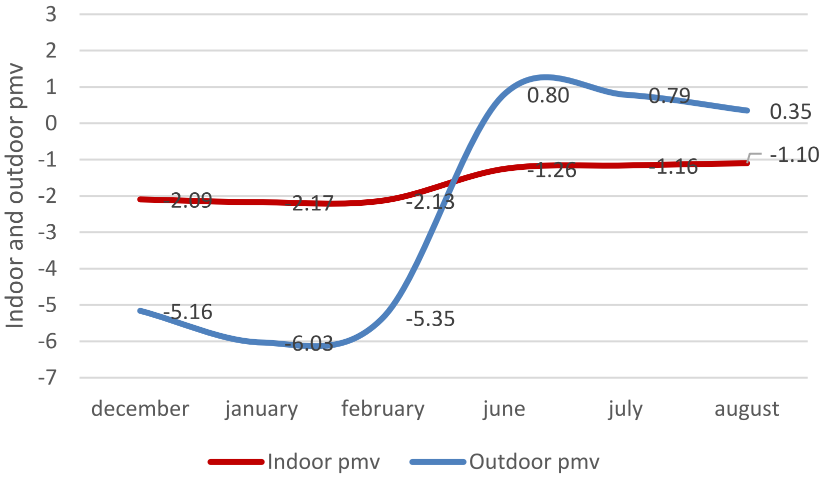

Fig. 6. Indoor and outdoor PMV average during study in winter and summer in Meymand.

Table 7
Comparison between buildings PMV in winter and summer.

Season	Building	PMV	Std deviation	Compare	Sig.	Z
Winter	1	−2.30	0.084	1–2	0.000	−5.88
	2	−2.45	0.124	1–3	0.000	−9.04
	3	−1.07	0.072	1–4	0.000	−9.03
	4	−2.64	0.108	2–3	0.000	−9.04
				2–4	0.000	−6.79
				3–4	0.000	−9.04
Summer	1	−2.18	0.623	1–2	0.000	−8.71
	2	−0.92	0.292	1–3	0.000	−8.69
	3	−1.41	0.200	1–4	0.000	−8.71
	4	0.21	0.455	2–3	0.000	−7.02
				2–4	0.000	−8.96
				3–4	0.000	−9.62

Table 8
Group statistics in T-test between p(w) and p(s).

Code	N	Mean	Std. Deviation		Std. Error mean
T-test p(s)	1.00	55	.5765	.28657	.03864
	2.00	55	.2155	.09209	.01242
T-test p(w)	1.00	55	.3144	.11063	.01492
	2.00	55	.0979	.03595	.00485

Table 9
Levene's test for equality of variances between p(w) and p(s).

		F	Sig.	t	df	Sig. (2-tailed)	Mean difference
ts	Equal variances assumed	62.301	.000	8.895	108	.000	.36103
	Equal variances not assumed			8.895	65.036	.000	.36103
tw	Equal variances assumed	41.648	.000	13.807	108	.000	.21657
	Equal variances not assumed			13.807	65.282	.000	.21657

between buildings 3 and 4, sig < 0.05, Z $= (-9.046),(-9.044)$ Therefore, the PMV in all of the selected buildings displays a mean with a significant difference during the winter and summer, indicating a difference in their indoor comfort behavior due to architectural diversities such as the discrepancy in the thickness of the stone walls, surface of the openings, area of the semi-open space, and depth of such Buildings (Table 7).

3.4. Comparing the comfort percentage in the indoor and outdoor environment of buildings based on PMV level

The percentage of comfort level (p) is calculated according to the following equation after determining the significance of the difference between indoor and outdoor PMV level in buildings.

$$p = 1 - \frac{|\mathrm{pmv}|}{\max(\mathrm{pmv})}$$

The percentage of indoor and outdoor comfort during the winter and summer is obtained utilizing the above equation, where p(w) and p(s) represent the percentage of comfort corresponding to PMV for winter and summer, respectively. Finally, the above-mentioned indices are compared with each other. The data achieved for p(w) and p(s) are examined by the Kolmogorov–Smirnov and Shapiro–Wilk tests, resulting in confining the normality of their distribution $p > 0.05$, df $= 55$. Then, the mean percentage of the indoor and outdoor comfort levels acquired with the t-student test is compared with each other. The hypothesis of data homogeneity is rejected with Levene's test $p < 0.05$, f $= (62.30), (41.64)$ and a significant difference is reported between the mean percentage of the comfort level of indoor and outdoor spaces during the winter and summer, $p > 0.05$, df $= (65.03), (65.28)$ (Tables 8 and 9). The difference equals about 22% and 36% for winter and summer, respectively, meaning that such buildings provide more comfortable conditions during the summer than the winter, resulting in creating a greater sense of thermal comfort than the zero point of the PMV index.

4. Discussion

The cases discussed here include evaluating the indoor and outdoor climatic conditions of the selected buildings in Meymand World Heritage during the winter and summer to measure their PMV index. The occupants in the aforementioned buildings provide their general opinions about the thermal comfort sensation during the winter and summer, as well as collecting the climatic data. All of the selected buildings are excavated in the stone mass in the foundation of the village and only the wooden entrance doors provide their light and ventilation. Penetrating the above-mentioned bed and high thickness of the stone layer in the building create a kind of earth-sheltered architecture, in which the groundmass plays a critical role in the stability of temperature and humidity, as well as regulating the bio-climatic conditions. In addition, the high penetration depth in such buildings plays a significant role in creating temperature stability, resulting in reducing the temperature exchanges between indoor and outdoor spaces. No cooling instrument is used in such buildings and their PMV level during the summer (−1.17) is in the cool range, indicating the appropriate level of their thermal comfort. Further, the PMV in such buildings during the winter is in the cold emotional range (−2.14), which requires a little heating to reach the comfort level (Fig. 6). Energy is utilized for heating in the aforementioned historical site only during extreme cold hours in winter, resulting in providing the thermal comfort conditions due to the low heat exchange stemming from the mass. In other words, such buildings create stable conditions during the summer due to lack of energy consumption to reduce the temperature, and provide comfort and stability with minimal energy consumption during the winter. The results indicated that the emotional conditions of the occupants match the PMV level calculated in the buildings. In addition, the comfort percentage of 36% and 22% during the summer and winter shows the better comfort performance of the buildings during the first season (Table 9 and Fig. 3). Further, the indoor relative humidity (41.77 and 49.91%) is considered as lower compared to the outdoor one (38.8 and 68.09%) during the winter. Furthermore, the indoor relative humidity (26.94 and 27.63%) is regarded as higher compared to the outdoor one (17.97 and 22.86%) (Figs. 4 and 5) during the summer due to absorption and retention of the humidity during the cold season by the groundmass and its slow transfer to the interior space during the warm season. The relative stability in the rate of changes in relative humidity during the winter and summer indicates that the moisture absorbed by the stone wall is transferred to the indoor space uniformly and calmly. Such slow process of temperature changes can be observed like humidity (Figs. 4–6) due to role of the earth and its thermal mass in the temperature changes inside the buildings.

A limited number of studies in the field of climatic knowledge of rock-cut architecture have focused on their indoor thermal comfort. Based on the results, such buildings exhibit a constant and uniform behavior with the process of slow temperature changes, an example of which can be observed in the underground rock-cut buildings in Dezful in the hot and humid climate of Iran due to their great depth compared to the open air surface (Sadooghi et al., 2019). Based on another study, such buildings retain about 59% of energy, indicating better performance in the field of energy consumption compared to clay ones with 35% energy conservation level. Further, the temperature in the above-mentioned buildings is in the range of (22.8–26.7 °C), which is considered as close to the comfort zone (Zhu and Tong, 2017). The aforementioned result is in line with those obtained here. Furthermore, Khaksar argued that the buildings in Meymad are more compatible with comfort conditions during the summer than the winter due to their penetration depth and low ratio of the opening surface to the total one of the building (Moradinasab and Khaksar, 2021), which is in line with the results achieved here. The modeling conducted in another study confirmed the role of the penetration depth in such buildings and their amount on comfort performance, as well as its slow changes during different seasons, indicating that buildings with greater depth exhibit lower temperature fluctuations (Khaksar et al., 2022). Comparing the penetration depth of buildings 1 and 3 with that of buildings 2 and 4, along with comparing their temperature, relative humidity, and PMV level confirm the above-mentioned argument (Tables 1, 3, and 4).

Finding a building which is regarded as accessible and uninhabited at the time of installing the monitoring instruments and collecting data during the winter and summer is considered as a limitation which results in selecting only four buildings from the site. Lack of a local climate data collection station (synoptic) limits the possibility of judging in the long term by accurate monitoring and analyzing the general weather data governing the region.

The studies that have been done on the rock-cut architecture show the importance of this particular type of vernacular architecture and its ecological nature which how it has a favorable relationship with its natural environment and settlement and provides thermal comfort for inhabitants with minimum energy consumption. Different methods of data collection and analysis have been used in various researches carried out around the world that in some of them, it is in the form of a combination of field study and energy and thermal simulation with software (Zhu et al., 2020; Zhu and Tong, 2017; Li et al., 2017). In few of them, only the field study method has been conducted (Barbero-Barrera et al., 2014; Mazarrón et al., 2012; Moradinasab and Khaksar, 2021) or just thermal simulation is research design tool (Khaksar et al., 2022; Zhao et al., 2020) (Table 10). Meymand world heritage rock-cut complex is an outstanding example of the coexistence of nature with built environment that In spite of its importance, a comprehensive study regarding thermal comfort has not been addressed on it. The limited researches were just by thermal and energy behavior simulation (Khaksar et al., 2022) or just in a season controlled the indoor thermal changes (Moradinasab and Khaksar, 2021) and not addressed relationship between indoor and outdoor thermal range.

In this study, it has been tried using appropriate field and software methods to investigating the indoor thermal comfort of selected building in addition to the outdoor climatic parameters and thermal comfort range which calculated in both cold and hot seasons to make a more accurate comparison to that the impact of this type of architecture on the formation of thermal comfort conditions can be more tangible.

5. Limitation and future suggestion

Based on the results, such type of native architecture exhibits the lowest amount of energy loss due to use of groundmass heating, high thickness of the building layers, structural integrity, low level of openings, and material of the excavation bed, and indoor temperature is adjusted more by the groundmass and drilling bed rock. The effect of each of the aforementioned components on the comfort behavior in such architecture through monitoring and modeling is regarded as another field of study, which helps complete the knowledge for the performance of the energy cycle and thermal comfort in these buildings. Comparing such architecture with the current standard one in the region in the field of thermal comfort is considered as another field which needs further study. This type of vernacular architecture can be an appropriate model for modern architecture, which suffers from energy loss crisis. A detailed understanding of such architecture and their behavior results in protecting and restorating their valuable heritage better. Studies which aim to evaluate the role of other effective phenomena such as geographical conditions, architectural shape and elements, as well as technique and excavation plan of the buildings in the level of comfort performance of rock-cut buildings help complete our knowledge of this ancient model of architectural heritage. Future studies should focus on understanding the specific techniques of adapting human life to aforementioned architecture qualitatively and its role in creating physical comfort.

6. Conclusion

The present study seeks to review the indoor comfort level of PMV in four rock-cut residential buildings in Meymand World Heritage Site in Iran. To this aim, two seasons including winter and summer with the most cold and heat were studied to determine their PMV index. The study was conducted as a combination of quantitative and qualitative applying the acquired data to monitor the climatic conditions inside the buildings. Based on the results, a significant difference was observed between the above-mentioned PMV levels, as well as that inside the buildings during the winter and summer. The aforementioned index indicated the cold comfort level for the indoor space and cooling range during the winter and summer, respectively. The comfort percentage related on the indoor environment of the buildings was calculated utilizing the analyzed PMV and determined mathematical formulas, indicating that the buildings exhibited a percentage of thermal sensation close to the thermal comfort range of 36 and 22% during the summer and winter, respectively, and performed better during the summer, which was consistent with the results of the questionnaire which included the occupants' feedback with components such as age, gender, height, weight, length of residence, type of seasonal clothing and physical activity, level of satisfaction, feeling of temperature, and reasons for discomfort. The results indicated that the occupants in such

Table 10
Compare related researches based on result and method.

Reference	Location and climate based on Koppen (Kottek et al., 2006)	Methodology	Conclusion
Zhu et al. (2020)	China (cold and mountainous) with compacted clay settlement	Field study and thermal simulation	Passive architecture system and low energy consumption and suitable thermal behavior in summer based on ground temperature
Zhu and Tong (2017)	China (cold and mountainous) with compacted clay settlement	Field study and thermal simulation	Neutral thermal comfort in summer and being in comfort zone in winter by impact of traditional heat system (Yaokang)
Li et al. (2017)	Chinas (hot and humid)	Field study and thermal simulation	In humid climate modern underground buildings need ventilation by HVAC systems to be in comfort zone
Zhao et al. (2020)	China (cold) with compacted clay settlement	Thermal simulation	52% days are in comfort zone. best thermal function in summer and lack of ventilation and natural day light is main problem
Barbero-Barrera et al. (2014)	Spain (cold) with pyroclastic settlement	Field study	The orientation and the ventilation together with the thermal inertia of the soils are the applied bioclimatic mechanisms and high thermal inertia which allows the upkeep of indoor average daily and even annual temperatures without energy requirement
Mazarrón et al. (2012)	Spain (cold) with pyroclastic settlement	Field study	In the autumn and winter, the stability of the wine cellar is reduced by the increased ventilation, reducing the influence of the ground temperature and increasing that of the outside air temperature
Khaksar et al. (2022)	Iran (cold) with pyroclastic settlement	Thermal simulation	That buildings with greater depth exhibit lower temperature fluctuations
Moradinasab and Khaksar (2021)	Iran (cold) with pyroclastic settlement	Field study	Compatible with comfort conditions during the summer than the winter due to their penetration depth and low ratio of the opening surface

buildings feel cold without applying the heating system during the winter and feel cooler inside the building without using the cooling system during the summer, indicating their comfort performance during the hot season. Based on the results, the above-mentioned architecture exhibits an appropriate comfort function in times of extreme cold and heat and provides a range close to comfort for human life without energy consumption, which can be utilized in formulating standards to reduce energy consumption in buildings. The achieved results help protect such architecture and understand the issues which have been given less attention, as well as indicating the significance of thermal comfort for human life in a modern method during designing the revival of the buildings. This study increased our knowledge of an architectural heritage with a high level of sustainability and low energy consumption.

Declaration of competing interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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Data availability

No data was used for the research described in the article.

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