



A study on the thermal behavior of traditional residential buildings: Rasoulian house case study



Somayeh Asadi^{a,*}, Maryam Fakhari^b, Mona Sendi^c

^a The Pennsylvania State University, University Park, PA, USA

^b Tehran Art University, Tehran, Iran

^c University of Tehran, Tehran, Iran

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ABSTRACT

Traditional buildings throughout the globe provide instructive examples of sustainable solutions to building design problems. In recent years, researchers and architects have conducted different studies that represent the principles of Iran's climate-responsive architecture. Yazd traditional buildings are examples of Iranian architecture that bear characteristics of environmentally friendly buildings. Thermal performance and comfort condition of these buildings in summer have been the matter of interest in recent studies.

In this article, summer sections of Yazd traditional homes and their thermal behavior were studied. Yazd is located in hot and arid regions of Iran. EnergyPlus software program was used to investigate the thermal behavior of this house. To validate the developed model, a field study was carried out with lascar electronics data logger. The results reveal that internal temperature of summer sections in all seasons has less fluctuation than the outdoor temperature. Also, weather temperature in underground spaces is closer to the comfort temperature in comparison with spaces near to the ground floor. Therefore, to provide thermal comfort condition in these homes the least amount of non-renewable energy is needed.

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1. Introduction

Buildings account for 45% of worldwide energy use. Urban residential sector is one of the main contributors of energy consumption in each country [1]. In recent years, due to the building's impact on the environment (more than any other human activity), researchers and architects have focused to find sustainable solutions reducing energy consumption and negative environmental impacts. Vernacular buildings across the globe provide instructive examples of sustainable solutions to building problems [2]. It is believed that sustainable architecture can be achieved by using "the best of the new and the best of the old" [3]. Consequently, researchers assess different aspects of vernacular buildings to understand and identify sustainability principles applied in these buildings. Certain construction features for shelter and protection and the need to create the tolerable levels of comfort were considered in ancient design and not surprisingly, still remain important today [4].

Very long time ago, before the development of the sustainable architecture concept in scientific societies or even among

architects, principles of Iran's architecture were established based on exact criteria. These principles covered a wide variety of issues including environmental, architectural and energy-saving features [5]. Based on these studies, Iran's traditional buildings adopted strategies consistent with ecological condition. For example, hot and dry region's architecture was in accordance with regional factors such as desired and undesired winds, humidity, sun, etc. [6]. As one of the famous architectural design, Yazd, a city in hot and dry regions of Iran accommodates buildings that appropriately characterize Iranian regional architecture. Yazd's residential buildings have a specific spatial configuration that makes it a suitable place for cold and intense hot seasons. Sections like three-door, five-door and seven-door in northwest and northeast orientations, subject to sun radiation, are suitable for cold seasons, and sections such as hall, coastal, cellar in southwest are suitable for warm seasons. Other principles are also used in other cities in hot-arid area such as Esfahan and Kashan [7].

Different studies have investigated the application of sustainable features of vernacular buildings and suggested various solutions to modern architecture. Some of these studies are based on the researcher's observations and descriptive methods which are not corroborated. In a study conducted by Shahamat, [5] an interpretive-historical research method was used to compare the principles of Iranian traditional architecture and sustainable

* Corresponding author.

E-mail address: asadi@engr.psu.edu (S. Asadi).

architecture. Despite the diversity of society at different regions and the variety of climates, this study proved the conformity of both architectures (i.e. traditional and sustainable) in the field of architectural form [5]. Also, other researchers have performed detailed studies on different traditional houses in different regions of Iran in order to understand sustainable principles in Iranian traditional buildings. The evaluation of ecological approaches in Shiraz's traditional houses [8] or the study of Alyasin house in Kashan by Jalilpour revealed the sustainable approaches applied in these buildings [9]. Furthermore, some studies have focused on components of traditional buildings. For instance, Akbarian and Kazemi [10] focused on cellars in Rasuliyan house and analyzed their performance in Yazd extreme weather condition. Based on their study, cellars and coastal are summer sections of Yazd's traditional houses that provide thermal comfort for residents via ecological approaches applied in them [10]. In another study conducted by Shojaei and Khodayari [11] different types of Iranian traditional architecture were investigated which present the Iranian culture in the best way. On the other hand, different ecological techniques were employed in these buildings to save energy consumption which is one of the old sustainable features [11].

Some other studies have utilized numerical methods to analyze the performance of traditional buildings. These studies mainly used a combination of computer simulation and field measurement to investigate the climatic components of traditional buildings such as wind catcher and cellar. In a study conducted by Du et al. [12], field measurements were carried out to investigate the thermal performance of a Chinese vernacular house. They also developed a simulation model to understand the microclimate effect of a Chinese traditional vernacular house. The field measurements showed the Chinese vernacular house has its own independent building microclimate in summer which is in accordance with the main character of microclimate in terms of different distributions of solar gain, air temperature and wind velocity in different spaces. According to the simulations, at night, a comfortable temperature could be obtained throughout most of the summer period whereas in the daytime the operative temperature was higher than the comfortable temperature for one-third of the summer period. However, wind velocity in the semi-outdoor and outdoor spaces improved the thermal comfort significantly [12].

Climatic elements of Iranian architecture and their performance have also been of great interest to researchers. For example, Mahdavinejad et al. [13] conducted an experimental study on the efficiency of YAZDI wind tower using both simulation methods and logical reasoning. Results indicated that YAZDI wind tower with four openings had a positive air flow rate in hot and cold seasons respectively (air flow rate of 0.018 and 0.012) [13]. Another study was conducted by Mahmoudi [14] on the wind catcher and its effect on natural ventilation. The results obtained from analyses showed the proper specifications of wind catchers with optimum operation in Yazd [14].

In another study Moradi and Eskandari [15] were performed an experimental study to investigate Shovadan performance during a year. Shovadan is an underground room which has been designed in several areas of Iran for heating and cooling purposes. When the ambient temperature is 7 °C in January and 47 °C in July, Shovadan

average temperature is 17 °C and 23 °C, respectively. The suitable Shovadan temperature range proves the ability of this space in architecture optimization to save energy consumption [15]. Later, Kazemi and Mahmood abadi [7] studied winter sections of one of the Yazd's traditional houses and its optimum situation. Yazd traditional building architects tried to coordinate the design with the ecological conditions and in all of their designs set special places for cold and warm seasons. In every section, they adopted special solutions. In winter sections, solutions such as absorbing direct sunshine, transparent walls in front of the sunshine, using thermal capacity of building materials to save energy, building half-open sections in front of the entrance doors were considered. In comparison with winter sections with different dimensions such as three-door, five-door, and seven-door room in northwest and northeast orientation, it was concluded that five-door section in northwest orientation has the best thermal behavior in winter. All studies described above demonstrated the ecological characteristics of vernacular buildings in Iran and other countries that are designed based on regional factors.

According to the aforementioned studies, the ecological principles of traditional buildings is a critical factor in design of sustainable building and identifying new solutions to today's building's problems. Therefore, this paper investigates the summer sections of Yazd traditional homes and evaluates thermal performance of these spaces in order to understand different aspects of their ecological features. To achieve this objective, EnergyPlus version 8.0 was used to assess their thermal performance. The developed model in EnergyPlus was validated with collected experimental data.

2. Case study

2.1. Thermal analysis of Rasulian's house

The Rasulian house is located in the center of Iran, Yazd (Northern latitude: 31.880 and eastern longitude: 54.280). Table 1 shows the monthly climate data in the typical meteorological year of Yazd. As it indicated in this table, the average temperature in Yazd is about 18 °C while the average temperature in the hottest month is nearly 32 °C and in the coldest month is about 5 °C. The average relative humidity is 25%. Based on the Yazd's weather data, it has a hot-dry and uncomfortable condition in summer. This weather condition demands humidification and cooling in Yazd's houses during summer. As mentioned above, different strategies such as, specific spatial configuration, using surface evaporation, locating some spaces under the ground or applying materials with high thermal capacity, etc. were some approaches applied in order to mitigate uncomfortable weather conditions.

The building performed as a free-running building with natural ventilation without any heating or cooling which is consistent with real situation of the studied house. For validation, the simulation results were compared with the field measurements taken on the 21st of July. Figs. 1 and 2 show different thermal zones of Rasuliyan's house in ground floor and underground floor that were simulated in this study.

Table 1
Monthly climate data in Yazd in a year.

	1	2	3	4	5	6	7	8	9	10	11	12
Average air temperature (°C)	4.91	7.38	12.94	12.94	25.75	30.88	31.87	30.79	25.18	19.92	12.07	7.45
Average relative humidity (%)	50.6	42.3	32.6	31.5	22	15.6	15.4	17	17.9	22.2	37.6	46
Wind Speed (m/s)	0.96	1.4	2.7	3.2	2.5	2.3	2.6	1.8	2.2	1.3	1.2	1.4

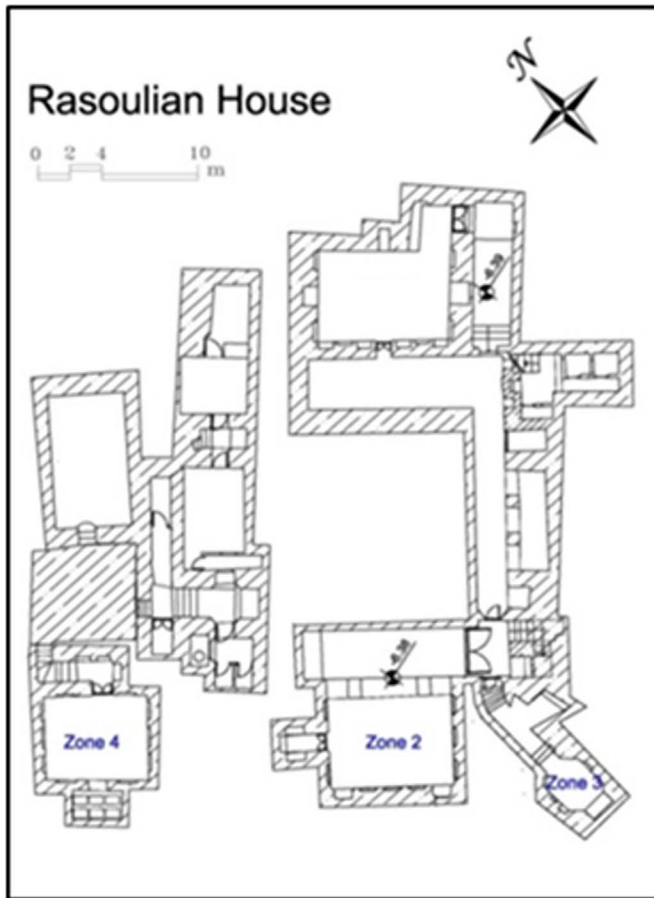


Fig. 1. Underground plan of Rasouliyan's house.

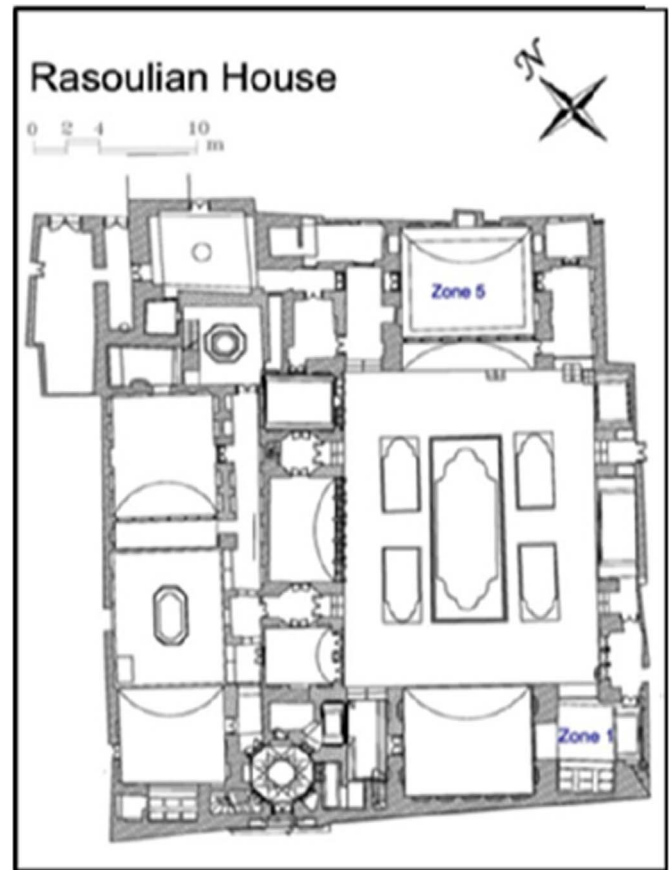


Fig. 2. Ground floor plan of Rasouliyan's house.

2.2. The summer sections of Yazd's traditional houses

One of the main reasons for regional differences in architecture is the way that buildings respond to climate. This becomes apparent when looking at indigenous buildings, because they usually respond to the climate in which they were built [3]. Yazd's architecture is strongly under the sway of its climate.

One of the main designing features of buildings located in hot-arid regions is their orientation which innovatively was considered in design of Rasouliyan's house. Rasouliyan's house was defined in a way that constantly part of the buildings was in shadow and the other part was exposed to sun radiation. For example, in Yazd, houses were oriented in north east–southwest direction. Consequently, some spaces were convenient for cold seasons and some for hot seasons. Hall, wind catcher room as well as underground spaces such as cellar and coastal are all summer sections of these vernacular houses. Despite accepted thermal behavior of wind catchers in traditional buildings, in Rasouliyan's house the wind catcher space didn't work and were closed during measurement period. Thus, the space attached to wind catcher is defined as a separated zone. These spaces were located in south part of the house's yard or under the ground. Hall was a semi-open space in ground floor and south–west of the building that was open toward the central courtyard. This part of the building is used in early hours of the day and also in the evening, when the ambient temperature is low. Wind catcher room was another space in south–west of the building and ground floor which was surmounted by wind catcher, intensifying natural ventilation in the room.

Another measure taken to adapt to the weather condition in Yazd was some parts of the house located underground to achieve

temperature balance. For example, cellar was an underground space that was used in hot hours of the day. This space was located near coastal—a space near the running water under the ground—used for preserving foods. Cool air and humidity of the coastal was transferred to cellar. Furthermore, specific types of materials such as brick, sun-dried brick for floor, wall and ceiling were used in construction of this house which was consistent with Yazd weather condition. This was another way to deal with Yazd's intolerable hot weather in summer. These materials have a high thermal capacity that let them to save the received thermal energy from the sun. Therefore, the internal surfaces reach to their temperature peak later than external surfaces [16]. Moreover, in underground spaces, appropriate materials, such as brick used for floor which result in space cooling through surface evaporation.

In addition, the connection of cellar with coastal via a channel caused the circulation of cool and wet air. This air channel which was placed between the upper part of the coastal wall and the lower part of the cellar's wall due to the height difference, sent the cool and wet air from the lower part of the cellar's wall out. Consequently, via the creation of a mild air current in the room, hot weather was discharged from the upper window of the cellar's wall (Fig. 3).

Additionally, underground spaces had vertical connection with Hall and wind catcher, constructed on top of the Hall. This connection resulted in two benefits for living spaces located in underground. The first one was during a day, favorable air, distributed by the wind catcher, entered the cellar via an opening between cellar and Hall and contacted with underground moisture that led to a pleasant living condition for residents. The second one was at night, due to the pressure difference; the incoming of air by wind catcher was replaced by suction. Therefore, thermal energy, saved in the materials of the underground spaces, was

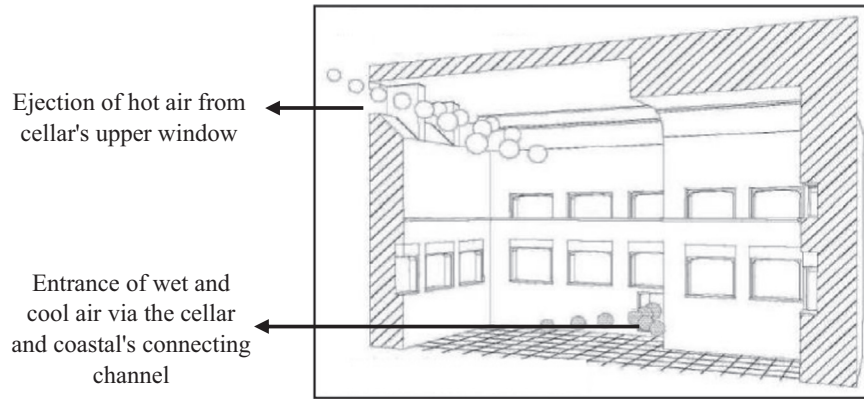


Fig. 3. Air circulation in cellar via the release of cool and wet air. from coastal to cellar in Gorji house [10].

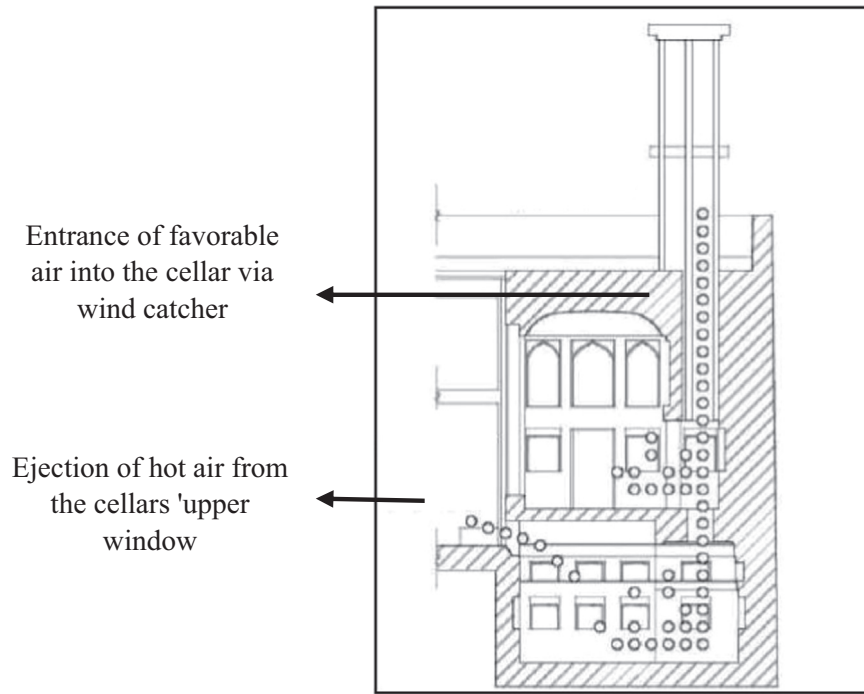


Fig. 4. The connection among wind catcher, Hall and cellar [10].

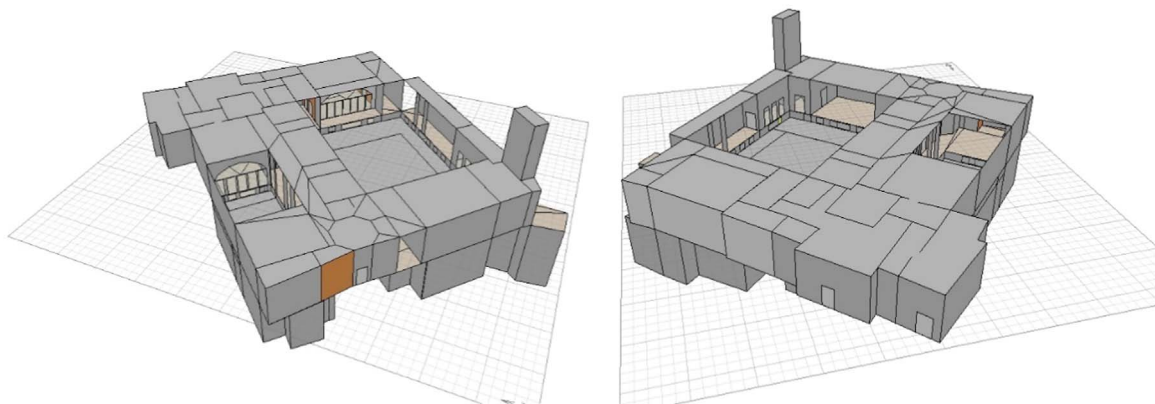


Fig. 5. Rasulian's house modeled in Ecotect software.

directed out of the underground spaces and replaced by central courtyard air that was cool and favorable (Fig. 4).

3. Methodology

Vernacular architecture which its design decisions was influenced by local climate and culture has been gleaned through a

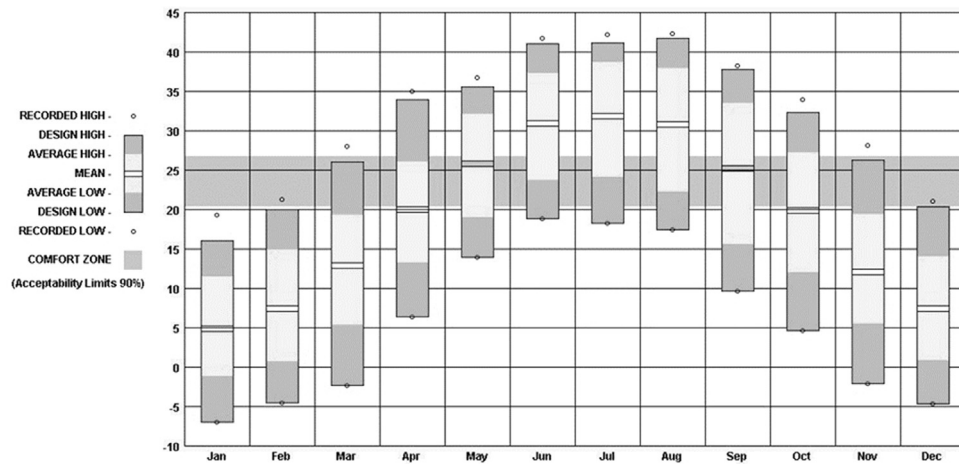


Fig. 6. Temperature range ($^{\circ}\text{C}$) ref: Climate consultant software ver.4.0.

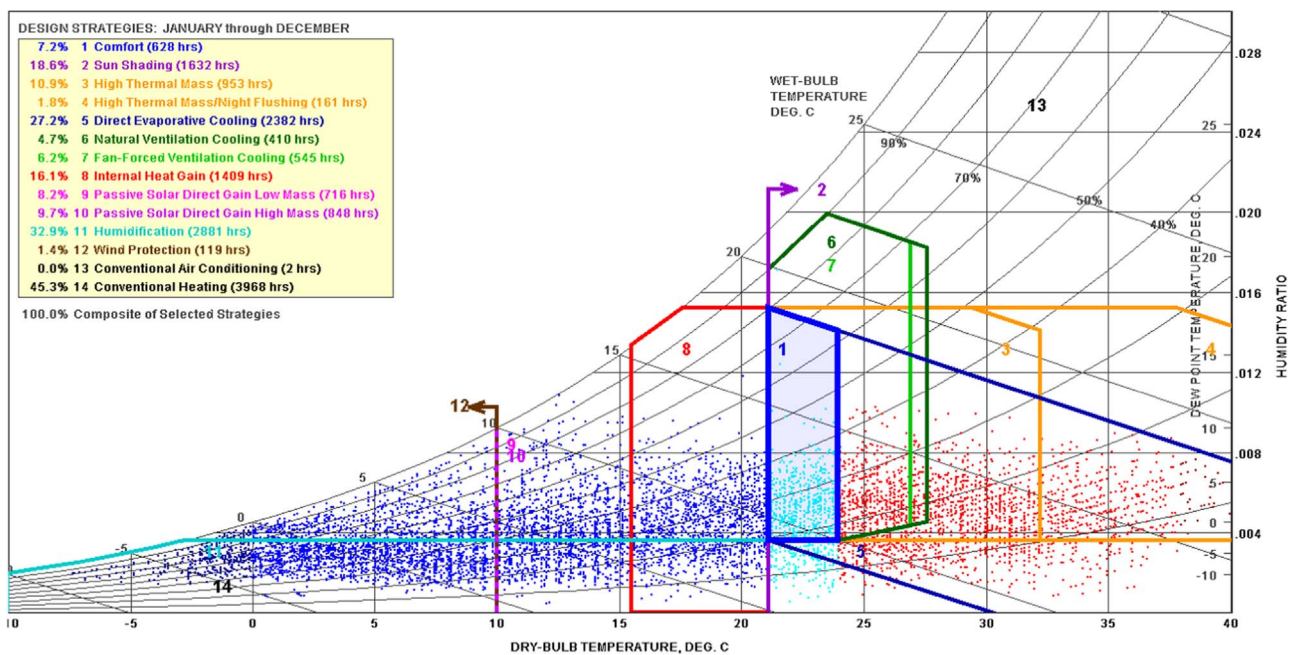


Fig. 7. Psychrometric chart ref: Climate consultant software ver.4.0.

long period of trial and error. In addition, the ingenuity of local builders who had specific knowledge about their location was valuable in promoting the bioclimatic design approach to modern buildings.

In many traditional buildings, climatic design strategies were applied to achieve an appropriate indoor climate for thermal comfort. In this study, in order to investigate a traditional building's thermal performance in hot regions of Iran, a vernacular house, located in Yazd, Rasulian house, was studied. At the first step, the geometry of the model was created in Ecotect software, version 2011 as a graphical interface and then it was imported to EnergyPlus software version 8.0 (Fig. 5). Then, EnergyPlus was utilized to model energy performance of the Rasulian's house. Simulation was done for 2 days, the hottest and coldest day which is 21st of July (summer), and 26 of December (winter). According to daily air temperature, 21st of July is the hottest day of the year and 26 of December is the coldest day. Yazd's weather data was obtained from Energy plus website. In order to compare thermal behavior of selected zones, hourly mean temperature of the zones in different seasons was measured in degree of Celsius. Finally, the simulation results were validated with field measurements.

4. Results and discussions

Fig. 6 shows dry bulb temperature ranges enclosing comfort temperature range (Gray bar) in each month of the year in Yazd and Fig. 7 (psychrometric chart) shows comfort condition. Based on this chart, comfort temperature is nearly between 21°C and 24°C . This chart is driven from climate consultant 5.4. Climate consultant reads the local climate data in EPW (EnergyPlus Weather Data) format and displays dozens of different graphic charts of various weather attributes.

The hourly temperatures of the house on the hottest and coldest days are obtained from the simulation. In Figs. 8–10, the simulated outdoor air temperature and air temperature in the different spaces in a typical day are illustrated. Based on the simulation results, internal temperature of summer sections has less fluctuation than outdoor temperature.

According to Fig. 8, the air temperature in zones 1 and 5 located in ground floor vary between 33°C and 15°C which was above the comfort upper temperature limit. However, the temperature of the zones located underground is close to comfort range. The air temperature in zones 3 and 4 is around 19°C and in zone 2 was 25°C .

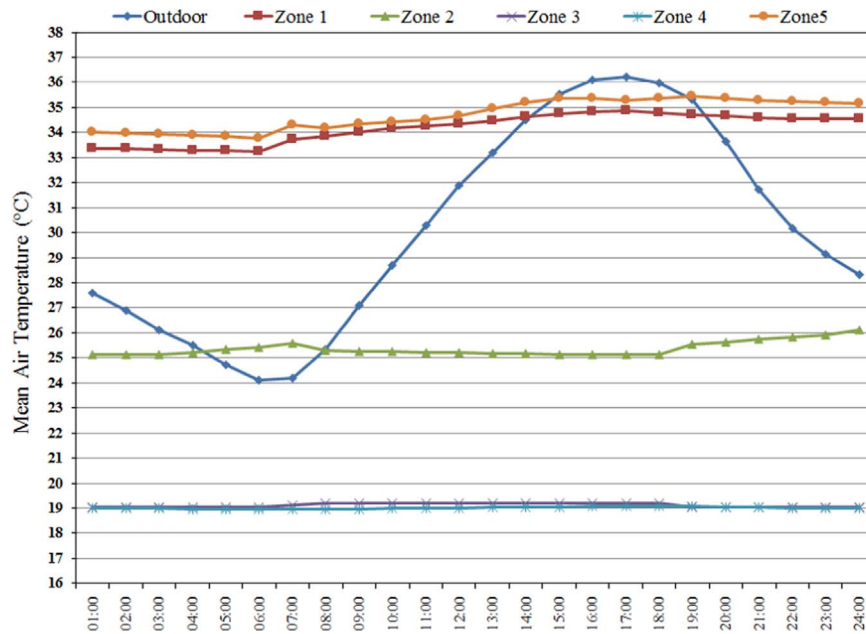


Fig. 8. The comparison of air temperature in summer sections in 21st of July.

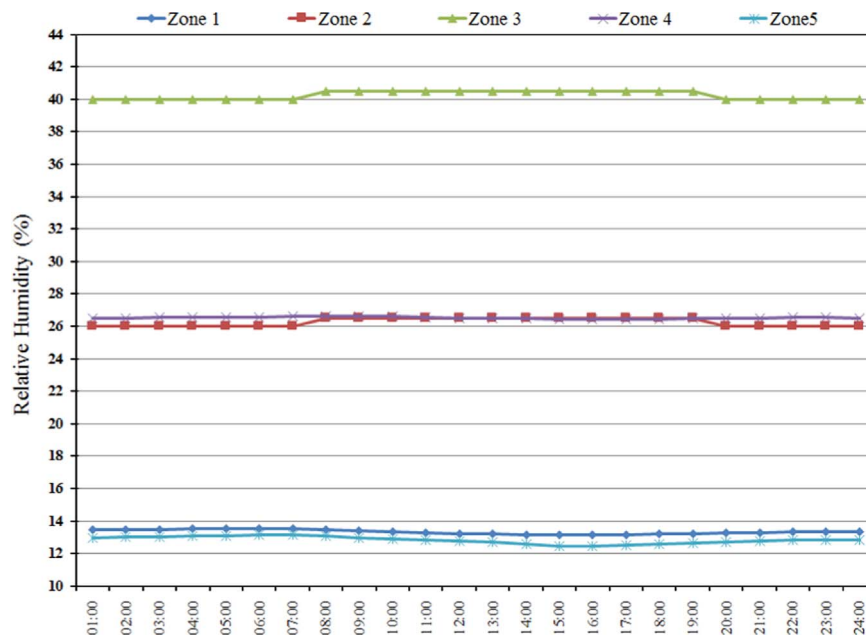


Fig. 9. The comparison of relative humidity in summer sections in 21st of July.

Fig. 9 shows that the relative humidity in zones 1 and 5 which is between 12–14%. As it can be seen, the relative humidity is below the comfort lower temperature limit. But, the other zones relative humidity is within comfort range. The relative humidity in zones 2 and 4 was between 26–27% and in zone 3 is 45%.

According to Fig. 9 and psychrometric chart, zones 2–4 are in comfort range even in hot days. These zones were located in underground floor. This means that underground zones can offer a comfortable thermal environment for the occupants without mechanical cooling.

As it can be seen in Fig. 10, the indoor thermal condition during day and night in all zones is almost constant despite the fluctuation of outdoor air temperature. The indoor air temperature of summer sections is lower than thermal comfort conditions. Also, the mean air temperature in zone 1 is lower than the others (around 8 °C), however, in zone 2 air temperature is about

13–14 °C and the air temperature in zones 3 and 4 is between 17–18 °C. This figure shows that the summer sections do not have thermal comfort condition in cold days.

Fig. 11 shows that the relative humidity in zones 3 and 4 is between 14–16% which is below the comfort lower temperature limit. In zone 2, relative humidity is around 19% which is not in comfort range while in zones 1 and 5 relative humidity is in comfort range (around 28% in zone 1 and between 25–27% in zone 5).

According to Fig. 12, the mean air temperature in zones 1 and 2 which are located on ground floor is above outdoor air temperature. This means that these zones do not have appropriate thermal condition during summer days. However, the indoor air temperature in these zones is above outdoor temperature during winter. Therefore, these zones can be used as winter sections.

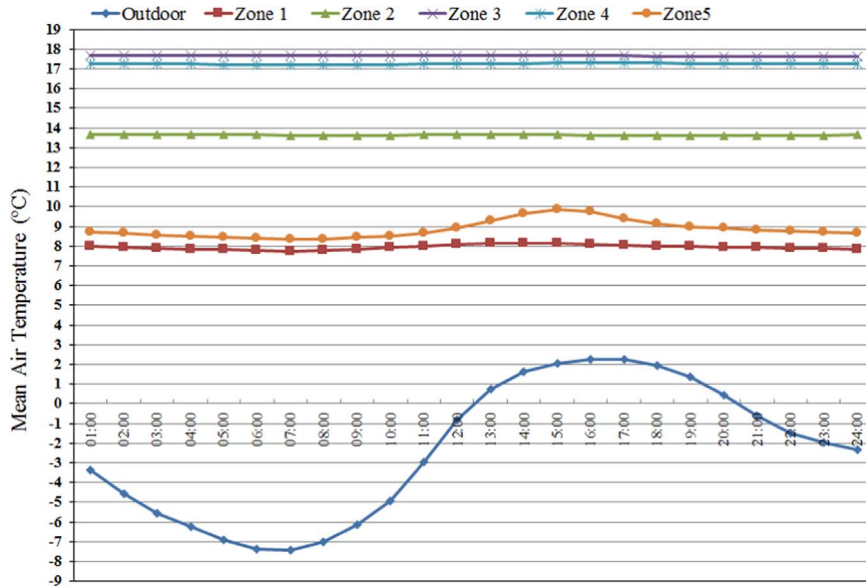


Fig. 10. The comparison of air temperature in summer sections on 26st of December.

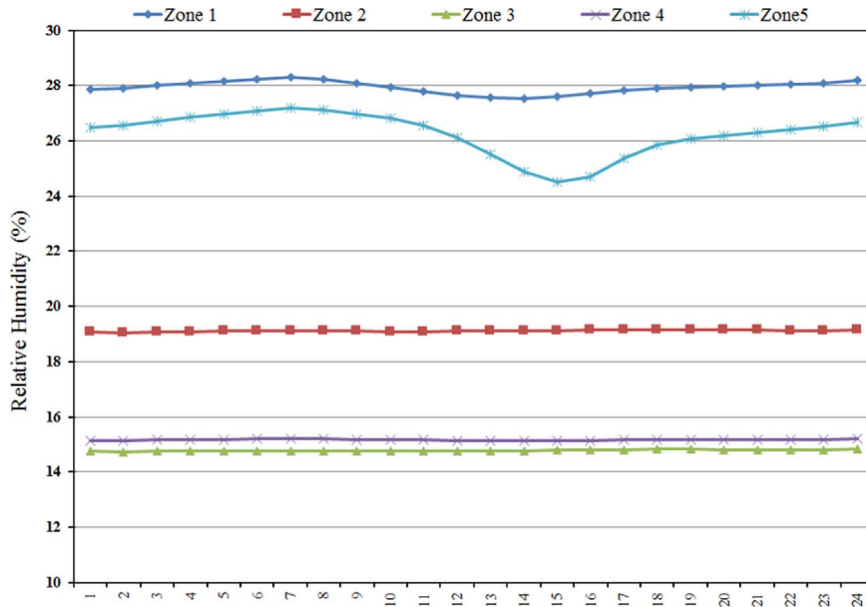


Fig. 11. The comparison of relative humidity in summer sections on 26st of December.

On the other hand, zones 2–4 which are located underground floor have less temperature fluctuation in comparison with outdoor air environment during the whole year. This happens because in a reasonable depth, temperature is close to its average throughout the year, due to the ‘thermal inertia’ of the large mass. Air temperature in zones 3 and 4 is up to 9 °C below outdoor air temperature (in July). Therefore, zones 2–4 are appropriate to be used as summer sections.

According to Fig. 13, relative humidity in zones 2–4 is in comfort range (above 20% according to Fig. 7) entire year. But relative humidity in July and August in zone 2 is below the comfort lower temperature limit (about 0.5%). Relative humidity in zones 1 and 6 is in comfort range only during 6 month of year (January, February, March, April, November, and December). Therefore, these zones could be used as winter sections.

5. Model validation

To validate the developed model in EnergyPlus, the indoor air temperature in three sections including wind catcher room, cellar and coastal was measured from 8 a.m to 6 p.m. with lascar data logger type EL-USB-2-LCD2 on July 21st. Five sensors were used in this experiment. This equipment measured and saved more than 16,379 temperature data points between –36 to +80 °C or –31 to +176 °F. The accuracy of these sensors was in a range of ± 0.5 °C or ± 1 °F. Figs. 14–17 compare the results of the field measurement and simulation in wind catcher room, cellar and coastal zones.

As shown in these figures, there is a slight difference between indoor air temperature based on field measurements and simulation results. The error was about 1 °C. This proves the reliability of the developed EnergyPlus model. Table 2 also shows the root mean square error (RMSE). RMSE calculates how much error there

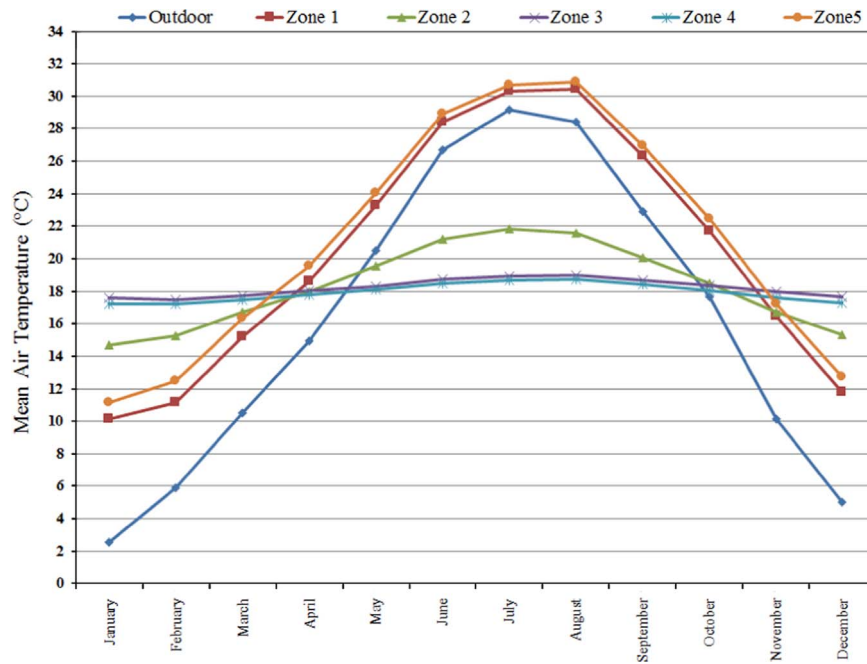


Fig. 12. The comparison of air temperature in summer sections.

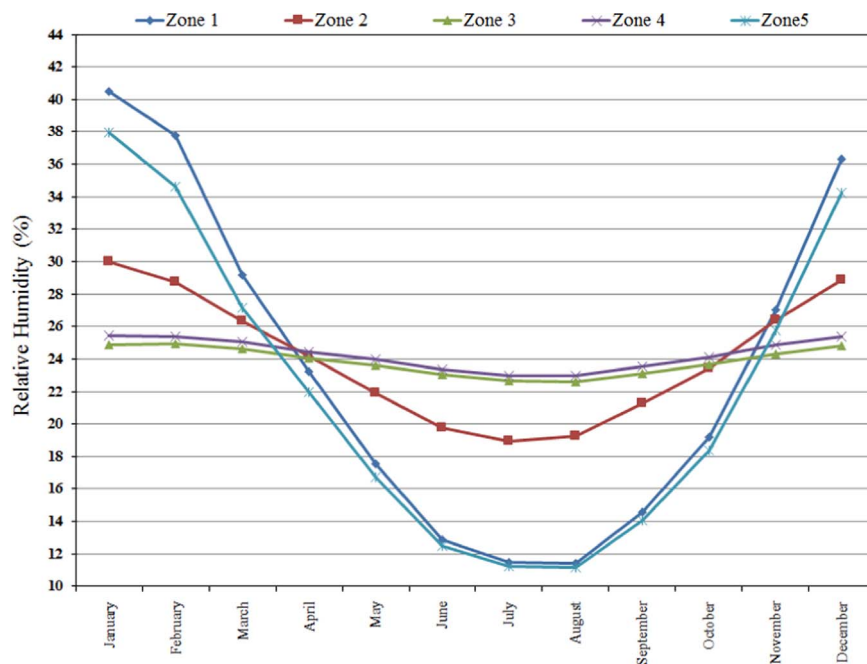


Fig. 13. The comparison of relative humidity in summer sections.

is between predicted and measured data. As it can be seen the RMSE is not significant. Low values of RMSE indicates there is a good agreement between predicted and observed data.

6. Conclusions

Climatic based design strategies for buildings can help to create a comfortable living condition and lessen energy consumption in buildings. In this paper, a case study was carried out in order to prove the effectiveness of climatic strategies in Iranian architecture in hot- arid regions of Iran. An appropriate organization of spaces, building form and using suitable material were among the main bioclimatic strategies adopted in Rasulian's house. These

strategies contributed to building thermal performance and consequently obviated energy demand in summer days.

Results showed that the zones have less temperature fluctuation in comparison with outdoor air. Also, coastal (zone 3), cellar and other underground spaces (zone 4–6) temperature, in south-east of the building, revolved around comfort condition temperature (21–25 °C) on summer days. On 21st of July which is assumed as the hottest day of the year, the temperature of the zones located underground were in comfort range while the temperature of zones 1 and 5 that were situated in ground floor was above the comfort upper temperature limit. This means that mechanical cooling was not required in extreme hot weather of Yazd city.

This study also showed the better thermal condition in underground zones in comparison with other zones. This thermal

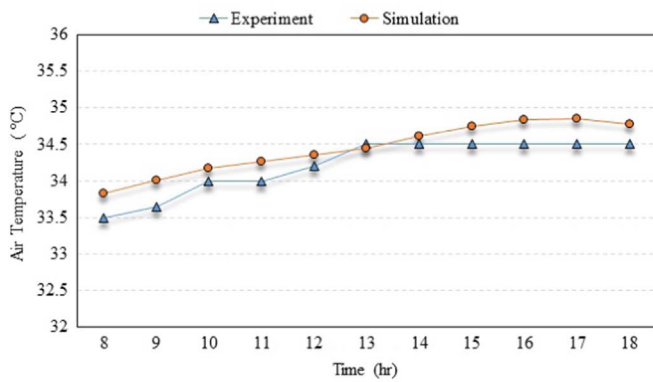


Fig. 14. The comparison of computer simulation and field. Measurements of wind catcher room on 21st of July.

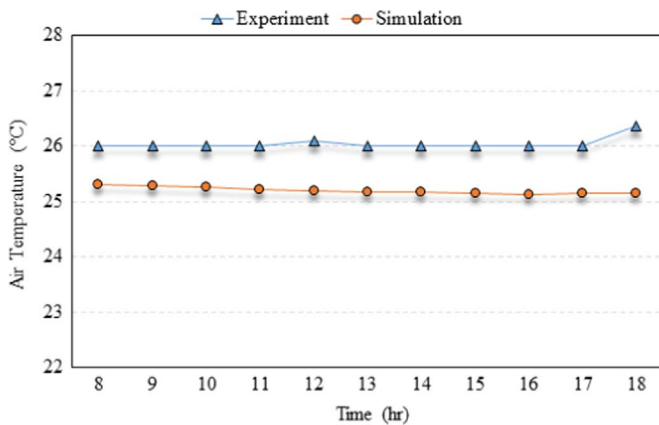


Fig. 15. The comparison of computer simulation and field measurements of cellar on 21st of July.

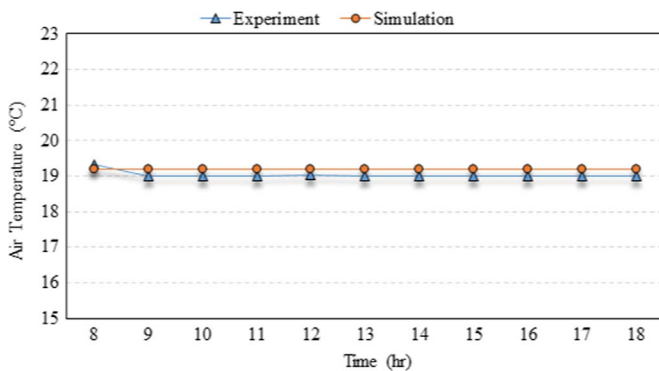


Fig. 16. The comparison of computer simulation and field measurements of coastal on 21st of July.

comfort takes place due to thermal mass properties of the ground. The ground works as a thermal storage, which can control temperature fluctuation. While, the outdoor temperature in this climate has significant fluctuation during day and night.

Furthermore, this study can be an inspiration for contemporary buildings' ecological design in hot regions. It divulges that building orientation, building form, spaces location and also materials have a substantial effect on buildings thermal performance. Thermal performance can be evaluated via energy simulation software programs in design phase by architects and consequently energy performance of the building can be optimized.

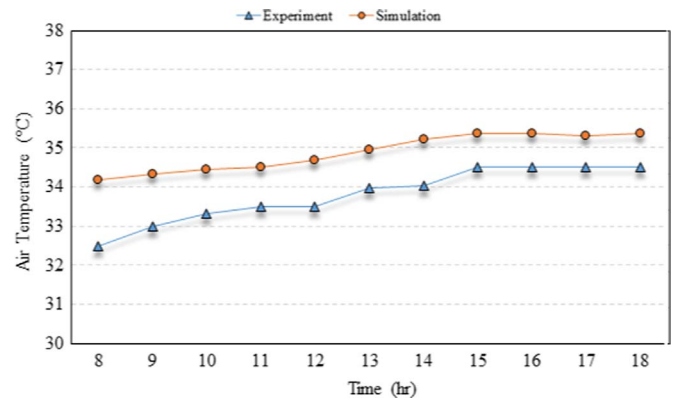


Fig. 17. The comparison of computer simulation and field measurements of Panjdari on 21st of July.

Table 2

Root means square errors.

Zones	Root mean square error (RMSE)
Wind catcher room	0.26
Cellar	0.19
Coastal	0.84
Panjdari	0.97

References

- [1] S. Jeberaj, S. Iniyar, A review of energy models, *Renew. Sustain. Energy Rev.* 10 (4) (2006) 281–311.
- [2] R. Mamun, R. Dilshad, Modernity in tradition: reflections on building design and technology in the Asian Vernacular, *Front. Archit. Res.* 4 (2015) 46–55.
- [3] L. Norbert, Heating, Cooling, Lighting: Sustainable Design Methods for Architects. New Jersey, John Wiley and sons, NJ, 2009.
- [4] J.T. Philip, S. Deriven, *The greening of Architecture: A Critical History And Survey of Contemporary Sustainable Architecture and Urban design*, Ashgate, London, 2013.
- [5] S. Hadi, Formal sustainability in traditional architecture of Iran according to five principles of traditional architecture of Iran, *J. Appl. Environ. Biol. Sci.* 4 (1) (2014) 100–110.
- [6] B.A. Maleki, Traditional sustainable solutions in Iranian desert architecture to solve the energy problem, *Int. J. Tech. Phys. Probl. Eng.* 6 (2011) 84–91.
- [7] M. Kazemi, A.R. Mahmoodabadi, Studying the thermal behavior of winter sections in Yazd traditional homes and its optimum situation, *Int. J. Archit. Urban Dev.* 4 (3) (2014) 30–50.
- [8] R. Eghbali, S. Parvanezhad, An evaluation of the patterns of urban texture design and contemporary and traditional residential buildings in Shiraz against its extreme weather condition, in: *Proceedings of ICSAU, Tehran, Iran, (2014)* [in Persian].
- [9] S. Jalilpoor, A. Dehghan, L. Zare, The presentation of a sustainable pattern based on Iranian traditional buildings (case study: Kashan's Al Yasin Historical house), in: *Proceedings of the National Conference on Architecture and Sustainable Urban Architecture, Tehran, Iran (2014)*.
- [10] M. Akbarian, M. Kazemi, The study of the thermal behavior of cellar in Yazd's traditional houses and its optimum situation, in: *Proceedings of the Architecture and Sustainable Urban Spaces Conference, Mashhad, Iran (2013)*.
- [11] S.A.E. Shojaei, Z. Khodayari, Sustainable architecture in arid regions of Iran, in: *Proceedings of the 5th Symposium on Advances In Science and Technology, Mashhad, Iran (2011)*.
- [12] X. Du, R. Bokel, A. van den Dobbelsteen, Building microclimate and summer thermal comfort in free-running buildings with diverse spaces: a Chinese vernacular house case, *Build. Environ.* 82 (2014) 215–227.
- [13] M. Mahdavejad, K. Javanroodi, M.H. Ghasempoorabadi, M. Bemanian, Evaluating the efficiency of Yazdi wind tower, an experimental study, *Int. J. Archit. Eng. Urban Plan.* 23 (1) (2013) 17–22.
- [14] M. Mahmoudi Zarandi, Analysis on Iranian wind catcher and its effect on natural ventilation as a solution towards sustainable architecture (Case Study: Yazd), *World Acad. Sci. Eng. Technol.* 54 (2009) 574–579.
- [15] M. Moradi, M.M. Mahmoudi, Experimental and numerical Investigation of Shovadan heating and cooling operation, *Renew Energy* 48 (2012) 364–368.
- [16] M. Kasmaei, *Climate & Architecture*, Khak Publication, Isfahan, Isfahan, 2003.