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THE INVESTIGATION OF THE FUNCTION OF THE CENTRAL COURTYARD IN MODERATING THE HARSH ENVIRONMENTAL CONDITIONS OF A HOT AND DRY CLIMATE (CASE STUDY: CITY OF YAZD, IRAN)

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As one of the arid areas of Iran, Yazd is always exposed to extreme winds with dust and shifting sands. Therefore, the architectural principles in the residential architecture of the city need be adapted to such environmental conditions in order to minimize the influence of the severe winds on the interior spaces. This study investigates the influence of storms on the interior space of the central courtyards in Yazd, constructed during the Muzaffarid, Safavid and Qajar periods using CFD simulation. Three-dimensional models were prepared via Gambit software and studied in Fluent software. The wind speed entering the computing field was equal to 26.4m/s and the Dutch wind nuisance standard NEN 8100 was applied as the comfort criterion. The results showed a relationship between the extent of the central courtyard and the impact of severe storms on it, since an increase in the area of the courtyard provides enough space for the wind flow and move around it. This feature reaches its climax if the length to height proportion increases, as the wind brings the shifting sands into large courtyards, therefore, the architects tried to provide better conditions by creating microclimates.

Key words**: residential architecture, Yazd area, CFD simulation, historical houses, storm.**

INTRODUCTION

The city of Yazd is located in an arid area, with summer temperatures very frequently above 40 °C (104 °F) in blazing sunshine and low humidity. Even at night the temperatures in summer are rather uncomfortable. In the winter, the days remain mild and sunny, but in the morning the thin air and low cloud cause very cold temperatures that can sometimes fall well below 0 °C (32 °F). Obviously this climate has a direct effect on the architectural principles in this city (Memarian and Brown, 2003).

Although the wind has always been a comforting element for the people, severe sand storms also affect people's lives at certain times of the year; these more or less destructive winds blow in a north-eastern – south-western direction and usually contain dust and shifting sands, thereby affecting the constructions in the city (Omidvar, 2010).

The historical development of Yazd's residential architecture throughout different periods indicates no significant difference in locating spaces like summer and winter rooms, central courtyards, iwans and so on. Many houses from the Muzaffarid period (1314-1393 CE) and the Qajarid period (1789-1925 CE) have been identified in Yazd, most of which have a southwest-northeast oriented courtyard, since the summer quarters of the house are on the southwest and the winter quarters are located on the north-eastern side of the house. The direction of the house has a direct influence on the comfort of the residents by providing suitable interaction with solar energy, making the best use of the favorable wind and minimizing the effects of harsh winds (Appah-Dankyi and Koranteng, 2012). However, through more precise studies, some differences can be seen in the proportions between the central courtyard and the walls, and each of them has different ways of dealing with the climate in Yazd. The Muzaffarid houses have smaller courtyards with an area that does not exceed 30 m^2, whereas the area of the courtyards increased in the subsequent periods, for instance

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the area of the courtyard of Lariha House is more than 600 m^2. Increasing the area of the courtyard and changing its proportion in relation to the surrounding walls directly influences the life of the residents because these proportions cause the courtyard to receive enough solar radiation and energy in the cold months (Mirdehqan, 2016). Accordingly, the traditional houses of Yazd have courtyards with a variety of different dimensions. The purpose of the current study is to investigate the performance of courtyards in the harsh conditions of the hot and dry climate of Yazd particularly in relation to their dimensions.

REVIEW OF THE RELATED LITERATURE

Climate and architecture are the most fascinating subjects in terms of the influence of the environment on residential buildings specifically and the human living space in general. Throughout history architects have been familiar with climatic factors and their influences over years of experience, so they have striven to control them by the optimal use of environmental factors to improve the living conditions as well as decrease their undesirable effects by means of creative strategies (Widera, 2014).

The role of climatic factors is even more crucial in the province of Yazd, taking into account the environmental conditions of this region. Wind is one of the main influential environmental elements in Yazd and the architectural spaces need to be designed in order to avoid harsh winds as much as possible and yet benefit from the favorable wind for the internal ventilation of buildings (Memarian and Brown, 2003).

Other factors such as dunes also stress the importance of the winds, since they are carried around by winds and clearly influence the lives of the residents. Dust storms require a wind speed of only about 14.4 km/h to lift the dust off the ground; however, most substantial dust storms have a much faster wind speed than this (Elbashan, 1981).

According to the synoptic weather station in Yazd, the wind speed was always more than 15 m/s during June, July and August in the period between 1952 and 2010. The station's wind rose results over the course of twenty years revealed that winds with a north-western – south-eastern directions are the main causes of the sand and dust storms in the region (Ekhtesasi *et al.*, 2006), while the lowest percentage of winds blow in a north-eastern – south-western direction with a relatively low speed (Omidvar, 2010). These storms can be considered as one of the reasons for avoiding the construction of residential space on the south-eastern side of the yard. Therefore, the central yard in the houses in Yazd must be in close interaction with their surrounding environment in order to benefit from suitable climatic condition such as solar energy or favorable winds, and also avoid harsh conditions such as sand storms.

In order to study the influence of the central yards' patterns on moderating the harsh environmental conditions of the hot and dry climate, simulation software was utilized. Using this software, researchers are able to completely simulate buildings and study the interactions between the house and the environment in as close a way as possible to real situations (Hensen *et al.*, 2004). This software can define factors, including the energy consumed within different periods and the cost of consuming energy, as well as make estimations of temperature and humidity, which are the main indicators of the energy performance of a building, in the form of different outputs (*Ibid.)*. In the presented study, to simulate the wind streams FLUENT 6.3.26 software was utilized.

Among studies using similar methods, Sami (2003) used CFD simulation in order to examine the Iranian wind catchers' function in relation to the natural ventilation and comfort in the traditional houses of Yazd. Nguyen *et al.* (2011) also studied the vernacular architecture strategies in providing thermal comfort conditions by means of CFD simulation. The results showed that although the vernacular architecture in Vietnam is totally adapted to the environmental conditions of the country, these houses cannot provide the required thermal comfort for the residents. In another study conducted by Hooshmand Aini *et al.* (2012), a type of wind catcher known as an Egyptian wind catcher was examined by means of CFD simulation. Kristianto *et al.* (2014) used the same method to investigate the indoor thermal comfort conditions in the traditional houses of Minahasa. Natural ventilation produced by underground spaces called Shavadoons[2] in the city of Dezfoul was examined via CFD simulation in the Design Builder software in a study conducted by Hazbei *et al.* (2014). Zarei and Behboodi (2016) used CFD simulation to study the buildings in the central part of Varmal castle settlements in the Sistan and Baluchestan Province, Iran.

Unlike the limited studies on historical houses, there are many studies regarding modern residential architecture, including Tantasavasdi *et al.*, 2001; Wang *et al.*, 2012; Sapian *et al.*, 2012; Zajiček and Kic., 2013; Khan *et al.*, 2014; etc.

GENERAL INTRODUCTION TO THE CITY OF YAZD

The samples required for the present study and the CFD simulation were selected from the city of Yazd. Located at the geographical coordinates of E: 52° 55' - 56° 37' and N: 29° 52' - 33° 27' and with an area of 99.5 km^2 and a population of 500,000, the city is the capital of the Yazd province, Iran (Soltanhosseini *et al.*, 2013) (Figure 1). The climate of this region is hot-dry. Whereas the maximum temperature in the summer reaches 50 °C, the minimum temperature at night in summer reaches 15 °C, which shows high fluctuations in temperature between daytime and night time. The urban design aspect of Yazd city provides a shady area for people (Mashhadi, 2012). Therefore, the city has a compressed urban form whereby all buildings are adjoined (Hejazi and Saradj, 2014).

According to local texts, Yazd was known in early times as Katha, after a fortress and prison alleged to have been founded by Alexander. According to legend, later foundations grew up on this site (Lambton, 2007). There is not much information about this city after the arrival of Islam in Iran by the 5th century AD; however, the archaeological data acquired from three seasons of excavation and speculation in the old city have not revealed any remains older than the early Islamic centuries (Mirdehqan *et al.* 2014). In the

[2] A space built at the depth of 5 to 12 meters underground to moderate and adapt the houses' climatic conditions.

11th century AD, the Kakuyids ruled (c. 1008–c. 1051) in Yazd. Within this period, there were many activities in the development and prosperity of the city of Yazd, including the construction of the tower of the city and various buildings with different usages, such as schools, mosques, inns, etc. (Katib, 1965). The shrine of Davazadeh Imam in the Fahadan neighborhood is one of the few memorials of this period, which, according to the inscription, was built in 1036 AD (Anisi, 2009).

After the Kakuyids, the Atabegs (c. 1141–c. 1319) gained power. For this period, there are also many measures regarding the development of the city that can be referred to as the expansion and modernization of the tower of Yazd and the construction of various buildings such as schools, mosques, inns, etc. (Katib, 1965). One of the most devastating events in this period was the Mongol invasion of Iran; however, Yazd was protected against the danger of destruction because of the policies adopted by the Atabaki ruler of Yazd.

It should be noted that the Muzaffarid period (c. 1314–c. 1393) is one of the most important historical periods in Yazd. Due to the great power of this family, Yazd became one of the most important cities of Iran at that time (Katib, 1965). Some of the measures that this dynasty made for the development of Yazd were the expansion of the city of Yazd and its neighborhoods inside the wall, the development of the tower, the securitization of the roads that led to the city's commercial prosperity, and the construction of various buildings such as mosques, schools, monasteries and inns. These actions caused Yazd to become one of the major cities of its time (Mustowfi Bafqi, 2006). During the attack of Amir Timur (c. 1370–c. 1405), the Muzaffarid dynasty collapsed, and until the formation of the Khavanin dynasty (c. 1748–c. 1830) Yazd was run by rulers appointed by the central government (Lambton, 2007). However, during the reign of Amir Chakhmmaq Shami, some measures were taken to further its development, yet the city lost its past prosperity.

During the time when the Khavanin Dynasty ruled, Yazd attained its importance again, and this dynasty did much for its development and prosperity. After this dynasty, by the end of the Qajar period (c. 1789–c. 1925), Yazd was run by rulers determined by the central government (*Ibid*).

THE SAMPLE HOUSES

As one of the most important elements for houses in a hot and dry climate, the courtyard has different usages (Memarian and Brown, 2006). "In the compact urban texture of historic towns such as Yazd, the house is usually bounded either by neighbouring dwellings or by narrow streets. Access could be circuitous and, for the reasons of privacy, openings on to the external spaces were avoided. The house was therefore entirely inward-looking and the courtyard became a small garden, which, with its pool, provided a cool space in the spring and summer. Also, seasonal rooms, private and reception areas were organised around different parts of the courtyard, which served to relate these different spaces one to another." (Memarian and Brown, 2003).

In addition, this element was important due to the climate, because it provided a microclimate inside the house, which created conditions for thermal comfort and reduced the amount of energy required to cool the building (Al-saud and Al-hemiddi, 2006). Accordingly, the important role of the yard in the hot and dry climate of Yazd region can be recognized. With regard to the purpose of the present research, three houses were selected as case studies, each of which has different dimensions of its courtyard. The aim of the selection of these examples was to investigate the relationship between the dimensions and proportions of the courtyard and its performance in creating comfortable conditions in the interior of the house in the hot and dry climate of the Yazd region, and also to investigate which one of the samples showed better performance.

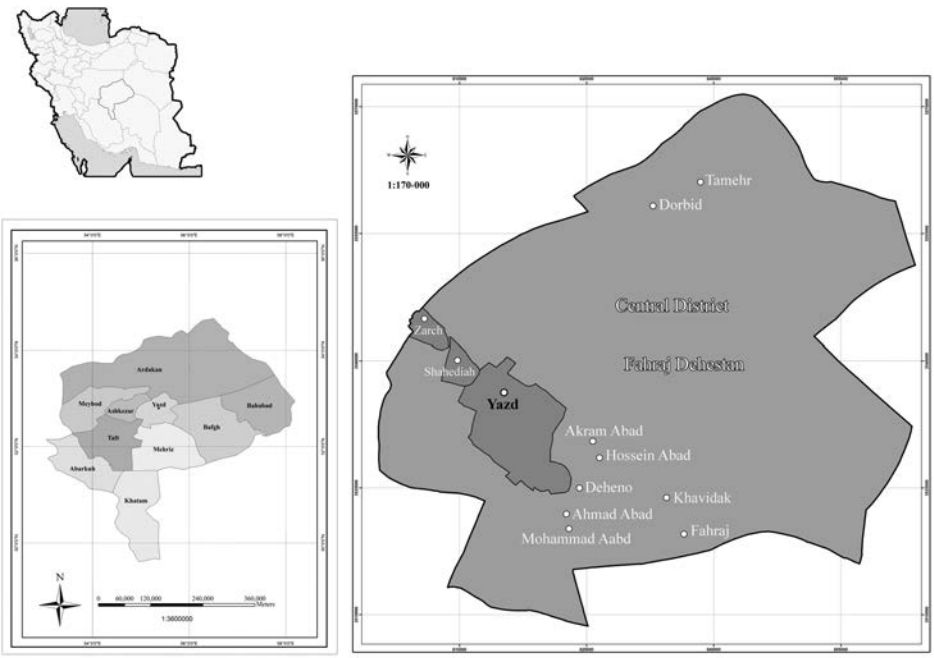


Figure 1. The location of the city of Yazd in the province of Yazd
(Source: Archive of cultural heritage, handicrafts and tourism of Yazd Province)

Like all traditional houses in Yazd, the three selected houses had a western south–eastern north orientation, and with the exception of the south-eastern front, residential spaces were spread over the other three fronts. As already mentioned, the reason for the lack of residential space on this front from the yard was the dominant wind direction that affected it.

The house of Karimi dates back to the Muzaffarid period. The entrance of the house, which has been destroyed, was on the north-eastern side of the house, and like similar houses it was connected to the central courtyard through a small iwan (eiwancheh)[3] with ninety-degree rotation. The area of the small, rectangular courtyard is about 17 m^2. The summer quarters of the house are on the south-western side and the winter quarters are on the north-eastern side of the courtyard. There are two small iwans (eiwancheh) on the other two sides of the courtyard providing access to other spaces and the roof as well. The main iwan is 8 meters high and stands much higher than the rest of the building; access to the adjoining chambers is only possible through this iwan. The garden behind the house, mentioned in local historic texts like the Sarabostan (Katib, 1965), has been totally destroyed. There is also a chamber behind the small iwan on the north-eastern side of the central courtyard which is only accessible through the small iwan (Figure 2). The length and width proportion of the courtyard in Karimi's house is about 1.27 and the proportion of the length and height, except the southwest side, is about 1.1 (Table 1). Note that the houses from the Muzzafarid period identified in different cities and villages of the Yazd region are comparable with each other in terms of their plan and proportion, and particularly their style of decoration (Zarei *et al*., 2016). For example, Boruni House is fully decorated, especially with mud decorations, while Karimi House is decorated using the common simple methods of that period *(Ibid*).

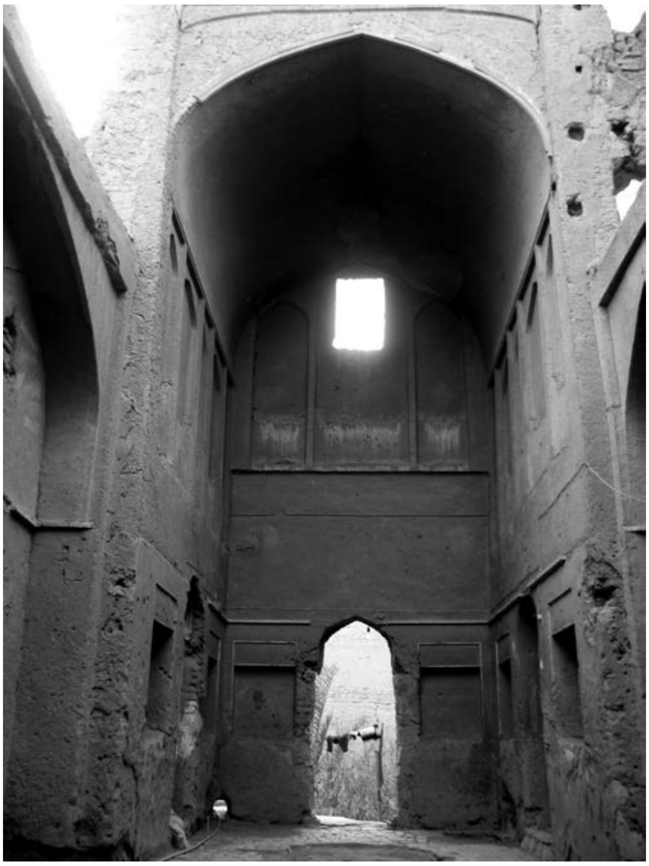


Figure 2: Karimi house
(Source: Archive of cultural heritage, handicrafts and tourism of Yazd Province)

The Mashrootah House is located in the Shahzadeh Fazel Community. The central courtyard of the house with an area of 104 m^2 has created a microclimate by means of having several trees around a central pool. The summer quarters, with a large iwan and two wind catchers (Bad-gir) in each chamber of the room, are on the southwest side of the building and they are right in front of the winter quarters. Two entrances on both sides of the iwan provide access to this chamber. The residential units are built on the northwest of the courtyard, yet there is no residential section on the south-eastern side (Figure 3). The proportion of the length and width of the yard in this house is 1.3 and the proportion of the height and length of it is about 0.5 (Table 2).

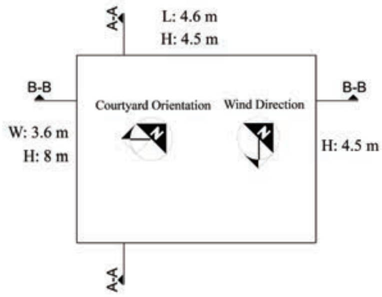
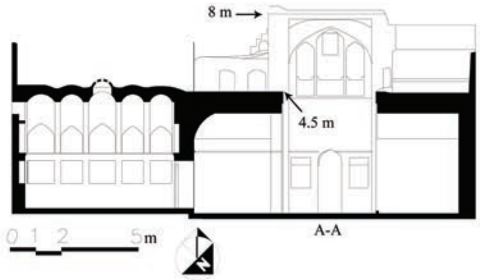
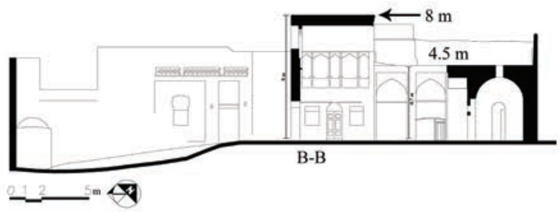
The Shokuhi House dates back to the Qajar period, located in the Chaharsuq Community in the city of Yazd. The house contains four courtyards. The main one, which is called the inner courtyard (Andaruni[4]), has an area of 379 m^2 and like the previous sample has a microclimate influenced by means of several trees and a central pool. The hall (summer quarters) of the house is on the south-western side and the winter quarters (Panjdari) are right in front of it. Despite the construction of the residential units on the north-eastern side of the courtyard with seasonal functions, the south-eastern side has no residential units. The other courtyard, which is called the outer courtyard (Biruni) also contains summer and winter quarters, as well as a small courtyard used to provide access to other adjoining sections such as the stable. The house has an octagonal wind catcher (Bad-gir),

Figure 3: Mashrootah house
(Source: Archive of cultural heritage, handicrafts and tourism of Yazd Province)

[3] In Iranian architecture, the Eiwancheh is a semi-open space that is smaller than the Iwan and provides access to other spaces (Shams 2009). It can be seen in some historical monuments such as the Shrine of Masoumeh in Qom (Blair, 1984).

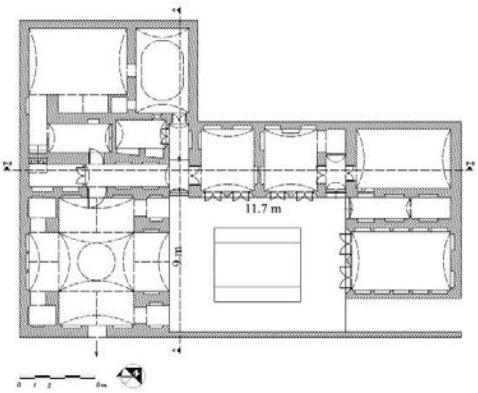
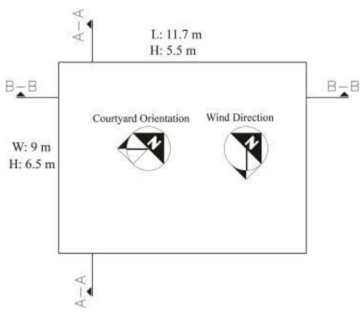
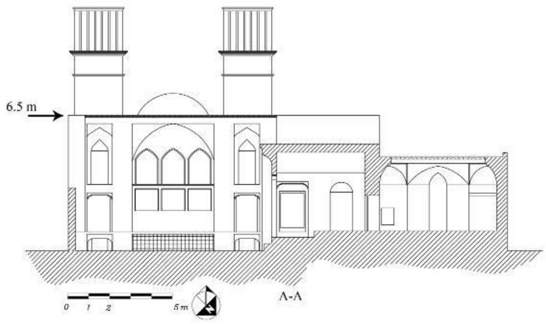
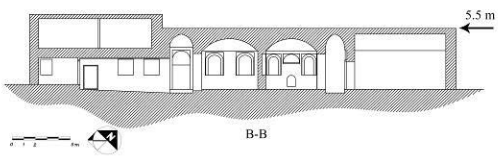
[4] In traditional Persian residential architecture, the andaruni, is in contrast to the biruni, and is part of the house in which the private quarters are established. This is specifically where the women of the House are free to move about without being seen by outsiders (Amiriparyan and Kiani, 2016)

Table 1. Karimi house

Plan and Proportions and courtyard's wall sizes		
Sections	 	
courtyard's Proportion	L/W ≈ 1.27 South-western Side: H/W ≈2.2 north-eastern Side : H/W ≈1.1 Other Sides: H/L ≈1.1	

(Source of Plan and sections: Archive of cultural heritage, handicrafts and tourism of Yazd Province)

Table 2. Mashrootah house

Plan and Proportions and courtyard's wall sizes		
Sections	 	
courtyard's Proportion	*L/W ≈ 1.3 H/W ≈0.7 H/L ≈ 0.5*	

(Source of Plan and sections: Archive of cultural heritage, handicrafts and tourism of Yazd Province)

and the Narnijestan yard[5] is right behind it with chambers on both sides (Figure 4). The proportion of the length and width of the courtyard to each other is approximately 1.17 the proportion of the height to length is 0.27 (Table 3).

METHODS

The main objective of the present study was to simulate the CFD using Fluent software in order to simulate the severe winds and storms blowing in the central courtyards of the three sample houses from the Muzzafarid, Safavid and Qajar periods. Gambit pre-processing software was utilized in order to construct three-dimensional models of the houses and then Fluent software was used to analyze the wind flow around them (Figure 5).

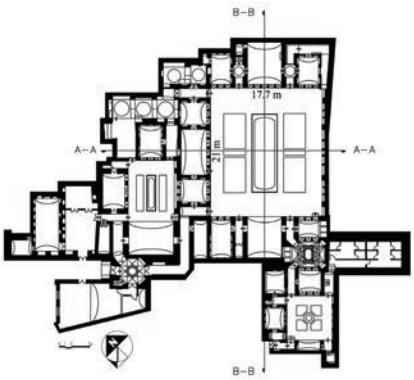
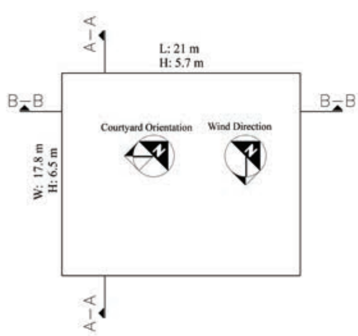
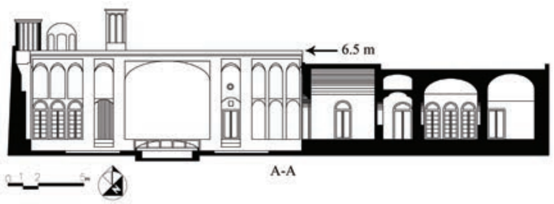
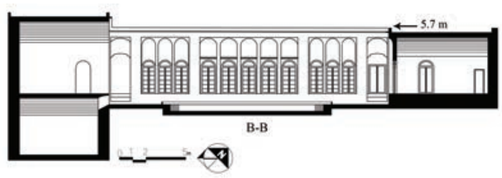
[5] A very small yard where the citrus, fruits and plants can be protected against the winter cold. (Amiriparyan and Kiani, 2016)

A numerical analysis was conducted in order to confirm the confrontation of the wind and the interior central courtyard of the houses. The theoretical approach of the analysis is based on the steady state solution of the three-dimensional equations of mass and momentum of the wind flow for the low-speed turbulent isothermal flows in the computing field. K-epsilon was the turbulence model considered in this study. The velocity boundary condition at the entrance point was determined based on the northwest – southeast direction of the wind perpendicular to the building. Regarding the extension of the computing field and the distance of the area's frontiers from each building, the boundary condition for the sides and top of the building was considered as symmetry and it was considered as the wind's outflow for the outlet.

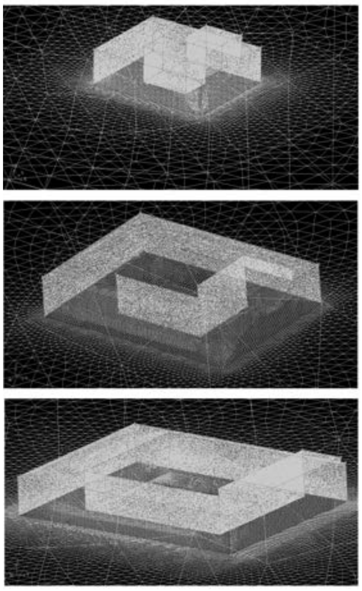
The simulated storm took place on May 29, 2003 and its influence was studied on the interior spaces of the

Figure 4. Shokuhi house
(Source: Archive of cultural heritage, handicrafts and tourism of Yazd Province)

Table 3. Shokuhi house

Plan and Proportions and courtyard's wall sizes		
Sections		
courtyard's Proportions	*L/W ≈ 1.17 H/W ≈0.36 H/L≈ 0.27*	

(Source of Plan and sections: Archive of cultural heritage, handicrafts and tourism of Yazd Province)



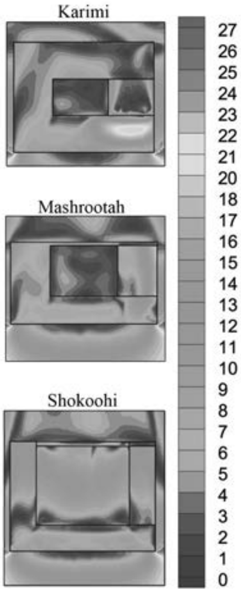


Figure 5 (left). Schematic view and the three-dimensional models of each of the houses in the computing field, respectively from up: Karimi, Mashrootah and Shokuhi

Figure 6 (right). The comfort condition of the central courtyard in stormy conditions on a plate with 1.75 meters height from the ground

houses' courtyards. This storm, with a dominant north-western direction passed through a large area with a speed of more than 25 m/s which increased up to 26.4 m/s in the city of Yazd and continued for 22 hours and 30 minutes of local time with lower speed. The storm caused severe dust in the region, which reduced the horizontal viewing to zero. The ambient pressure and temperature were 876.2 Hpa and 31° Celsius with a viscosity of N.s/m2-5 1/844 × 10, respectively (Omidvar, 2010); therefore, the wind's speed was considered to be 26.4 m/s in the simulation process. The elevation plate (contour plate) was considered as 1.75 m in order to assess the comfort condition. An elevation plate (contour plate) means that the wind flow condition is studied at this elevation and the results are clear; this elevation is almost equal to the average height of an adult who stands in the courtyard and feels the flow of the wind and the sand on his face. In other words, a hypothetical plate with a height of 1.75 m was considered in the courtyard and the wind speed in different parts of this plate is specified as a colored map. The descriptive mathematical equations were discretized using the finite volume method and the SIMPLE numerical method was also applied for coupling the velocity and pressure equations. The convergence criterion in a steady flow field for this matter was considered with an accuracy of 10-5 for all flow variables.

RESULTS

The results of the simulations revealed that the wind approached the north-western side of the buildings in all of the cases (bottom of the image) and passed through the south-eastern side (top of the image). The wind's flow reduced due to collision with the buildings and entered the central courtyard from the upper edge of the building and flowed all over the courtyard at different speeds. As the objective of the present study was to assess the comfort condition of the interior courtyard of the houses in stormy weather, the Dutch wind nuisance standard NEN 8100 was applied as the comfort criteria.

According to this standard, activities are divided into three categories of sitting, strolling and traversing so that the comfort conditions can be categorized into three states of good, moderate or poor at different rates of speed. Note that the speed threshold for the safety of the individuals is 15 m/s (Jadidi and Heidarinejad, 2014). Table 4 shows the summary of the comfort standard in the Dutch wind nuisance standard NEN 8100.

The initial velocity of the wind in all samples was identical and equal to 26.4 m/s. Figure 6 represents the wind's speed inside the central courtyard of Karimi house as 0 - 4 m/s in almost every corner of the courtyard; it also created a high speed eddy current in a small part of the courtyard, right in front of the winter quarters of the building whose quantitative value was approximately around 4 - 7 m/s. According to the Dutch standards, those parts of the house with low wind flow speed have comfort conditions in all of the three states; while in those parts with a wind speed of 2.5 – 3 m/s, the comfort condition is moderate for a sitting person, however, the two other states have good comfort conditions.

Figure 6 shows the wind speed in the courtyards of the Mashrootah where the speed is between 0 – 5 m/s. In comparison with the former case, the larger the courtyard the larger the area for swirling the wind and creating more and bigger eddy currents inside the courtyard; as a result, the wind flows at a higher speed in a larger space, and the quantitative amount is around 5 – 8 m/s. The Dutch criteria showed that most of the central courtyard of this house provides good comfort conditions for traversing and strolling positions while the comfort condition for the sitting position

Table 4. The summary of the comfort standard in the Dutch wind nuisance standard NEN 8100

Probability of Exceedance $P(V_{loc} > V_{threshold;wind\ nuisance})$ in percentages of the number of hours per year	Quality-level	Activity-level		
		I. Walking, normal pace	II. Walking Leisurely-strolling	III. Sitting longer time
< 2.5	A	Good	Good	Good
2.5 – 5	B	Good	Good	Moderate
5 – 10	C	Good	Moderate	Poor
10 – 20	D	Moderate	Poor	Poor
≥ 20	E	Poor	Poor	Poor

(Source: Aanen & Van Uffelen, 2009)

is moderate. However, in those parts of the courtyard which are capable of causing the eddy currents, only someone who is traversing can have comfortable conditions, while for strolling or sitting, the comfort conditions are poor.

The area of the courtyard in Shokuhi House is larger than the two previous cases. According to Figure 6, the analysis of the wind flow in the courtyard shows that the wind blows at high-speed in most of the courtyard and that it blows far from the front edge of the roof with a quantitative amount between 8 – 13 m/s. Note that the high speed of the wind affects the main iwan and the turmoil and high speed flow is obviously visible in that part, while this part was calmer in the two previously mentioned houses. The wind flow speed was only reduced between 0 – 2 m/s in a narrow strip area near the north-western side of the building which is where the wind enters the courtyard.

According to the Dutch standards, only this small part has suitable comfort conditions; however, most of the courtyard provides moderate comfort conditions for someone who is traversing and poor comfort conditions for a person who is strolling or sitting, which is due to the larger area of the courtyard in comparison with the other two houses. Moreover, the stronger the wind blows, the more the dust and sand spread inside the house and reduce the thermal comfort conditions of the house.

CONCLUSION

The presence of the courtyard in the traditional houses of Yazd has played an important role in creating thermal comfort conditions because it was considered as one of the key spaces in the home, which allowed access to most of the home spaces. The results of simulations show that houses with a length to height proportion of nearly 1.1 have better performance in hurricane conditions, since when the length and height proportion of the yard is close together, it creates a closed space that reduces the wind speed inside the central courtyard. This performance can be seen at Karimi house because the wind speed in the interior of the house is about 11 km / h. If this proportion changes and the length to height proportion increases, the courtyard will show a weaker performance, because the yard has enough space to inflate the wind and make non-thermal comfort conditions. This feature is visible in Shokouhí house because the wind speed in the interior of the house is around 46.8 km / h. The large central yard provides enough space for the wind to carry sand and dust inside the yard and disturb the residents. Creating a microclimate by means of planting trees and constructing central pools is a solution to overcome this problem; this is because the trees can act as a barrier against the wind and decrease the wind speed, and also the pool's water can absorb the particles in the air and prevent them from spreading everywhere in the house.

The simulation results indicate a direct relation between the courtyard area and the level of its interaction with strong storms. In small yards, like the Muzzafarid yards, this interaction is very desirable, while increasing the central yards' area directly influences this interaction, so the microclimate is used as a way to ameliorate the comfort condition. Modern designers can be inspired by this pattern in designing constructions and the use of small courtyards recommended for contemporary architecture by specifying the size, position, and the height of the walls in a hot and dry climate. Also, it can be said that the courtyard in the traditional houses of Yazd, with proper distribution of residential spaces, provides residents with thermal comfort and reduces the impact of the hot and dry climatic conditions in the Yazd area in the interior of the house, which has direct a connection to its the proper orientation.

Moreover, the high potential of the simulation software utilized in this study was also considerably useful in studying historical monuments from different aspects; since it provided precise results in the shortest time possible and at the lowest price. This software can be a great help in studying buildings that are partially destroyed, yet their proportions are still measurable; it is also possible to achieve a better comprehension about the architectural elements of different periods in order to apply previous experiences to modern architecture.

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