



# Article Natural Ventilation in Vernacular Architecture of Sistan, Iran; Classification and CFD Study of Compound Rooms

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Abstract: Extensive energy consumption in construction and ventilation has caused numerous environmental problems alongside huge waste of nonrenewable natural resources in today's world. Meanwhile, vernacular architecture has been able to sustainably adapt to climate by developing creative and local solutions which provide a comfortable living environment, consume less energy and cause less pollution than the new ways of construction, one of which is wind induced ventilation. Vernacular architecture of Sistan (southeast of Iran) is not an exception to this rule. It utilizes its own set of unique elements and techniques that are compatible with region's climate. This original article studies wind induced ventilation and its elements in Sistan's architecture, including: (1) roofs (Sistani, Filpush and Barrel); (2) ventilator openings (Kolak, Surak and Dariche); and (3) walls. Then, this paper continues to classify three different compound room types in Sistan's architecture, based on orientation and use of mentioned elements by documenting thirty-two sample houses across the region: (1) stretched against the prevailing winds; (2) stretched aligned with the winds; and (3) L shaped. CFD simulations are used to study the wind behavior and evaluate the ventilation performance of these room-types. These simulations lead to guidelines to enhance the ventilation performance of existing buildings and future constructions, including: where to put the windows, which orientation maximizes the natural ventilation performance, where to consider precautions to block the undesirable winds from entering and how far from each other should different room types be built.

Keywords: vernacular architecture; natural ventilation; Sistan; Iran; CFD simulation

## 1. Introduction

One of the main concerns in the contemporary world is to reach an equilibrium equation between man and environment [1]. The gap between these two has exacerbated drastically in the recent century due to the extensive constructions across the globe. These constructions were supposed to solve the problems caused by massive increase in the population and provide a better living environment for mankind, but had the opposite effect. Not paying enough attention to climate factors and being heavily dependent on electro-mechanical devices to provide a comfortable setting [2], mentioned constructions are now considered to be one of the main sources of the environmental crises facing the earth.

More than a third of all of the world's energy is spent on heating and cooling buildings [3]. This massive energy consumption leads to pollution of natural resources across the globe, especially in less developed countries with less clean technologies [4].

On the other hand, traditional climate aware construction, known as vernacular architecture, has been able to sustainably adapt to climate, consume less energy and cause less pollution than the new constructions [5,6]. A vernacular building refers to a building built by local people using traditional technologies from locally available materials matching the environmental context to accommodate domestic ways of life [7]. This kind of building and architecture is able to achieve three key themes of self-sustainability which are as follows [8]:

- 1. Managing natural environment, protecting its sources and ecological system.
- 2. Managing financial aspects, reducing costs and increasing values.
- 3. Improving social responsibility to improve the quality of life and equality among individuals and groups.

Despite all of the developments and innovations in the field of construction, a considerable number of Iranians still live in vernacular dwellings and continue to build such buildings [7]. Regarding the harsh outdoor conditions such as heat storms, frost bites and wind flow with dune sands, this method of construction has been able to create a suitable indoor environment and continues to do so [9].

Any form of architecture, including vernacular, is interdependently related to its local cultural and environmental context [10]. Iranian vernacular architects and masons have come up with different solutions according to different cultures and climates across the country; for example, vernacular architecture of Yazd (center of Iran) uses its own special wind-catchers to ventilate the building; in Bushehr Port (south of Iran near the Persian Gulf), native people have come up with Shanashils, which are porous wooden cantilever boxes working as terraces, blocking the harsh sunlight and letting in the cool breeze coming from the sea; and in Gilan (north of Iran near the Caspian Sea), which has moderate weather, the people build open terraces all over their houses above the ground level with only a wooden railing for safety and let in the cool breeze from every front. There are several other examples from all over the country and there have been numerous studies about them in different resources but this paper specifically concentrates on Sistan.

Comparing to other regions, Sistan (located in the southeast of Iran) has almost gone unattended and few studies have been carried out on its vernacular architecture. Vernacular architecture of hot-arid-windy region of Sistan exhibits its own set of defining aspects [11,12]. It is generated from a single cell room (called "khoná" in native language) and is mainly affected by two factors: 120-Days Winds and the presence of "Hamoun" Lake [13,14]. Native masons of Sistan have come up with innovative solutions and elements in response to these factors to reduce the energy consumption, utilize natural ventilation, provide a comfortable setting and shape a sustainable method of construction [15].

This paper seeks to detect and categorize these elements and solutions through a comprehensive field study on rural houses across Sistan; and categorize different types of compound rooms and decide the best scheme for future constructions in the region using simulation/analysis studies of wind flow in different room types that are recognized in the field studies.

#### 2. Literature Review

Numerous studies have been done on the issue of natural ventilation and its role in buildings. Alongside these efforts, Computational Fluid Dynamics (CFD) has become a very powerful and popular tool in building simulation and has been widely used to simulate indoor and outdoor airflow, heat transfer, containment transport [16] and in a wider sense, natural ventilation performance of buildings [17].

Van Hooff and Blocken [18] categorize different methods to assess natural ventilation into three sections: full-scale measurements, reduced scale measurements and CFD and describe the advantages and disadvantages of each. As they have argued in their paper [18], one of these advantages is that CFD simulations easily allow parametric studies to evaluate alternative design configurations, especially when different configurations are all a priori embedded within the same

computational domain and grid, which the most principal reason for using CFD simulations in this article.

Several studies have been done on Iran's vernacular architecture using CFD simulations on single buildings [19,20]. For example Montazeri and Azizian [21] have studied the performance of one sided wind-catcher using CFD and Montazeri and Montazeri [22] have studied the performance of two-sided wind-catchers. At the international level, Mora-Pérez and Guillen-Guillamón [23] evaluated the façade opening distribution impact on natural ventilation performance in Valencian coastal region and Liu and Huang [24] tried to find out the natural ventilation values and limitations of "Yinzi" dwellings as well as designing an optimum ventilation strategy for such dwellings in their paper. Similar studies were carried out on native wind-catchers of Sistan in this paper.

The people of Sistan have built their homes in exceptional harmony with the environment for centuries now. There are several resources that certify this fact; one of the oldest resources available is the written report of "George Peter Tate", British historian and archeologist who resided in Sistan between 1903 and 1905. Describing the features of Sistans architecture, he wrote: "Sistan people show great skills in adapting to environment factors. Their residents are built in remarkable harmony with region's climate [25]". Most of the studies on architecture and vernacular housing in Sistan region are qualitative and use a descriptive/analytical approach. The documentation of "Qele-no" village in Sistan by Davtalab [26] was done to present the vernacular architecture of this village; some of the sample documented houses in this article are chosen from this village. Ali Sargazi [27] has described different techniques used by native people of Sistan to achieve a sustainable environment in their vernacular houses; this paper has followed the same goal but with a different approach. Fazelniya and Kiani [14] studied the accordance of native pattern of physical development of "Tombaka" Village in Sistan with the direction of sand storms of the region and suggested this pattern to be used in the design of new developments across the region; this paper has checked these qualitative speculations using numerical studies with CFD simulations. Yarmohammadi and Akrami [28] have studied the common natural ventilation systems in "Khor" village with a similar climate to Sistan region. Mirlotfi and Tavakoly [15] have tried to propose practical scientific solutions to construct rural houses in Sistan, and this paper has suggested several guidelines based on its findings.

Concerning how vernacular architecture deals with natural ventilation, Khalili and Amindeldar [9] studied the traditional solutions of vernacular architecture in hot-arid regions of Iran. Saadatian and Haw [29] reviewed and provided a comprehensive literature on wind-catcher system for space cooling and ventilation. Haghighi and Golshaahi [30] studied the role of vaulted roofs in natural ventilation of vernacular buildings in Iran. Foruzanmehr and Vellinga [10] surveyed how prevalent the passive vernacular cooling systems are in Iran's different regions, as is done in this paper across Sistan.

However, there are no comprehensive studies available about natural wind induced ventilation in Sistan vernacular architecture based on Computational wind Engineering (CWE), applying Computational Fluid Dynamics (CFD) method to reach concrete data.

#### 3. Materials and Methods

This paper seeks to identify different types of Khoná (rooms) as the generative single cell of vernacular architecture in Sistan according to their natural wind induced ventilation performance, study the wind's behavior in each room type and propose practical solutions for future constructions. The research process is divided into three sections:

1. Qualitative phase: In this phase, vernacular architecture of Sistan, its aspects and elements were studied through a comprehensive literature review, which was discussed in previous manuscript [12], a series of interviews with local masons and direct field studies carried out across the whole region of Sistan. The interviews were a series of informal conversations between authors and native masons, which is a dying profession, with only few who are still alive. They are the living history of the region's architecture and are commonly known and greatly respected in academic society of architects. Some of the questions that were asked during these interviews include: "how did you supply the necessary materials?", "how did

you used to build the roofs without any scaffolds?", "how did you make sure that ventilator openings would work correctly?", "how did you choose the right openings for each house, etc. This section resulted in identification and classification of different compound room types.

- 2. Quantitative phase: Parameters involved in natural ventilation were detected and ventilation simulations were carried out on all three identified compound room types using Gambit<sup>™</sup> and Ansys Fluent<sup>™</sup> software. There were no existing similar studies in the field to refer to and the authors have used an original approach to achieve their goal in this phase.
- 3. Verification phase: Considering the necessity to verify the results of the CFD simulations [31], the results were confirmed, using an empirical research method and direct measurements in a period of four months using a digital anemometer (June to September 2015). In the end, according to the verifications achieved in the third phase, the simulation results were confirmed and concluding guidelines were educed (Figure 1).



Figure 1. Research Process.

# 4. Sistan

Sistan region (30°5′N–31°28′N and 61°15′E–61°50′E) in the southeast of Iran is located close to the joint borders between Iran, Pakistan and Afghanistan [32].

Sistan is a lowland shaped by the alluviums of "Hirmand" river, the longest river in Afghanistan and the main watershed for Sistan basin. Hirmand River (or as it is known in Afghanistan: "Helmand" River) finally drains into the natural swamp of "Hamoun" Lake, the greatest sweet water lake on the planet (before the previous droughts) located in the northern and western parts of Sistan region [33]. This lake plays an important role in providing the whole region with humidity. Prevalent winds of the region pass this lake on their way to the population centers and move the lake's humidity to these parts, providing them with a cool pleasant breeze during the hot summer days, an important factor in natural ventilation performance of Sistan vernacular houses (Figure 2).

According to the weather information of the last 30 years, Sistan has a hot arid climate with an annual average precipitation of 55 mm occurring mainly in winter (December to February) while its evaporation exceeds ~4000 mm/year as a result of high temperatures and frequent winds (Figure 3) [34,35].



Figure 2. Sistan's location in the world.



**Figure 3.** Minimum and maximum temperature, precipitation and wind speed between October 2014 and October 2016 in Zabol city, Sistan's capital [35].

In summer and specifically in an approximately 120-Days period, between June and September, strong northern winds called "Levãr" in the native language, also known as "120-Days Winds" [36] affect the area, passing Hamoun Lake and spreading its humidity across the region and also (due to recent droughts) causing frequent storms of great magnitude and velocity [37]. These winds are the most important climatic feature of the region and heavily affect different aspects of natives' lives, especially their built environment. As Figure 4 shows, the direction of these prevalent winds is from north and northwest to the southeast with an average speed of ~32 km/h [38] (Figure 5), conveniently passing Hamoun Lake on their way to the region and spreading their humidity through the populated areas in southeastern parts of the region [39] (Figure 6).



Figure 4. Wind-rose diagram in a period of 30 years in Zabol city, Sistan's capital [35].



Figure 5. Monthly Wind speed diagram in a period of 30 years in Zabol city, Sistan's capital [35].



**Figure 6.** 120-Days Winds' direction. Circles show population centers: (**a**) before droughts; and (**b**) after droughts [40].

## 5. Sistan's Vernacular Architecture

Climatic factors play an important role in the day-to-day lives of native people in every region. As mentioned in the previous section, in Sistan, the most influential climatic factors are 120-Days Winds and Hamoun Lake. To deal with these two factors, Indigenous people of Sistan have come up with sustainable as well as viable solutions that can be easily recognized in different aspects of their lives, from their traditional attire to their vernacular architecture [12,41–44].

The history of architecture exhibits a positive correlation between the environment and vernacular buildings which are designed with respect to climatic requirements and socio-cultural contexts [45]. The vernacular architecture of Sistan is not an exception to this rule; it uses different elements and mechanisms to overcome the climatic conditions and provide the dwellers with a comfortable living environment [46,47].

To detect the most commonly used elements and techniques, a comprehensive field study was carried out across the region to document a sample population of vernacular houses and determine their different aspects of sustainability. Thirty-two vernacular houses were chosen from the most intact buildings in the region and across all districts of Sistan. Number of houses in each district was decided in terms of the number of villages in that district (Table 1 and Figure 7).

City/Town	Dependent The Percent of Dependent Villages Villages		Respective House Number for Each City or Town	
"Zabol" City	77	9.5%	3	
"Zahak" Town	148	19.7%	6	
"Hamoun" Town	160	19.8%	7	
"Hirmand" Town	305	27%	12	
"Nimrouz" Town	118	14%	4	
Total	808	100%	32	

Table 1. The number of documented houses in each district of Sistan.



Figure 7. Documented vernacular houses across Sistan.

According to the field studies and documentations carried out on these houses, different elements and techniques of vernacular architecture of Sistan are presented in the following sections.

## 5.1. Roofs

Three different roof types were identified in Sistan vernacular architecture: (1) Sistani; (2) Filpush; and (3) Barrel Domes. Among these three, Sistani Roof is the native roof of the region [43,44] and has not been documented elsewhere in Iran. According to the field studies and surveyed samples, Sistani roof is the most frequent type of roofs in living rooms and Filpush roof with 50% is the most common one in service rooms (Table 2). 3D modeling of these roofs shows that the volume underneath the Sistani dome is greater than any other type of roof in vernacular architecture of Iran which helps this type of roof hold a great volume of warm air underneath itself, far from the ground, where the residents live and work; this fact helps provide a better airflow in the room and a more comfortable and cooler living environment.

Living Rooms					
Room	Daricheh	Sorak	Kolak Count	Roof Count	Roof
Count	Count	Count			Percentage
				Sistani = 125	83%
150	95 (63%)	37 (24.5%)	126 (85%)	Filpush = 16	~11%
				Barrel = 9	6%
Service Rooms					
Room	Daricheh	Sorak	Valak Count	Roof Count	Roof
Count	Count	Count	Kolak Count	Kool Count	Percentage
				Sistani = 12	33%
36	0	0	25 (70%)	Filpush = 18	50%
				Barrel = 6	~17%

Table 2. Frequency of use of each element in Living rooms.

#### 5.2. Ventilator Openings

Three different ventilator openings were identified in Sistan vernacular architecture: (1) Kolak; (2) Surak; and (3) Daricheh (Figure 8), none of which is documented elsewhere in the country. The fact that prevalent wind (120-Days Winds) is constantly blowing in hot months of the year has lead native people of Sistan to manipulate the winds through special openings in their houses' walls and roofs. These openings let the cool wind in, naturally ventilate the interior space, provide these spaces with fresh air and also play an important role in the hygiene of the dwellers [11,48].



Figure 8. Elements of natural ventilation in vernacular architecture of Sistan.

Kolak (Kōlak) is the native wind-catcher of Sistan. Wind-catchers in other regions of the country are normally tall structures over the building roofs working as a canal to direct the wind into the building through an opening in the roofs. However, in Sistan, since 120-Days Winds blow in lower

altitudes near the ground [39], the wind-catchers are far shorter comparing to those of Yazd or other central parts of Iran where wind blows at higher altitudes [49]; Kolaks are only open in one side and all of them face the northwestern winds. Suraks (Sü rrak) are oblique openings in higher part of the northern walls facing the northwestern winds. Darichehs (Da ri chə) are straight canals in lower part of the northern walls facing the same winds [43,47].

# 5.3. Walls

The main material used in vernacular houses in Sistan is adobe. It is made from the soil of the region which is abundant with clay (making it ideal to make adobe ingots) [50]. In hot arid regions of Iran, such as Sistan, walls are mostly made of adobe which can be easily dampened or slightly wetted by manual spraying of water in hot days of summer. These thick adobe walls (40 cm to 100 cm) work as temperature hampers and help keep the inside temperature of the house in a comfortable range—a great contribution to natural ventilation efforts in the building. Domes, Kolaks, Suraks and Darichehs provide the building with wind induced ventilation and prevent the living space from getting too humid or damp; thus, dwellers will experience a comfortable setting, especially during hot summer days [51]. These elements and their construction methods are illustrated in Table 3.

Table 3. Elements of Vernacular architecture in Sistan and their construction method.

Category	Element	Photo	Construction Method	Illustration
Roofs	Sistani Roof	Sistani roof, native roof of Sistan	Sistani roof is made of oblique arches built simultaneously on two sides of the roof which finally meet in the middle [11,47,48]. The volume underneath this roof is greater than any other roof in vernacular architecture of Iran which helps this roof hold a great volume of warm air underneath itself; this fact helps provide a better air-flow in the room and a more comfortable living environment.	Sistani roof, construction method
	Filpush Roof	Filpush roof	Vaults with different heights are built on all corners until they all meet in the middle and the room is covered [11,47,48]. This roof can also hold a great amount of warm air underneath itself and help provide a more comfertable setting near the ground.	Filpush roof, construction method
	Barrel Roof	Image: Arrel Vault	Barrel vaults are usually used in narrow rooms with great length. Building process starts from one side of the room and numerous individual arches are built side by side until the whole span is covered; then, sides of the vault are blocked by straight vertical walls ("Espa'ar" in native language) [11,47,52]. This roof can also hold a significant amount of warm air underneath itself and help provide a more comfertable setting near the ground.	Barrel Vault, construction method

40



Native one-sided wind-catcher

#### 6. Defining Different Room Types for Simulation

To decide and categorize different room types in vernacular architecture of Sistan through virtual simulations in Ansys Fluent<sup>TM</sup> software, first, main involved parameters in the room ventilation are determined considering the data presented in Table 3. According to field studies and documentation of sample houses, there are two general groups of rooms in Sistan vernacular houses: single rooms and compound rooms.

Single rooms have their own exclusive door and, to go from one of them to another, one should step outside the house and into the yard. These rooms have their own exclusive ventilator elements which work independently from the rest of the house.

Compound rooms are shaped by attaching two single rooms together with a door frame in between to connect them. There are no reports or evidence showing the composition of more than two rooms in Sistan's vernacular houses (this research's field studies certified this fact). Table 4 reports the three identified compound room types in Sistan's vernacular houses.

Room Number		Element	Plan and Orientation	3D Section		
Compound Room Type 1						
$\checkmark$	Room 1	<b>W</b> 1 1				
$\checkmark$	Room 2	Kolak		FI		
$\checkmark$	Room 1	Surak	12	B		
$\checkmark$	Room 2	ourun		B		
$\checkmark$	Room 1	D 11	4. W	0 800		
$\checkmark$	Room 2	Dariche		θ		
-	Room 1	Window		E o		
-	Room 2	WIIIdow	9, 2 - 6			
Compound Room Type 2						
$\checkmark$	Room 1	74.1.1				
$\checkmark$	Room 2	Kolak				
$\checkmark$	Room 1	Surak				
-	Room 2	Buluk		P P		
$\checkmark$	Room 1	Dariche	1/∞ ∭ 🛪 🛛 🔤 _	0 000		
$\checkmark$	Room 2			a de la constante de		
-	Room 1	Min Jan				
$\checkmark$	Room 2	window	0			
			Compound Room Type 3			
$\checkmark$	Room 1	Kolak				
	Room 2	Rolan				
-	Room 1	Surak				
-	Room 2		M M			
	Room 1	Dariche	× ×			
-	Room 2	Danche				
-	Room 1	Window				
$\checkmark$	Room 2	<b>vviiiu</b> 0W	21 - 5			

Table 4. Different Compound room types in Sistan vernacular architecture.

#### 7. Computational wind Engineering (CWE)

"In the last 50 years, Computational Wind Engineering (CWE) has undergone a successful transition from an emerging field into an increasingly established one in wind engineering research, practice and education" [31]; as one of the many branches in this field, Computational Fluid Dynamics or CFD has become a very powerful and popular tool in building simulations and has been widely used to model indoor and outdoor airflow [16], especially in the last two decades, due to increased computing hardware capacity as an integral part of scientific research [56]. CFD method is applied in three main fronts [31]:

- 1. CFD simulation of pedestrian-level wind conditions around buildings;
- 2. CFD simulation of natural ventilation of buildings; and
- 3. CFD simulation of Wind-driven rain in building façade.

CFD is particularly suited for simulating natural ventilation conditions in indoor spaces [17]; a process that utilizes natural outside air flow to both cool and ventilate a building passively, without the use of any electro-mechanical system [57]. CFD can be used to assess indoor natural ventilation by solving the interaction between the surrounding wind flow and the indoor airflow [18]; an ability that has been utilized in this research in order to analyze the natural ventilation and wind flow in vernacular architecture of Sistan.

## 8. Wind Behavior in Defined Room Types

Computational Fluid Dynamic (CFD) studies and simulations of the defined room types were carried out using "Ansys Fluent<sup>TM</sup> 15" software. Room types' geometries and 3D Meshes were built and entry/exit points along with the confining borders were defined in "Gambit 2.4.6" software, and then imported to the Ansys Fluent<sup>TM</sup> 15 as the entry data.

Considering the importance of wind's behavior after passing through and around the room, the domain study was extended in different fronts of the room. In initial simulations, the domain size and location of the room were based on the guidelines of COST732 [58].

The results of these simulations showed that wind turbulences happen far more near the room mostly because of the small dimensions of houses in Sistan along with the fact that they are rarely surrounded by any other building; therefore the domain size was reduced to the limits that wind turbulences were considerable. The domain was extended 10 times more than the room's length in flow direction behind the room. The wind's behavior alternates while approaching the front wall of the room; therefore, the domain was extended 2.5 times more than the room's length in flow direction and as for other sides of the room, the domain extensions are illustrated in Figure 9. In modeling and analysis of these simulations, the following settings were set for all simulations:

- Number of mesh cells = 1,800,000
- Used cell type: tetragonal
- Turbulence modeling: k-epsilon RNG
- Boundary condition:
- Walls: no slip condition
- Entry points: velocity inlet
- Exit points: pressure outlet



**Figure 9.** The domain study for the CFD simulation around the rooms (a: width of the room cell; b: length of the room cell; h: height of the room cell).

In defining the model and the domain size, simulations were done based on the data provided by Islamic Republic of Iran Meteorological Organization or I.R.I.M.O. [59] in Zahedan branch and also meteoblue [35]. According to the mentioned resources, average wind flow velocity of Sistan is 9 m/s, which was provided to the software as the entry for wind velocity in the simulations. Simulation results are presented in the following sections.

## 8.1. Wind Behavior in Compound Room Type 1

Wind enters the room with a velocity of approximately 12 m/s through the room's Darichehs, 14m/s through the Suraks and 11 m/s through the Kolak. Scattered openings in length and height, causes the air to flow in different parts of the room. Airflow circulates in the room and exits through doors in the southeastern front (leeward side).

Wind speed decreases to 0–4 m/s after passing the house barrier. Off wind area down the house is protected from prevalent 9 m/s winds of the region by the house's mass. Length of this area is 6–7 times the width of the room. In regards to the interior space, wind velocity decreases to 0 m/s in the door frame that connects room's two parts which shows the independent performance of the two parts in ventilation. Outside the house and on its sides, wind speed increases up to 13–14 m/s after passing the northern corners of the room's mass (Figure 10).



**Figure 10.** (**a**) Wind speed in Darichehs' height; (**b**) wind speed in Suraks' height; (**c**) wind speed in section; (**d**) wind direction in plan; and (**e**) wind direction in section.

## 8.2. Wind Behavior in Compound Room Type 2

Wind enters the room with a velocity of approximately 12 m/s through the room's Darichehs, 14 m/s through the Suraks and 11 m/s through the Kolak and exits the room through the window down the eastern part and the door in western part. In sides of the room, there is a triangle area in which the wind speed decrease to 0-4 m/s.

In southeastern area of the room, wind speed decreases and turbulences near the doors and windows. Scattered openings on the north wall cause the air to flow in all the spaces that is used by the dwellers. Leeward area in this room type is smaller compared to room type 1 and there are almost no areas without wind flow down the room. Green color shows tornado-like turbulences in the simulation which cause dust and pollution to accumulate in these parts and the wind to enter the room through the door in eastern part. Wind velocity decreases to 0–4 m/s in the door frame that connects room's two parts which shows the independent performance of the two parts in ventilation just like room type 1 (Figure 11).



**Figure 11.** (**a**) Wind speed in Darichehs' height; (**b**) wind speed in Suraks' height; (**c**) wind speed in lateral section; (**d**) wind speed in linear section; (**e**) wind direction in plan; and (**f**) wind direction in section.

#### 8.3. Wind Behavior in Compound Room Type 3

Wind enters the room with a velocity of approximately 9 m/s through the room's Darichehs, 9 m/s through the north Kolak and 8 m/s through the south Kolak. Wind speed is so high that passes the northern part of the room and enters the southern part through the connecting door frame. Wind speed in the junction area of two parts of the room is 4 m/s; therefore, there are two wind flows entering the southern part of the room: one through the southern Kolak and the other from the northern Darichehs. Wind turbulences around the room cause the northern door to act as an entry point for the wind. On the sides of the room (northeastern and southwestern areas), wind speed increases to 10 m/s almost immediately which is not a favorable occurrence due to the fact that entrance doors and dwellers traffic happen in this part (Figure 12).



**Figure 12.** (**a**) Wind speed in plan; (**b**) wind direction in plan; (**c**) wind speed in section; and (**d**) wind direction in section.

# 9. CFD Validation with Direct Empirical Measurements

To validate the numerical method, CFD results were compared against the direct measurements that were carried out over four months (June–August 2015), concurrent with the 120-Days Winds, within two rooms located in Qale-no village in Sistan which fall into the room type categories 1 and 2.

The measurements were done using a digital anemometer (Anemometer Kestrel 1000) during eight days in June, 13 days in July, 19 days in August and 11 days in September, which is fifty-one days in total (Figures 13 and 14 and Table 5).



**Figure 13.** (**left**) Direct measurement of wind velocity in the entry of Surak: room type 2 outside the room; and (**right**) Entry of Darichehs inside the room.



Figure 14. Direct measurement of wind velocity in the entry of Kulak: room Type 1.

Most of the measurements and CFD results were in good agreement, yielding an average error margin of 5%, which shows that the simulations correlate with the empirical data. Table 5 shows the average result of all the measurements in different points of room samples 1 and 2. The measurement points in these two rooms were selected based on the CFD simulation results, where the harshest turbulences occur.

Table 5. Direct wind speed measurement in two sample houses.

Room S	Sample 1	Room Sample 2		
Measurement Points		Measurement Points		
●B ●A ●C ●A ●D	F● ●E ●D B● ●C	●A ●A ●A ●B ●B ●B ●C	E● ●D F● ●G ●C ●B	
Plan	Section	Plan	Section	
Wind	speed	Wind speed		
VA = 0 M/S	VD = 1.5 M/S–1.7 M/S	VA = 3.5 M/S–9 M/S	VE = 7 M/S - 8 M/S	
VB = 3.5 M/S - 9 M/S	VE = 8 M/S - 13 M/S	VB = 5 M/S - 14 M/S	VF = 8 M/S - 9 M/S	
VC = 5 M/S–14 M/S	VF = 7 M/S - 8 M/S	VC = 1.5 M/S–1.7 M/S VD = 8 M/S–13 M/S	VG = 14 M/S–15 M/S	

## 10. Conclusions

Built environment's ventilation consumes a large portion of energy in today's world, which consequently leads to a great amount of pollution, especially in less-developed countries with less clean technologies. At the same time, vernacular architecture has come up with numerous effective techniques and elements to use natural wind induced ventilation to provide a comfortable setting for dwellers and reduce the energy consumption. Vernacular architecture of Sistan provides an exceptional collection of techniques and elements to naturally ventilate the built environment.

Through comprehensive field studies and documentation of 32 vernacular houses in Sistan, this paper identified these techniques and methods and illustrated their construction method and performance logic (Table 3). Elements such as Kolak, Surak, Daricheh and Sistani roof altogether make the natural ventilation of a vernacular house in Sistan possible.

Three different compound room types were identified and categorized as generative cell for vernacular houses of the region (Table 4) based on their orientation and utilization of ventilation elements. These compound room types were the subject of a series of simulations and computational fluid dynamic (CFD) studies using Gambit and Ansys Fluent<sup>™</sup> 15 software to determine the wind's behavior in and around rooms. These studies and simulations show that:

- Compound room type 1: Air flows through all the spaces that are used by the dwellers and it is
  only under the ceiling that wind speed drops to almost 0 m/s. This type has the widest leeward
  area which is caused by its elongation against the prevalent wind. This is the perfect area to
  build a terrace. Wind behavior analysis in this type shows that by extending the elongation on
  NE/SW direction and building several rooms of this type in this direction, off wind tranquil
  area down the rooms grows wider and wider.
- Compound room type 2: There is no ventilation between the two parts of this room (just like room type 1), but ventilator elements that are used in both parts of the room provide an acceptable level of air flow in all the spaces that are used by the dwellers. Turbulences in the leeward area cause the entrance door to act as an entry point for wind which can be a great problem, especially during the dust storms. Large surface of the door and the fact that most of the time its not properly sealed causes it to act as an entry point for contamination and dust; therefore, necessary precautions should be made to alleviate this problem. Off wind leeward area in this type is smaller than the one in type 1 and wind turbulences happen near the house mass. Due to these turbulences, it is hard to use the terrace in this room type, especially during high speed winds.
- Compound room type 3: This is the only type that two parts of the room do not act as separate cells and there is a wind flow between them. Wind flow is stronger in the northern part due to its Darichehs; therefore, it is usually used as living room. Wind behavior analysis shows that the wind enters the room through the doors which causes several problems similar to the problems in room type 2. In this type, window acts as a suction point and drives out the wind. Therefore, it can be opened for ventilation even during high speed winds. The area in front the room in southwestern part is parallel to prevalent wind direction and experiences high wind speed (up to 10 m/s) which makes it unsuitable for dwellers traffic; therefore, this paper suggests that room type 3 should be combined with other types with a perpendicular orientation against the wind. Off wind leeward area down this room type is pretty small and considering the doors position and dwellers traffic, it is practically unusable.
- Using room type 3 shapes alleys that are parallel to prevalent wind direction in the overall
  pattern of the villages. By building new houses on two sides of these alleys, they turn into
  canals that channel the wind through the village with an extremely high speed. This problem
  can be averted by combining this room type with other type,
- Parts of the room types that use all three ventilator elements (Kolak, Surak and Dariche) with an
  appropriate dispersion pattern, have the best ventilation performance and are usually used as
  houses' main space. Therefore, room type 1 has the best ventilation performance because of
  appropriate dispersion of openings and appropriate airflow all over the room.
- In room type 3, southeastern half of the room has a weak ventilation performance compared to the other types and as field studies show, it is usually used as service room. This half of room type 3 is especially suitable for winter, as it is built on the sunlight facing, southeastern part of the house and has no Darichehs.
- Openings' dimensions in Sistan vernacular architecture causes the wind to enter the room with the same speed as the regions prevalent wind. Native people block portions of the opening in response to the wind speed to reach the best ventilation performance in their houses. This paper proposes the same dimensions to be used in new buildings' openings in northwestern walls and suggests that builders refrain from using large windows (as is the case for majority of new constructions in the region).
- Studies show that off wind leeward areas behind the rooms' parts with Kolak is wider than the parts without it.
- Considering the turbulence area down the room type 1, new constructions should happen in a 16 m distance from this room type (four times the room length in prevalent wind direction), where the wind behavior returns to normal.

 Considering the fact that, in most cases, doors of these room types act as an exit point for the wind and leaving them open, can cause some problems, this paper suggests the builders to use the type of doors with some openings on their surfaces.

# 11. Outlook for Future Researches

Future studies can research and propose practical methods to utilize the results of this paper in new constructions across the region. In addition, updated construction methods can be proposed to use new and more seismically safe materials and structures. Future studies can also provide an outline plan for new villages in the region, considering the wind behavior which was studied in this paper.

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