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OPTIMIZING COURTYARD GEOMETRY FOR ENHANCED INDOOR VENTILATION IN CONTEMPORARY RESIDENTIAL BUILDINGS

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Abstract: This current research aims to investigate the influence of courtyard place, the length to width proportion, and its orientation on the rates of airflow inside the building spaces, using (Autodesk CFD 2024) program., to simulate the impact of the courtyard on the efficiency of internal natural ventilation, by studying the relationship between the courtyard position, different proportions and orientation, to reach the better geometry of the courtyard that improves the natural ventilation rates inside the residential buildings in Kharga city in the New Valley Governorate, Egypt. The reference area is 157.25 m2, which accommodates a square central courtyard with 5 m × 5 m dimensions. The results of the study indicated that the optimum position of the internal courtyard which improves the airflow rate, thus enhancing the natural ventilation inside the dwelling, was the position of the courtyard on the southwestern interface, with a length-to-width proportion (1:1.5) with longitudinal axis orientation to east-west.

Keywords
Internal courtyards, Courtyard Parameters, Ventilation inside buildings, and Residential buildings.

1. Introduction

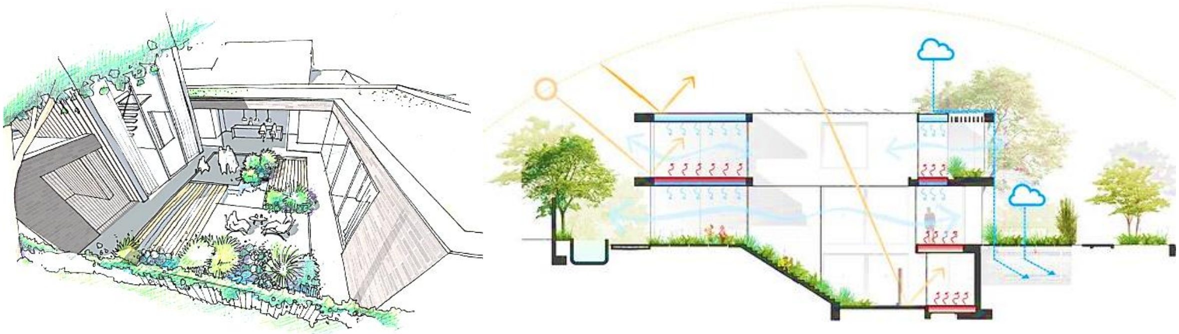
The residential buildings sector in Egypt is one of the largest electricity-consuming sectors. This shows the need to balance the energy consumed and achieve thermal comfort for users. The research problem lies in the design of most residential buildings in hot and hot dry areas does not sufficiently take into account energy-saving considerations, and ignores the impact of the climatic conditions surrounding those buildings on the creation of the internal climate of the buildings, and ignores the foundations and standards of climate-negative design, while the bulk of energy consumption in residential buildings is dedicated to ventilation. Natural ventilation is one of the most cost-effective passive cooling strategies [1].

The style of buildings with internal courtyards is one of the most important architectural styles that appeared in the architecture of buildings throughout the different historical eras, starting from the era of ancient Egyptian architecture until the modern era. That is because the internal courtyard is one of the most important vocabulary heritage elements that has successfully addressed the problems of the climatic environment and the problems of the environment in general, especially in desert areas. The courtyard effectively regulates indoor temperature throughout the day, [2] and the courtyard leads to achieving ventilation and protection from hot winds and sunbeams for the dwelling through proper design for the architecture of the building and the courtyard as well [3].

This study seeks to study the different alternatives for the internal courtyard, such as the position, elongation, and direction of the internal courtyard and its impacts on the rate of airflow inside the building to get the best benefit of natural ventilation. One of the residential models in Kharga city of the New Valley Governorate of Egypt was selected for assessment and simulation purposes as a case study for the current study.

2. Internal Courtyard

The inward-oriented building style through the use of the internal courtyard is one of the most important vocabularies of climatic treatments in traditional architecture [4]. especially in hot areas. The courtyard is used as an architectural element that secures protection from climatic factors, helps provide lighting and natural ventilation, uses natural energy, and reduces energy consumed [5]. Accordingly, the courtyard space plays the main role in providing ventilation and natural lighting for internal spaces [3] See (Figure1).



(A) **(B)**

Figure1: Courtyard in Buildings (A) Perspective in the Courtyard, (B) section in the Courtyard [16]

The internal courtyard is a part that has been truncated from the surrounding public space When encircled by the building's internal spaces in the architectural design process to achieve environmental [6], functional, social, or morphogenic goals [7].

According to the spatial characteristics, the position of the courtyard with architecture and also urbanization has an important value and an influential factor in the rate of efficiency of the dwelling from the environmental, morphogenic, and functional purposes, [8] as shown in (Figure 2).

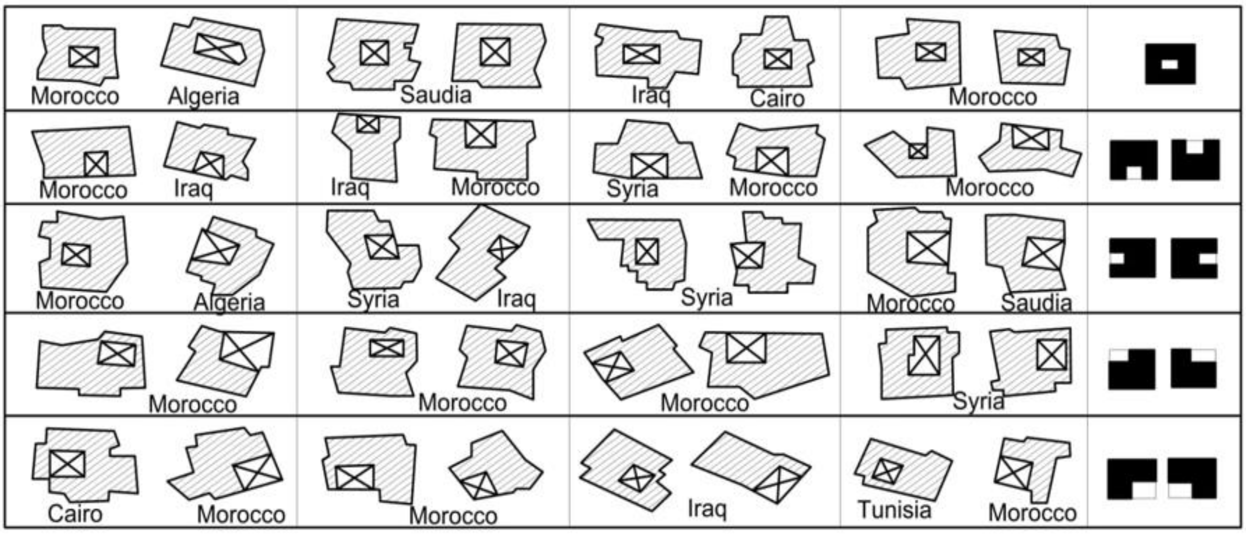


Figure2: Different courtyard Placement in the Arab heritage urbanism [19]

2.1 Environmental and climatic characteristics of the internal courtyard

2.1.1 Thermoregulation and ventilation

The internal courtyards regulate temperatures, provide natural ventilation, and achieve the greatest possible thermal comfort inside the dwellings inside which they are located. The mechanism of the internal courtyard function as a thermostat is evident through the night and day periods through the following:

First: During the Night: During the night with the first early morning breezes, the courtyard is filled with cold air that replaces the hot air that was in the courtyard, which in turn rises upwards (where cold air is heavier than warm air). This process is called convection, [9] as the different parts of the internal courtyard lose a part of their heat, and thus cool its surface and cool with the air in contact with it to settle to the bottom of the courtyard, and this mechanism continues throughout the night to turn the courtyard into a store for cold air [10].

Second: During the Day: With the brightness of the sun and during the first periods of the day, the air outside the building is hot while the air inside the courtyard remains cold until noon [11], which improves the internal climatic environment of the spaces overlooking it without the need to use industrial means or reduce them to some extent, See (Figure3). When the sun's rays heat the walls and floors of the internal courtyard gradually and gain heat as a result of exposure to sunlight, and thus the air in contact with it heats, and the spaces of the dwelling are affected by this heat, the cold air stored in the courtyard moves from the night through the lower windows in the walls of these spaces, replacing the hot air, which in turn rises upwards to come out of the upper openings of the walls [12].

2.1.2 Natural Lighting Provision

In areas with compact planning recommended in hot dry areas in which buildings are contiguous, it was necessary to have internal spaces open to the sky for light to reach the spaces of those buildings. The internal courtyard helped to provide natural lighting that is not dazzling in the spaces overlooking it [13], and thus this led to reducing electricity consumption.

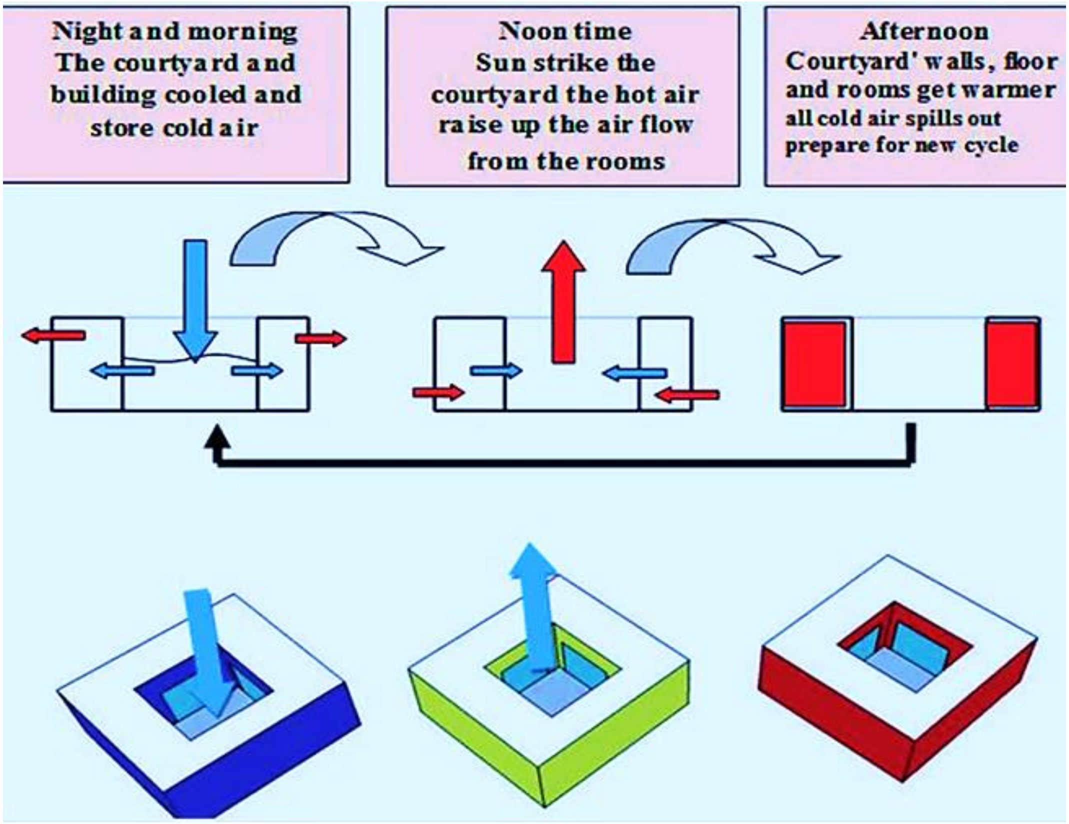


Figure3: The working mechanism of the courtyard [16]

2.1.3 Anti-Glare and Dazzle

The internal courtyard in Heritage Architecture, especially residential buildings, had a great impact in reducing the intensity of dazzling and providing comfortable natural lighting through the shadows that it provides, and organizing lighting in the covered and open space, which had an important role in mitigating the intensity of loudness and glare [12]

2.1.4 Noise Resistance

The internal courtyards have formed spaces away from noise and sound pollution. The use of the courtyard is an ideal solution to provide a quiet space inside the dwelling in which various activities can be practiced quietly and away from external noise through orientation towards the inside and the lack of openings towards the outside parts. This helps reduce the volume inside the courtyard and thus the sound was reduced in the spaces overlooking on courtyard [14].

Martin Evans indicated in the research he prepared to study the different methods of noise protection that there is more than one method to avoid noise, and the most important of these methods. Dwellings with courtyards achieve auditory privacy and protection from pollution, dust, and noise, which confirms their importance for Arab architecture [15].

2.1.5 Wind and Pollution Resistance

The desert areas are characterized by severe drought and winds loaded with sand and dust. The presence of the internal courtyard helped protect against these dusts, and the presence of trees and plants inside it purifies the air from dust and fumes that may spread in the atmosphere [13].

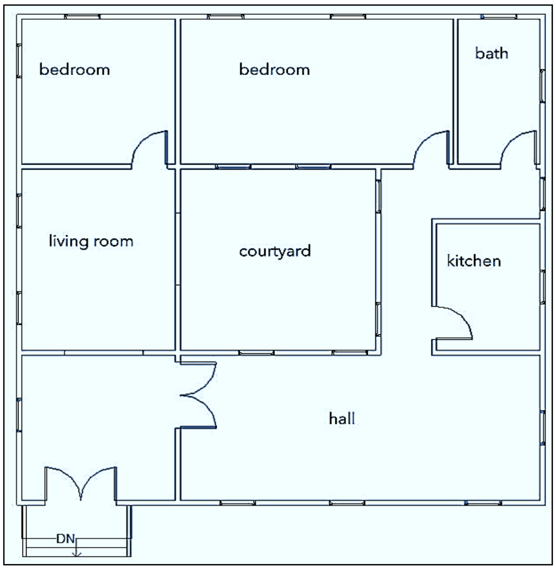
3. Method and materials

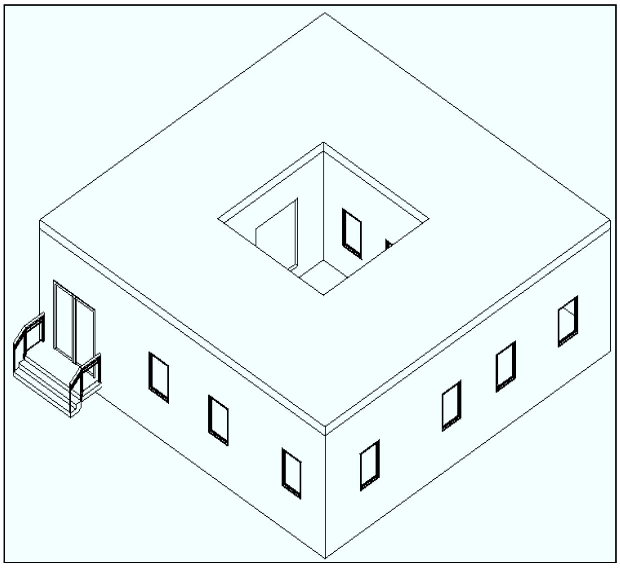
The second part of the study tackles the possibility of achieving the highest rate of natural ventilation inside the dwelling by investigating the relationship between the dwelling and the courtyard position. The research methodology included carrying out several experiments to determine the impact of different alternatives of courtyard design on improving internal natural ventilation, by applying to the city of Kharga in the New Valley Governorate, Egypt as a case study. The experiment included simulating the speed of indoor air in different courtyard cases, which were designed using the Architectural Revit 2024 program, while the simulation method was achieved using Autodesk CFD 2024 for simulation purposes, Excel 2016 was also used to determine the correlations between air velocity rate and courtyard design alternatives, which are the variables: position, elongation, and direction of the courtyard.

3.1 Simulation

3.1.1 Simulation reference model

The case study building consists of a one-story residential building in the city of Kharga, New Valley Governorate of Egypt, with an area of 157.25 m^2 with a square-shaped middle courtyard with dimensions 5 m × 5 m, and (Figure 4) shows the study building. The Revit2024 program was used to design the building and all design alternatives for the different courtyard positions.





(A) **(B)**

Figure4: Case study building (A) plan, (B) simulation model.

3.1.2 Field of Analysis

The tested model was placed in an external size to display the airflow in and around the model, and Abdelhady [16] was relied upon to set the dimensions of the external size of the study model as shown in (Figure 5).

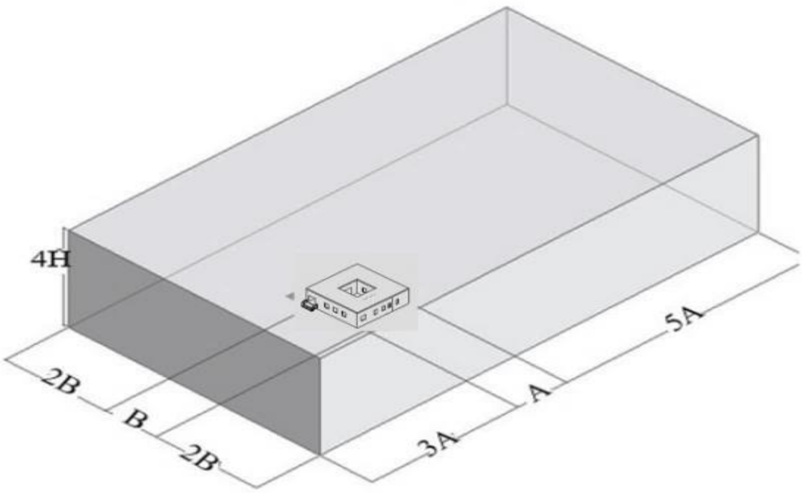
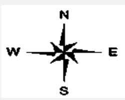
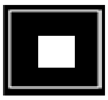
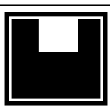
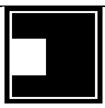


Figure 5: Perspective View of External Volume with Case Reference

3.1.3 Ventilation simulation

This study seeks to tackle the different design alternatives for the internal courtyard, such as the position, elongation, and direction of the internal courtyard and their impacts on the airflow rate inside the building to get the best benefit of natural ventilation., by placing the internal courtyard in the different positions of the courtyards in the dwellings in heritage architecture, see (Figure. 2), to reach the best position that achieves the highest rate of airflow and thus enhances natural ventilation inside the dwelling.

The Different design alternatives				
	**Courtyard placement in the building**	**orientation of the longitudinal axis of the Courtyard**		**length to width proportion**
	center of the building	East – West	North – South	1:1 1:1.5 1:2 1:2.5 1:3
	The placement is in the middle of the northern facade			
	The placement is in the middle of the eastern facade			

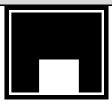
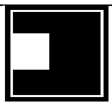
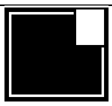
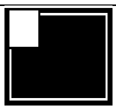
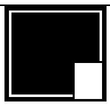
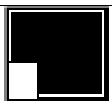
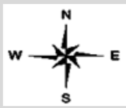
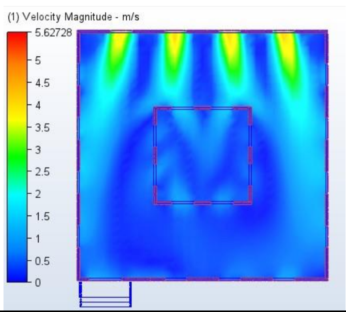
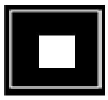
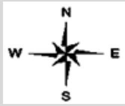
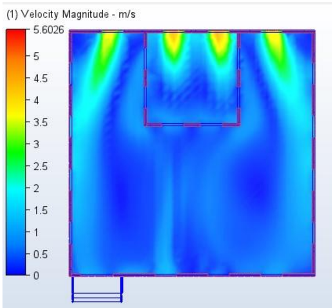
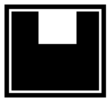
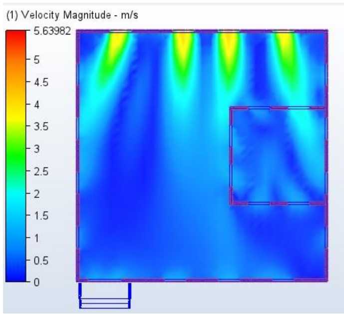
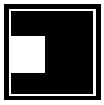
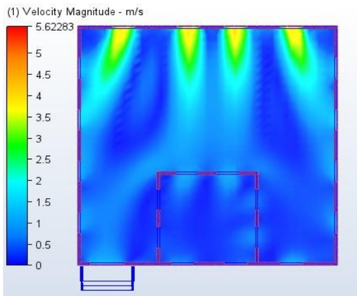
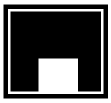
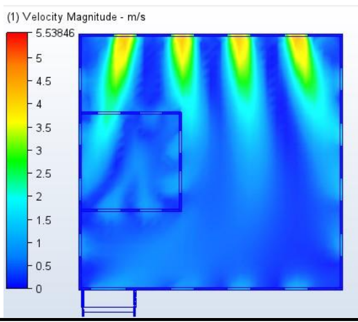
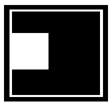
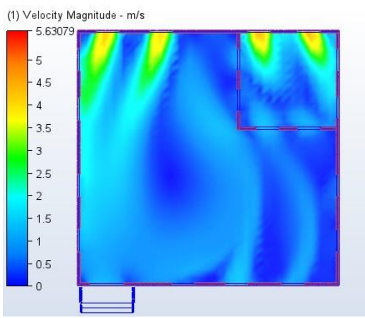
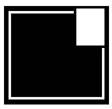
The Different design alternatives					
	The placement is in the middle of the southern facade				
	The placement is in the middle of the western facade				
	The placement on the north eastern facade				
	The placement on the north western facade				
	The placement on the south eastern facade				
	The placement on the south western facade				

Table 1. The Different design alternatives for the courtyard.

Status	**Courtyard Placement**	**Ventilation Simulation**	
1	center of the building		

Status	Courtyard Placement	Ventilation Simulation	
2	Northern position		
3	Eastern position		
4	Southern position		
5	Western position		
6	Northeastern position		

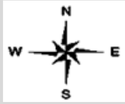
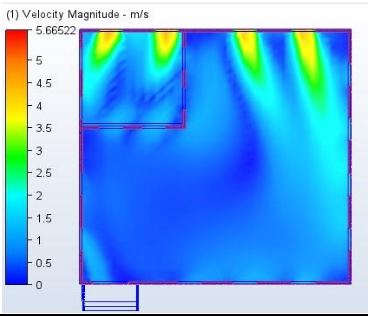
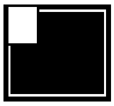
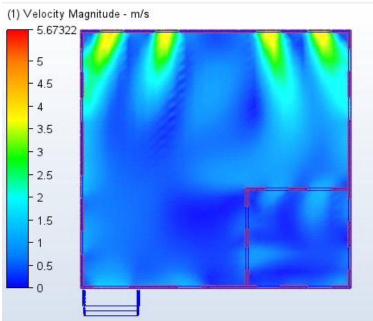
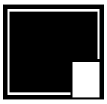
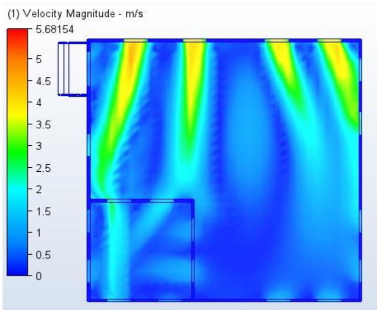
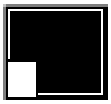
Status	Courtyard Placement	Ventilation Simulation	
7	Northwestern position		
8	Southeastern position		
9	Southwestern position		

Table 2. Air Velocity simulation for the study cases.

Different models of the building were made through modification in the position, direction, and elongation of the courtyard, in nine different positions of the courtyard, and the design alternatives for the courtyard, as shown in (Table 1). for the square-shaped courtyard, and the (Table 2) shown air velocity simulation for the study cases. Afterward, proportions were made for the courtyard on the best position that achieved the highest average air speed inside the dwelling in the following proportions: (1:1 - 1:1,5 - 1:2 - 1:2,5 - 1:3), and the longitudinal axis of the courtyard was oriented to east-west for all ratios. Also, a change was made to the longitudinal axis of the courtyard to be oriented to the north-south side for all ratios (zero orientation angle), as shown in (Table 4) to determine the best position and ratio of length to width and the best direction that achieves the highest rate of airflow inside the dwelling and helps in providing internal natural ventilation and thus reducing the energy consumed in buildings, and the (table 3) shows air velocity values for different design alternatives for the courtyard position of the study building, and then (Table 5) shows the air velocity values for the courtyard position on the southwest façade for all ratios and directions of the longitudinal axis of the courtyard.

Autodesk CFD software was used to simulate the courtyard in the dwelling to calculate the average air velocity of Vx, Vy, and Vz in all simulation cases using the following formula **(**$V_{avg}\sqrt{\ V_{X}{}^{2} + V_{Y}{}^{2} + Vz^{2}}$**)** and the observation was carried out at an altitude of 1.5 m and all readings were taken at a fixed specific point for all cases see (Figure 6).

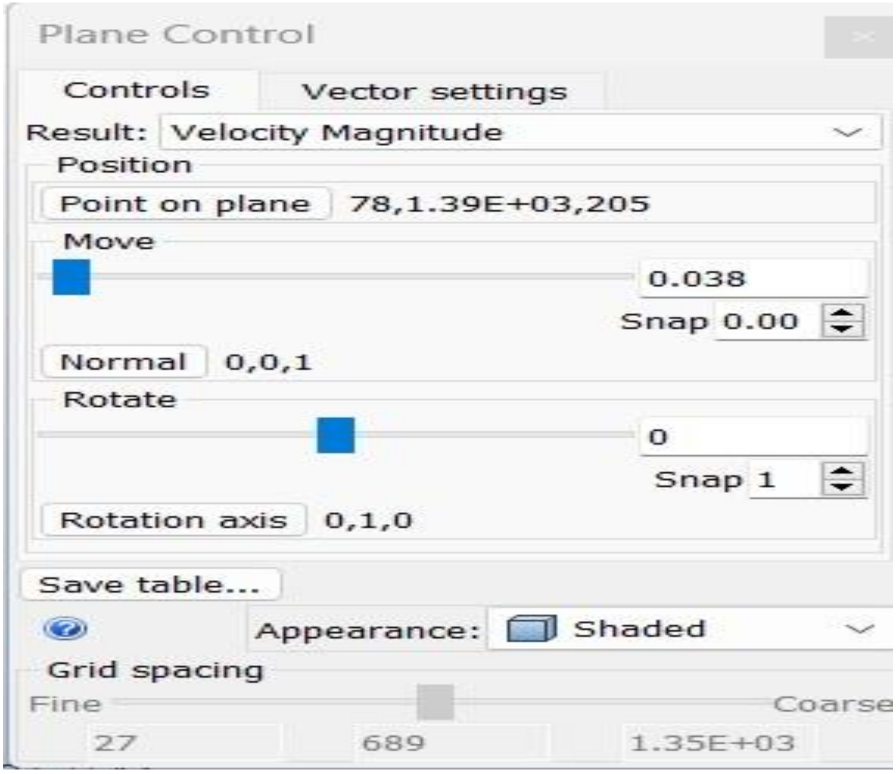


Figure6: Point of taking readings on the plane for all simulation cases

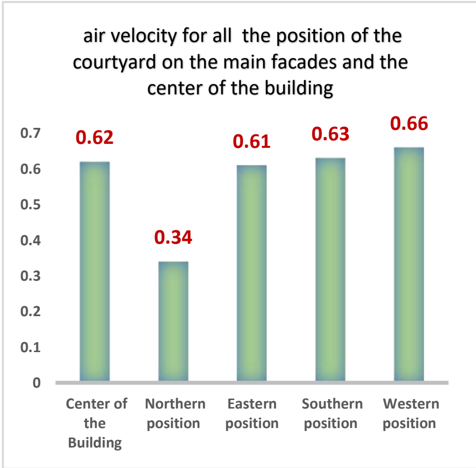
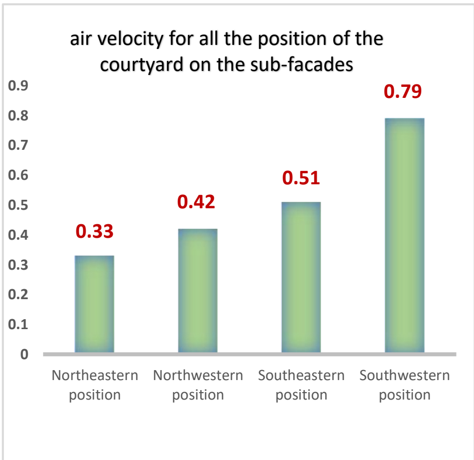
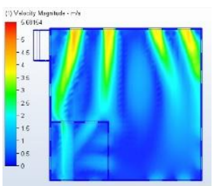
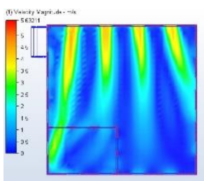
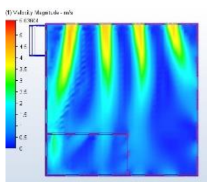
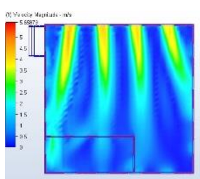
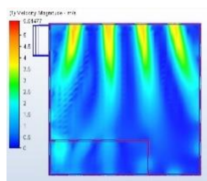
Courtyard placement	xv m/s	yv m/s	zv m/s	Velocity average m/s	
Center of the Building	-0.0371	-0.6168	0.0181	0.62	
Northern position	-0.0068	-0.3335	0.0355	0.34	
Eastern position	0.01952	-0.6115	0.0105	0.61	
Southern position	-0.0376	-0.6259	0.0045	0.63	
Western position	-0.0763	-0.6562	0.0145	0.66	
Northeastern position	-0.0101	-0.3278	0.034	0.33	
Northwestern position	-0.0271	-0.4117	0.0398	0.42	
Southeastern position	-0.0325	-0.5083	-0.0006	0.51	
Southwestern position	-0.0555	-0.793	0.003	0.79	

Table 3. Air Velocity values for the study cases.

length to width proportion and placement	1:1	1:1,5	1:2	1:2,5	1:3
Southwestern position in case of longitudinal axis of the courtyard has been orientated to the east-west.					

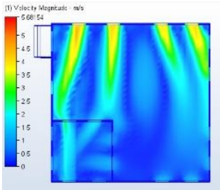
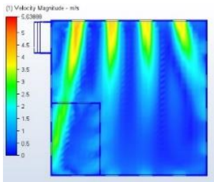
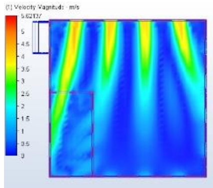
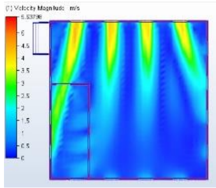
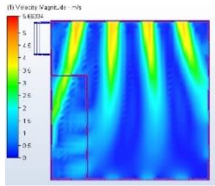
Southwestern position in case of longitudinal axis of the courtyard has been orientated to the north-south.					

Table 4. Ventilation simulation of the position and proportions of the courtyard on the southwest façade

Courtyard placement	the longitudinal axis of the Courtyard orientation	Length to Width Proportion	xv m/s	yv m/s	zv m/s	Velocity average m/s
Southwestern position	East –West	1:1	-0.05553	-0.79298	0.00305	0.79
		1:1,5	-0.036824	-0.96364	0.007194	0.96
		1:2	-0.053772	-0.937065	0.002772	0.94
		1:2,5	-0.023248	-0.938487	0.001242	0.94
		1:3	-0.026027	-0.828955	-0.00015	0.83
	North –South	1:1	-0.05553	-0.79298	0.00305	0.79
		1:1,5	-0.060367	-0.802872	0.00665	0.81
		1:2	-0.070164	-0.922379	0.008877	0.93
		1:2,5	-0.069234	-0.839309	0.008435	0.84
		1:3	-0.063469	-0.88824	0.010586	0.89

Table 5. Air Velocity values for the Courtyard Southwestern position with different proportions.

4. Results and discussion

The main results of the study are shown in (table 2), in which the results of the ventilation simulation of the nine courtyard positions are presented (the middle of the building - the northern position - the western position - the southern façade - the eastern position - the northwest position - the northeast position - the southwest position - Southeast position). as shown in (table 4), the results of the simulation of the courtyard position on the southwest position in the following ratios (1:1 - 1:1.5 - 1:2 - 1:2.5 - 1:3). and the (Figure 7,8) shows comparison between indoor air velocity values for different courtyard positions.

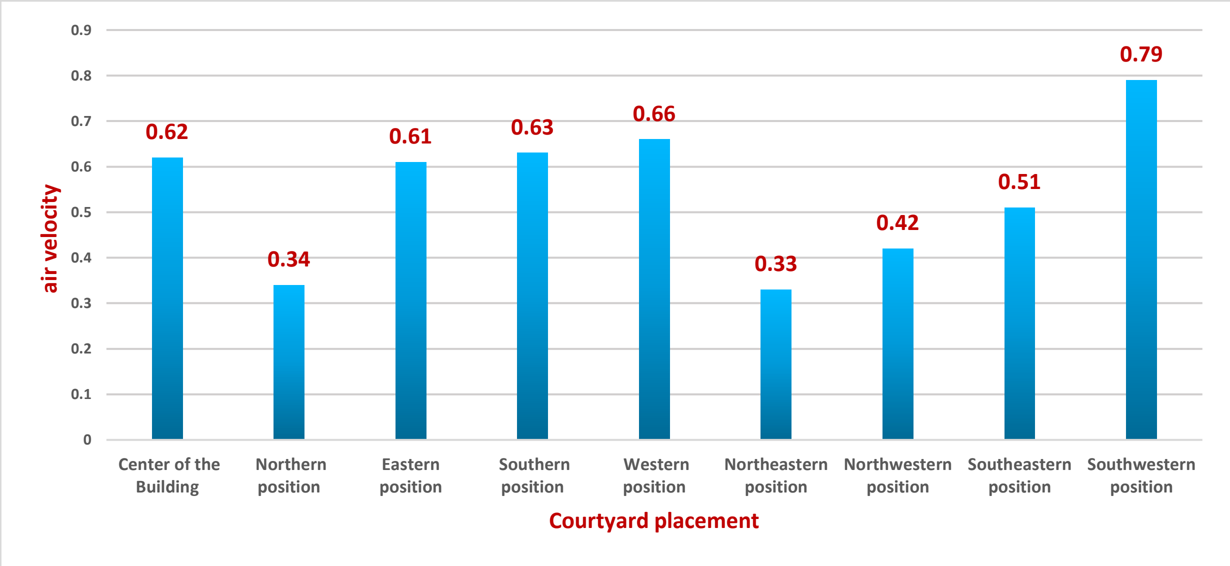


Figure 7: Air Velocity values for the study cases.

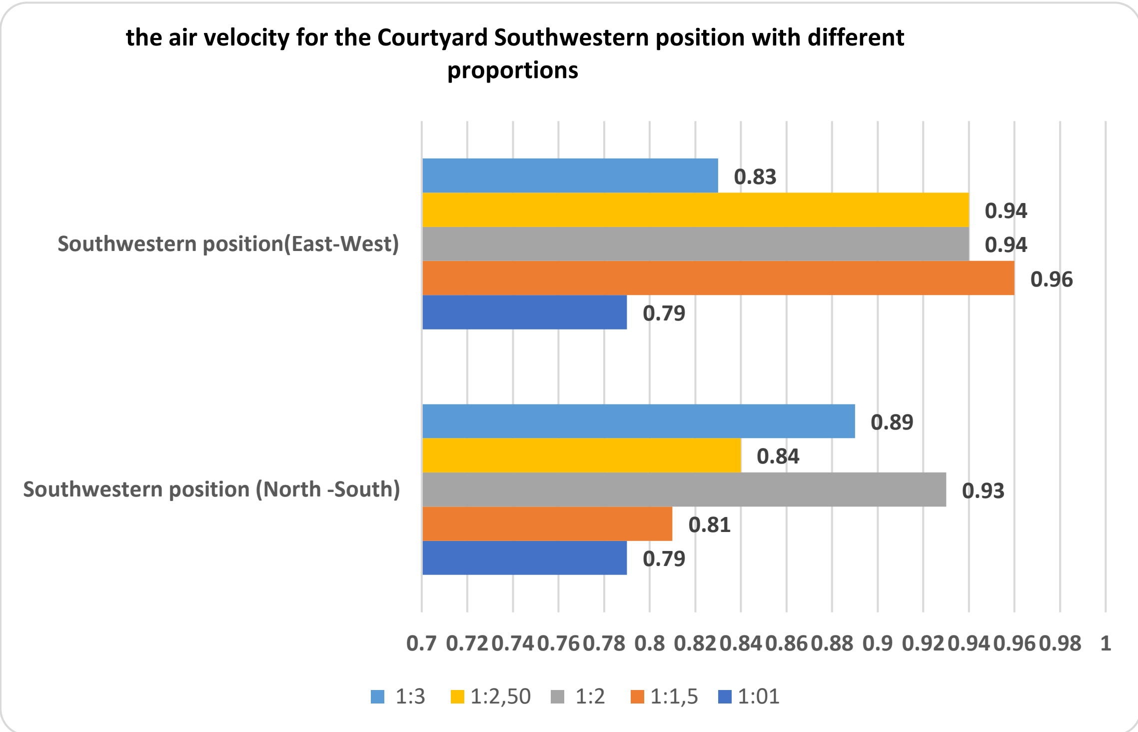


Figure 8: Air Velocity values for the Courtyard Southwestern position

- The results indicate a relationship between the placement of the internal courtyard and the rate of airflow inside the building, and that the position, elongation, and direction of the courtyard greatly impact the speed of airflow inside the building.
- As for the position of the courtyard on the main facades and the center of the building (north-west-east-south), the results indicated that the highest airspeed was in the case of the courtyard position on the west interface, and the lowest air velocity was in the case of the courtyard position on the north interface.

- As for the position of the courtyard on the sub-facades (northeast, northwest, southeast, and southwest), the results indicated that the highest airspeed was in the case of the courtyard position on the southwest interface, and the lowest airspeed was in the case of the courtyard position on the northeast interface.
- For the position of the courtyard on the southwest façade in the case of directing the longitudinal axis of the courtyard to north-south (zero orientation angle), the results indicated that the best aspect ratio of the courtyard was (1:2), but in the case of directing the longitudinal axis of the courtyard to the east-west (zero orientation angle), the results indicated that the best aspect ratio was for the courtyard are (1:1,5).
- The results indicated that a rectangular courtyard is more effective than a square-shaped one in terms of the quality of natural ventilation inside residential buildings.

It is worth noting that in the previous study of the researcher, which was entitled ***"Courtyard Geometry's Effect on Energy Consumption of AlKharga City Residential Buildings, Egypt"*** **One of the most important results** was that the better place for the courtyard for different designs alternatives in terms of energy consumption is the position of the courtyard on the southwest interface, where this position achieved the highest percentage of energy savings consumed inside the housing by 18.73%. By comparing the results of this research with previous studies, we find that the results of the case study are logical.

5. Conclusion

As a conclusion from the current research, the study confirmed that the courtyard is considered the optimum architectural solution that contributes to dealing with climatic issues, especially in hot dry areas. Also considered a main rule in the environmental design of residential buildings during the design process, is improving the natural ventilation rates, which affects in energy efficiency of the building. The study presented some important guidelines, which considered a methodological framework for residential building design containing internal courtyards for enhancing the internal natural ventilation rates, which help the buildings for adaptation with hot dry climate conditions. The key findings of this study can be summarized as the following:

- The results indicate that the best position for the internal courtyard for the different design alternatives achieved the maximum rate of airflow, thus enhancing the natural ventilation inside the dwelling. The position of such a courtyard was on the southwest façade.
- The best proportion between length and width is (1:1,5) with the east-west (zero orientation angle).
- The rectangular courtyard shape is the optimum shape for improving the natural ventilation rates inside the buildings.

6. Future research

The authors are highly recommended to study the following:

- Courtyard geometry Effects on the Efficiency of Natural Ventilation Inside Residential Buildings with vertical extension.
- The effect of courtyard geometry on energy consumption in residential buildings with vertical extension.
- Courtyard geometry Effects on the Efficiency of Natural Ventilation Inside commercial and public buildings.

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