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Original Research Article

Analysis of the Synergistic Performance of Sabat and Windcatcher in Enhancing Natural Ventilation in Traditional Architecture of the Persian Gulf Margin

(Case Study: Kong County, Hormozgan Province)

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Abstract

Problem statement: The traditional houses of Bandar Kong in southern Iran are an outstanding example of climate-responsive architecture that employs indigenous elements such as windcatchers and Sabats to combat intense heat and improve natural ventilation.

Research objective: This study aims to analyze the effect of these two elements on the quality of natural ventilation by numerically examining three design scenarios through computational fluid dynamics (CFD) simulation.

Research method: Varying the depth of Sabats, testing different windcatcher configurations, and optimizing the integrated performance of both systems. To evaluate the performance of each scenario, a baseline model was considered as the reference case (Case_Ref), which comprised a house with a central courtyard lacking a windcatcher and Sabat and represented the base conditions of airflow and natural ventilation. The performance of each scenario was simulated in Autodesk CFD 2018 and compared to the reference model using three indicators: airflow velocity, air age, and ventilation efficiency.

Conclusion: The research findings showed that both elements independently were effective in improving interior ventilation; the four-sided windcatcher increased ventilation efficiency by up to 16 times, and deep Sabats, by enhancing horizontal air movement, played an effective role in improving ventilation around the central courtyard. However, the simultaneous combination of these two elements in the optimized sample (Case_Fin) led to remarkable improvements in all indicators: airflow velocity increased up to 8.8times, air age decreased by up to 85%, and ventilation efficiency improved up to 34. 7 times compared to the reference case. These findings indicate that the synergy between traditional elements in climatic design can provide an effective model for improving living quality in hot and humid regions, and that intelligently integrating vernacular patterns with modern simulation tools is a meaningful step toward achieving sustainable architecture.

Keywords: *Natural Ventilation, Windcatcher, Sabat, Traditional Architecture, Hot-Humid Climate, Bandar Kong.*

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Introduction

Traditional houses in Iran's hot and arid regions, especially in coastal and southern areas, are specifically designed to cope with harsh climatic challenges. In these regions, high temperatures, intense solar radiation, and prevalent humidity are among the principal environmental characteristics that significantly affect occupants' comfort (Yazdi et al., 2021). In response to these issues, traditional architecture has employed various methods such as the use of windcatchers, Sabats, and central courtyards in residential design. These designs were developed to reduce heat, enhance natural ventilation, and provide occupant comfort, representing among the intelligent innovations of vernacular architecture in response to specific climatic conditions (A'zami et al., 2005). Windcatchers, as one of the important architectural elements in some hot and humid regions, play a key role in the natural ventilation of buildings (Sharifi et al., 2022). These structures draw fresh air into interiors by harnessing natural wind flows and replacing stagnant indoor air. In this way, they create a through-flow of air and prevent the persistence of humid air inside spaces (Ranjbar et al., 2010). The use of windcatchers in traditional architecture can be observed in various Iranian cities such as Yazd, Kerman, Isfahan, and Bandar Abbas, and numerous studies have emphasized their impact on improving indoor climatic conditions (Maleki, 2011; Moghaddam et al., 2011). Sabats, as intermediary spaces between the building and the outdoors, also help reduce direct solar radiation on walls and improve natural airflow. These features reduce the effects of summer heat and create more favorable living conditions.

Review of research conducted to date indicates that despite the widespread use of these elements in vernacular architecture, studies specifically focused on the combined effect of windcatchers and Sabat (covered passageways) on improving natural ventilation in traditional houses have been limited. Many of the existing studies have only examined the separate effects of these elements (Peker, 1991; Kalantari et al., 2015; Saadatian et al., 2012). Accordingly, the present paper attempts to fill this research gap using computational fluid dynamics (CFD) simulations. This tool can accurately model the complex interactions among the windcatcher, Sabat, central courtyard, and other architectural elements in creating favorable ventilation conditions and provide reliable results (Moukalled et al., 2011). Therefore, the present study aims to examine the effect of the simultaneous use of windcatchers and Sabats on improving natural ventilation in the traditional houses of Bandar Kong. Case study samples in this research were defined according to three scenarios as follows: 1) use of Sabat with different depths, 2) use of windcatchers with different numbers of openings, and 3) simultaneous combination of windcatcher and Sabat. These scenarios were compared with a reference model that lacks any windcatcher or Sabat, so that the effects of applying these elements can be analyzed practically and numerically. Numerical results obtained from the simulation of the case study models were extracted using Autodesk CFD software and were comparatively examined in terms of three variables: air velocity, air temperature, and ventilation effectiveness. The results of this research can serve as a scientific basis for the optimal design of residential spaces in hot and humid regions and help architects and designers use these tools and methods to create buildings with better environmental quality. With these explanations, the main research questions can be stated as follows:

What effect do different depths of Sabat have on enhancing natural ventilation in the interior spaces of traditional-pattern houses in Kong County, Hormozgan Province?

What effect does the use of windcatchers with different openings have on natural ventilation in the interior spaces of courtyard houses in the hot and humid climate of Bandar Kong?

What effect does the simultaneous use of windcatcher and Sabat in courtyard houses of the hot and humid southern Iran have on the ventilation performance of interior spaces?

Literature Review

The study of natural ventilation in traditional Iranian architecture, especially in the hot and humid climate, is one of the important topics in the field of climatic design. Traditional houses of southern Iran, especially in Bandar Kong, by employing vernacular elements such as windcatchers and Sabats, have used intelligent mechanisms for air circulation and thermal comfort in response to specific climatic conditions. The windcatcher, as the best-known ventilation element in the traditional architecture of hot-dry and semi-humid regions, has been examined in numerous studies. For example, the study by Dehghani Mohamadabadi et al. (2017) showed that multi-faced windcatchers, particularly four-sided ones, by utilizing differences in pressure and ambient temperature, can bring desirable airflow into the space and expel warm air from the building. Nekoufar et al. (2024) also showed, using CFD simulation, that increasing the height and side openings of a windcatcher significantly improves its performance in exhausting warm and polluted air.

Alongside windcatchers, Sabats, and semi-open spaces such as iwans and terraces, as intermediate layers between outdoor and indoor space, play a significant role in controlling solar radiation, reducing the external shell temperature, and directing airflow into interior spaces. Ghahraman Izadi et al. (2023) examined factors affecting the tarmeh as one of the semi-open elements in Bushehr traditional architecture and investigated the impact of the depth of this element on natural ventilation of the space behind it. They ultimately emphasized the importance of tarmeh depth for ventilation quality and proposed a depth of 3.5meters and an L-shaped form as the most suitable configuration for it.

Similar studies have been conducted internationally. For example, Ghaffarianhoseini et al. (2016) show that semi-open spaces such as terraces and balconies, if designed in interaction with prevailing wind flow, can play a complementary role to natural ventilation systems. Also, in the study by Heidari et al. (2025), various characteristics of balconies, including their depth, were examined in buildings adjacent to an urban valley, and their impact on pollutant dispersion and ventilation quality in the valley's open space was assessed. Their results indicated that increasing balcony depth reduces pollutant dispersion and increases the air changes per hour (ACH) in the valley space.

In most of these studies, the performance of windcatchers and Sabats has been examined separately, and few investigations have analyzed the simultaneous interaction of these elements in improving natural ventilation. The present research, focusing on traditional houses of Bandar Kong and designing three scenarios (Sabat, windcatcher, and their combination) within CFD simulation, seeks to numerically and precisely analyze the combined effect of these two elements on natural ventilation performance and thereby fill the existing gap in the literature.

Research Method

As mentioned earlier, the main objective of the present study is to analyze the impact of the simultaneous use of windcatchers (badgir) and Sabat on improving natural ventilation in traditional houses of Kong County in Hormozgan Province. For this purpose, a computer simulation using Autodesk CFD 2018 software was employed. The work process was carried out as follows: first, a traditional house that included the elements of interest in this study (Sabat and windcatcher) was selected as the validation model. The aim of this step was both to use the spatial proportions of that house to extract the geometric dimensions of the case study samples and to use it for validation studies of the software used in the present research. For this purpose, the Younesi house located in this city was chosen, and its various dimensions are presented below. After validating the software, the research case samples were selected and simulated in the CFD software environment. Three scenarios were chosen for determining the research case samples as follows:

1) In the first scenario, only the effect of the variable “Sabat depth” was considered. Accordingly, four samples with different Sabat depths from 1 meter to 2. 5 meters were selected as the case study samples.

2) In the second scenario, the effect of the number of openings of the windcatcher was considered; therefore, in this scenario, the case study samples included windcatchers with one, two, three, and four-sided openings. Thus, four case samples were also considered in this scenario.

3) In the third scenario, the simultaneous effect of using windcatcher and Sabat on the natural ventilation of the spaces under study will be considered. Accordingly, the most optimal samples extracted from the first and second scenarios will be used to construct the case sample in this scenario.

Fig. 1 shows the diagram of the research process; other dimensions related to the present study are also introduced below.

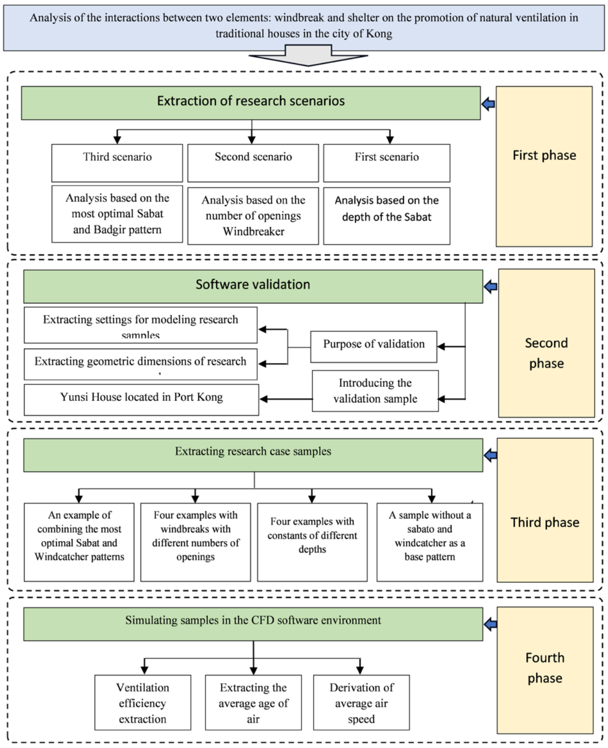


Fig. 1. Diagram of the research process. Source: Authors.

• Software validation

Given that computational fluid dynamics (CFD) is used in this study to analyze natural ventilation, validation of the simulation software is considered essential. In studies of this type, two methods are used for software validation: numerical analysis or experimental analysis (Zomorodian & Tahsildoost, 2016). In the numerical analysis method, an experimental study related to the subject that was previously carried out by other researchers is re-simulated, and its results are compared with those of the referenced experimental study. In the experimental method, the researcher personally collects quantitative data related to the study variables from a real or laboratory model, then simulates the corresponding model in the software and compares the obtained data with the collected measurements to validate the software. With this explanation, the present research uses the second method (experimental method) for validation of the CFD software. For this purpose, first a traditional house that included the elements examined in this study (windcatcher and Sabat) was selected. Next, after examining the meteorological data of the county during the field measurement period, wind speed values in the rooms under the windcatcher and in the central courtyard space were extracted and recorded. Finally, the chosen house was simulated in the CFD software environment, and its results were compared with the field measurement data.

The house selected for the validation study is the Younesi House located in Kong County. This house is one of the best examples of the house typology in Bandar Kong. The proportions of open, semi-open, and enclosed spaces in this house are such that environmental comfort inside the building is maintained even under unfavorable climatic conditions. This building has a distinctive entrance that is separated from the street level by several steps, and its interior is a pleasant space directly connected to the central courtyard (miansara). The Sabats of this house are located around the miansara, defining the boundary between open and enclosed space, and access to the roof is provided by a staircase within the enclosed space. In the miansara, due to the presence of an elder tree, the height of the courtyard walls has been increased, which results in improved shading by the trees (Figs. 2 & 3).

A collection of daily air-speed data over a nonconsecutive fifteen-day period during the months of Aban, Azar, and Dey 1403 was carried out using a Testo 405i smart hot-wire anemometer. This device is equipped with a thermal sensor system that, in addition to enabling the recording of low air speeds, allows connection to a computer for logging the captured data. Daily visits were conducted in four shifts—morning, noon, afternoon, and night—and finally, the daily average speed was extracted by averaging the speeds obtained in those intervals. In this regard, climatic data from the Bandar Kong meteorological station,

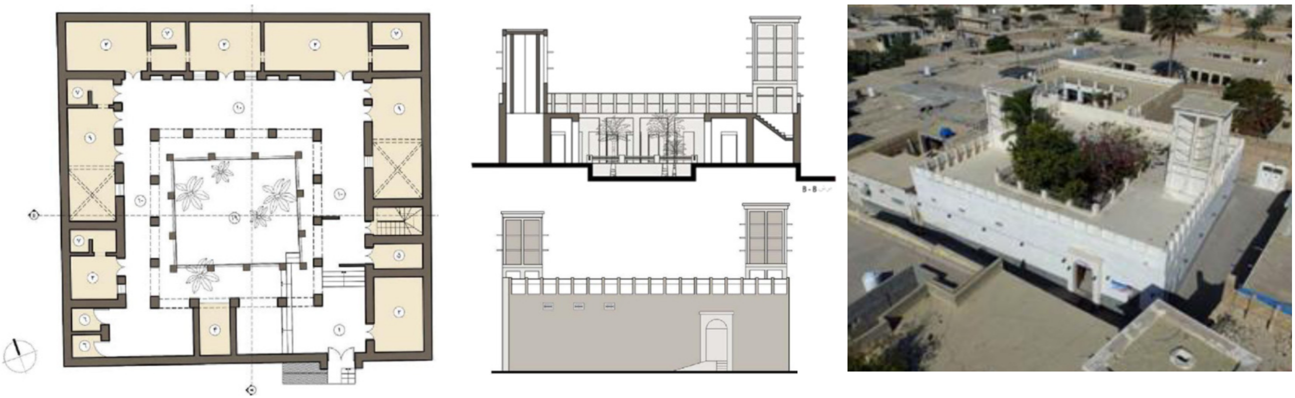

(a) (b) (c)

Fig. 2. Younesi House located in Bandar Kong, a) Plan, b) Section and elevation, c) Overall perspective. Source: Authors.

Fig. 3. Other architectural elements of the Younesi House located in Bandar Kong. Source: Authors Archive.

including mean monthly wind speed and the city's wind roses, were also used to extract the prevailing wind direction in this city; for this purpose, Climate Consultant version 6 software was used (Fig. 4).

After simulating the mentioned house in a CFD environment and inputting the county's climatic data into the software for the days of field measurements, the results were extracted and compared with the field measurement results for the two spaces: the windcatcher room and the central courtyard (miansara). The results are presented in Figs. 5 & 6.

As is evident from the Figs. 5 & 6, there is a relatively good agreement between the simulation data and the experimental results in both the windcatcher room and the miansara, such that an 8% error is observed for the windcatcher room results and a 6% error for the miansara results. This indicates the high validity of the computer simulation results in the present study.

- **Introduction of the research case studies**

As the title and objectives of the research suggest, the independent variables in the present study are two elements: the Sabat (covered arcade) and the windcatcher, which are recognized as identity-forming elements in the traditional architecture of Bandar Kong. Although various spatial characteristics of these elements can be mentioned, in the present study, the depth characteristic related to the Sabat and the number of openings related to the windcatcher will be examined. Accordingly, the research case studies in the first two scenarios are determined with respect to the two variables: Sabat depth and the number of windcatcher openings.

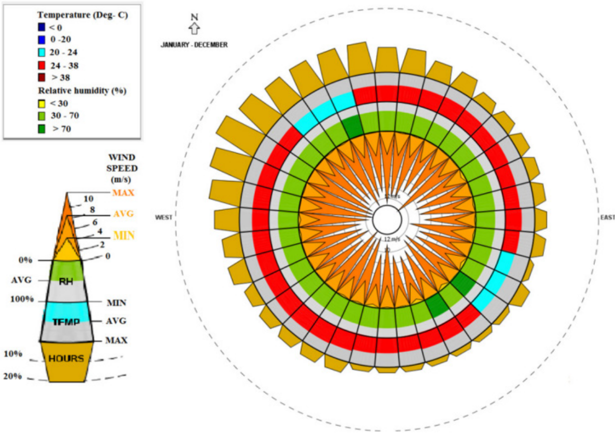


Fig. 4. Average speed and local wind directions in Bandar Kong derived using Climate Consultant software. Source: Authors.

Before addressing the case studies, it is first necessary to consider a building with a form lacking any Sabat or windcatcher as a reference sample so that the results of other samples can be compared to it to analyze the influence of the elements under investigation. For this purpose, a central-courtyard building with four surrounding rooms—each room equipped with one door and two windows facing the miansara (total area 4.5square meters)—was considered as the reference sample. The geometric proportions of this building were derived from the geometric proportions of the Younesi House, which was used as the validation sample, and this form was used as the base form, shaping the other research case studies as well (Fig. 7).

In determining the samples related to the first scenario, which concerns the Sabat depth, four Sabats with depths of 1 m, 1.5m, 2m, and 2.5m were added to the reference building. The added Sabats were attached around the central courtyard on all four sides. Accordingly, the samples related to this scenario were named Case_ 01 to Case_04.

Regarding the samples related to the second scenario, which concerns the number of windcatcher openings, four types of windcatchers—one-sided, two-sided, three-sided, and four-sided—were placed above the four rooms located on the different faces of the courtyard. The cross-sectional area, height, and opening area of the windcatchers were kept constant across all case studies and were taken

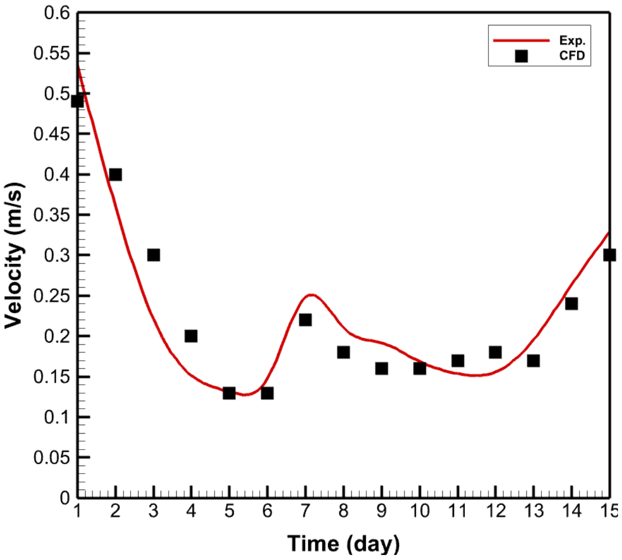


Fig. 5. A comparison of CFD simulation results and field measurements of air speed in the courtyard area of the Younesi House, located in Bandar Kong. Source: Authors.

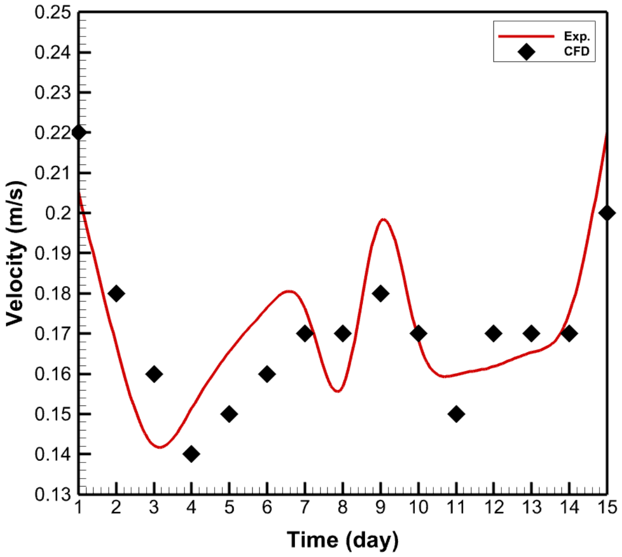


Fig. 6. Comparison of CFD simulation results and field measurements of air speed in the windcatcher room of the Younesi House, located in Bandar Kong. Source: Authors.

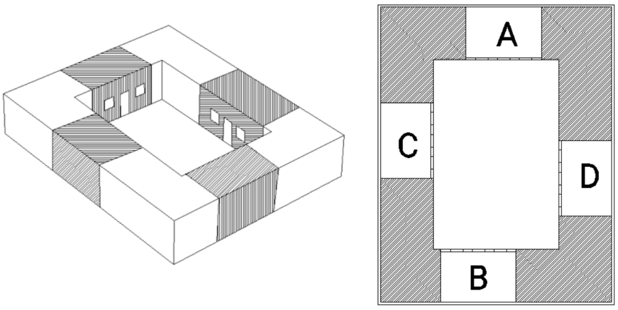


Fig. 7. Plan and perspective of the reference sample. Source: Authors.

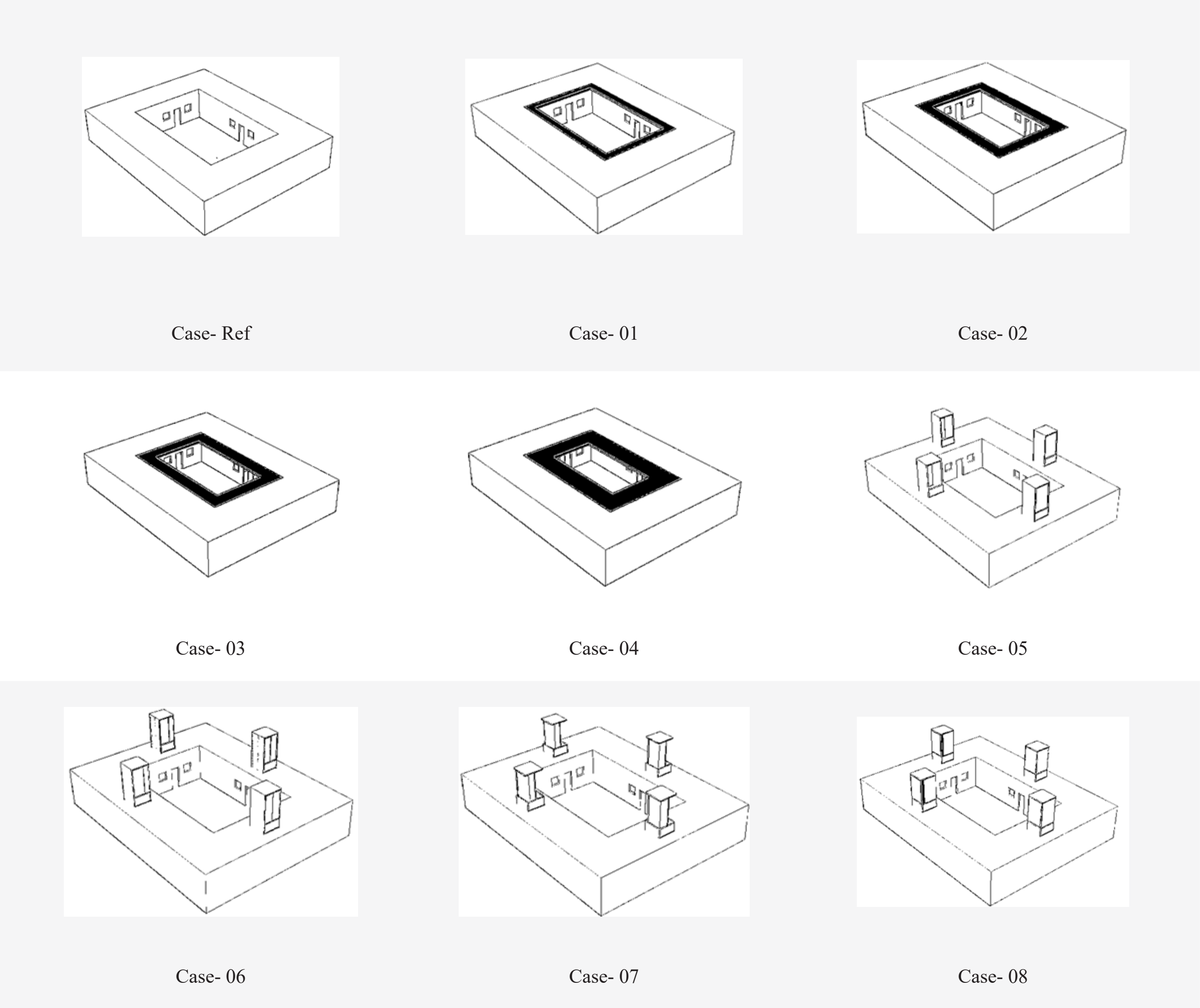
from common windcatcher patterns in traditional houses of Bandar Kong. Thus, a cross-sectional area of 4 square meters, a height of 4 meters, and an opening area of 4 square meters were considered for all windcatchers examined in this study. The samples related to this scenario were named Case_ 05 to Case_08. Fig. 8 shows three-dimensional views of the case studies related to the first and second scenarios of the research.

- **CFD settings**

In CFD simulation-based studies, presenting settings related to parameters such as the computational domain, boundary conditions, and mesh is essential. In determining the computational domain for analyzing the case-study samples in this research, the guidelines of Franke et al. (2011) and Tominaga et al. (2008) were used. According to these guidelines, the domain dimensions upstream and downstream are considered equal to 10H and 20H, respectively, and 10H on the sides. Considering that the building height (H) in the samples with windcatchers is 8 meters, the computational domain dimensions in this research were taken as L×W×H = 385 × 255 × 48 m^^{3} (Fig. 9). Also, in constructing the computational mesh, a mesh consisting of 1,230,150 cells was used. To increase convergence and reduce shear errors, hexahedral-shaped cells were used in the mesh construction in this study (Fig. 10).

In this study, the samples were modeled using atmospheric boundary layer (ABL) characteristics under neutral conditions (Richards, 1989; Harris, 1981). The inlet air velocity of the domain was set to 2. 7 m/s according to the ten-year mean wind speed at Kong port for the months of Aban, Azar, and Dey. Static pressure of zero was also set at the domain outlet.

Three-dimensional steady RANS equations were used in combination with the SST k-ω turbulence model to solve the equations in this study. The solution is steady-state, and the simulated flow



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Case- 06 Case- 07 Case- 08

Fig. 8. Three-dimensional images of the research case studies. Source: Authors.

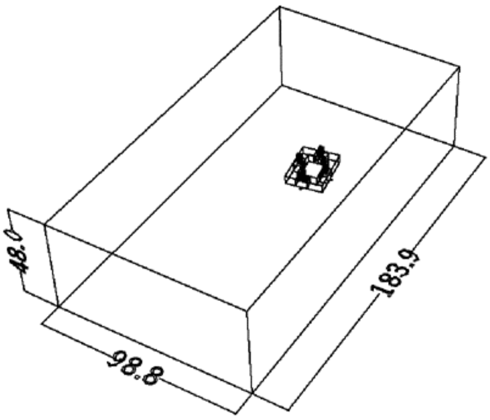


Fig. 9. Computational domain dimensions in the simulation of the case-study samples. Source: Authors.

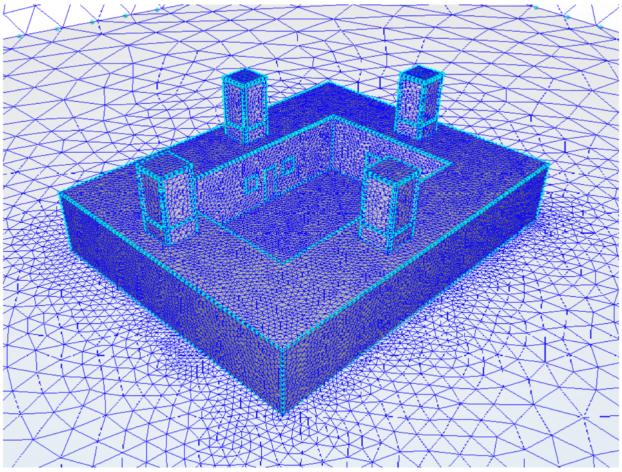


Fig. 10. Sample mesh in the CFD simulation of the case-study samples. Source: Authors.

is incompressible. The SIMPLE algorithm was used for pressure–velocity coupling, and the 5th-order (Petrov–Galerkin modified) discretization schemes were used for the RANS equations. The residual averaged outgoing (ARO) target values were set to 10^(-5) m/s for the u velocity field, 10^(-6) m/s for the v velocity field, and 10^(-11) Pa for pressure.

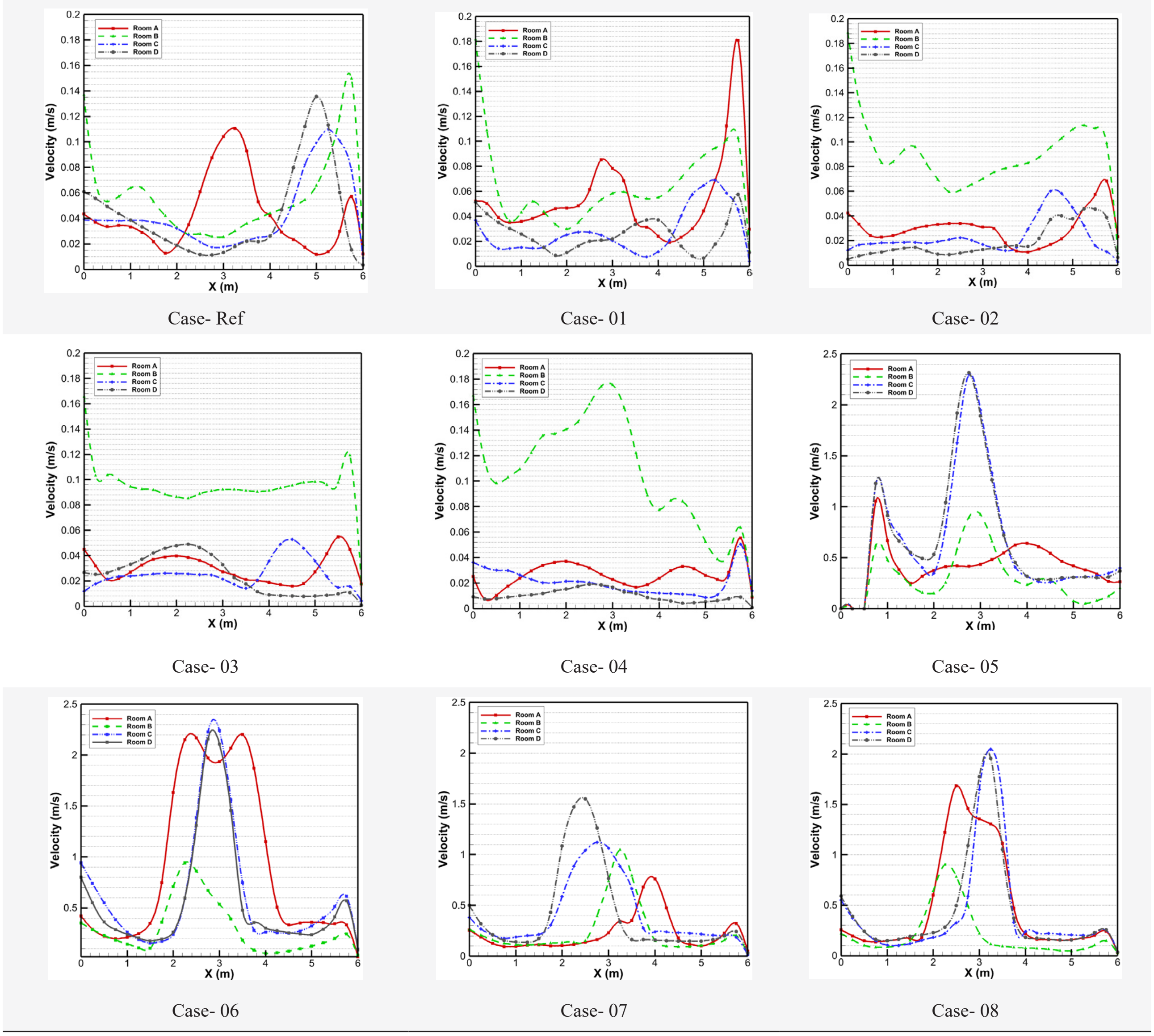
Findings

As previously stated, the main objective of the present research is to investigate the effect of the simultaneous use of two elements, windcatcher and Sabat (covered passage), on improving natural ventilation in traditional houses of Kong port. For this purpose, the case-study samples were selected based on three scenarios: in the first scenario, the effect of Sabat depth; in the second scenario, the effect of the number of windcatcher openings; and in the third scenario, the combined effect of using Sabat and windcatcher on the ventilation performance of spaces surrounding the central courtyard was evaluated. The indices examined to analyze ventilation performance in the present research include air velocity, air temperature, and ventilation efficiency. Since the sample examined in the third scenario was chosen based on the optimal results obtained from the first and second scenarios, its results will be discussed in the "Discussion" section. Therefore, in the "Analysis of Findings" section, the focus is solely on explaining and analyzing the numerical simulation results of the case-study samples in the first two scenarios.

• Analysis of the air velocity index

Air velocity is one of the most important indices in evaluating natural ventilation quality and indicates the amount of air displacement in a space per unit time. An increase in this index is generally associated with improved thermal comfort and increased ventilation effectiveness (Allard & Ghiaus, 2012). Fig. 11 shows the numerical plots of air velocity variations along the longitudinal axis of each of the rooms in the case-study samples. Fig. 12 also displays graphical contours of air velocity variations in these spaces. It should be noted that all numerical plots and contours presented were extracted at a height of 1.70meters above the ground.

Examination of the data for Case_01through Case_04, whose difference is in the depth of the Sabat (semi-open recessed passage), shows that with increasing Sabat depth, the mean air velocity in all four rooms increases. This trend is much more pronounced in room B, which faces the windward side, and can be attributed to the role of the Sabat as a semi-open space in guiding incoming wind into the room (Fig. 11). It appears that increasing the Sabat depth creates a pressure difference and reduces resistance along the wind path, resulting in air entering the interior space at a higher speed. This is clearly visible in the comparison of the overall mean air velocity in the four rooms of the samples, such that Case_ 04 has the highest mean at 0.23m/s and Case_ 01 has the lowest at 0.12m/s (Fig. 13). In the samples Case_ 05 through Case_08, which analyze the effect of windcatchers with different numbers of openings, observations show that in all samples the area beneath the windcatcher, particularly in rooms C and D (located on the sides of the central courtyard), experiences a significant increase in air velocity. This is due to the flow-amplifying mechanism of the windcatcher and the direct guidance of air into the space beneath it. Among these, the highest velocity was recorded for Case_05(single-sided windcatcher) at 0.83m/s, and the lowest for Case_ 07 (three-sided windcatcher) at 0.37m/s (Fig. 14). It seems that with an increasing number of openings, the negative pressure caused by pressure differences along the flow path is reduced and the airflow is distributed more evenly, which, while



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Case- 06 Case- 07 Case- 08

Fig. 11. Velocity variations along the longitudinal axis of the rooms located in each of the case-study samples. Source: Authors.

reducing flow concentration, also reduces its speed. These results are consistent with similar findings in windcatcher design, which show that concentrated flow in single-sided windcatchers produces faster flow, whereas multi-sided windcatchers create broader, gentler flow (Givoni, 1994).

- **Analysis of air age index**

Air age, or the residence time of air in a space, is one of the most important qualitative indices for evaluating the effectiveness of natural ventilation. Lower air age indicates better air circulation and faster entry of fresh air, while higher air age indicates stagnation and poor ventilation (Etheridge & Sandberg, 1996). Fig. 15 shows the changes in mean air age broken down for each of the rooms in the case study samples.

Considering the above data, it is observed that in the first scenario (Case_ 01 to Case_04), Room B (located on the windward façade) has the lowest mean air age compared to the other rooms in the building. This means that the residence time of air in this room is shorter than in the other rooms. Quantitative examination of the air age data in this room also shows that the mean

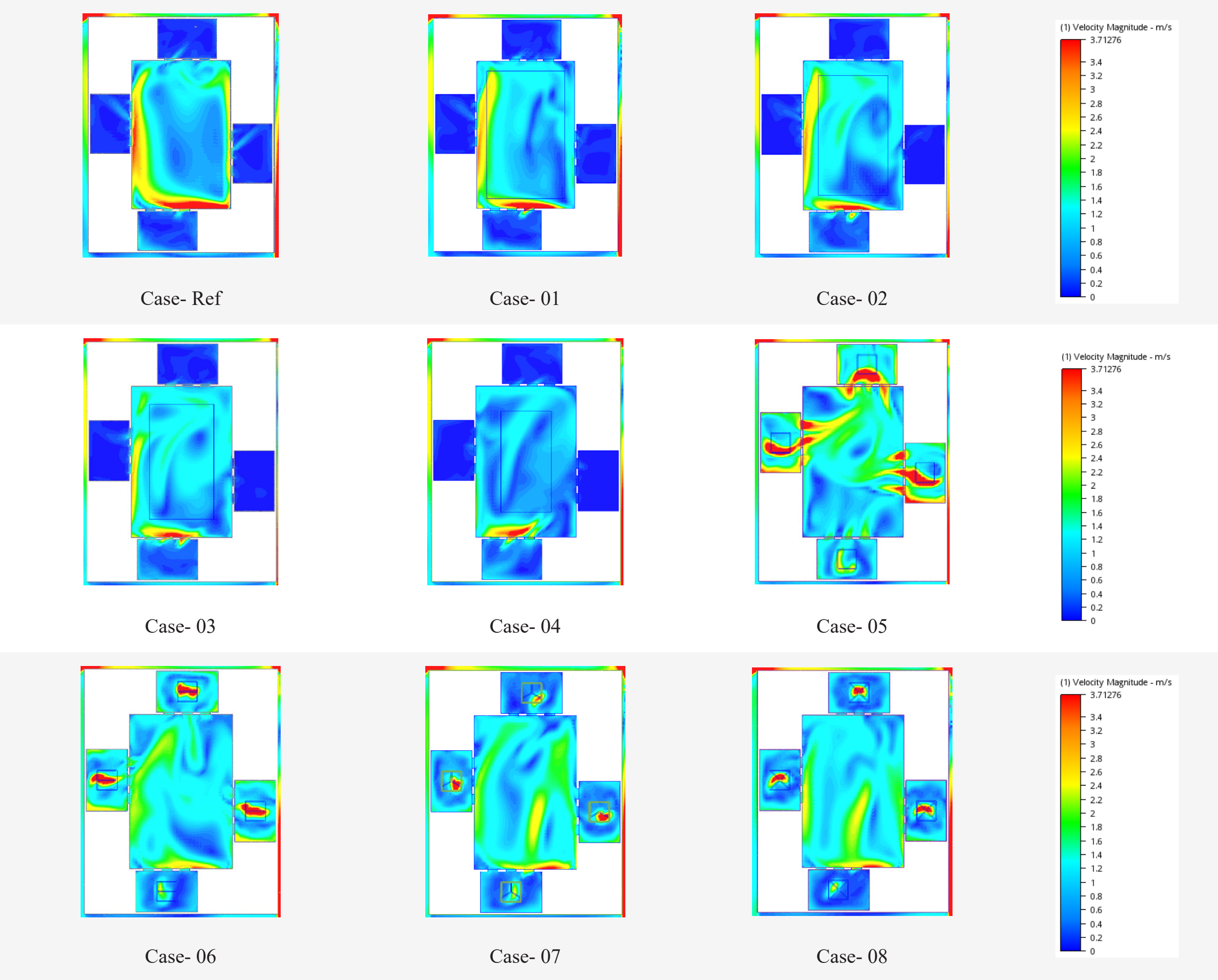

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Fig. 12. Contour display of air velocity in the rooms and central courtyard of the case-study samples. Source: Authors.

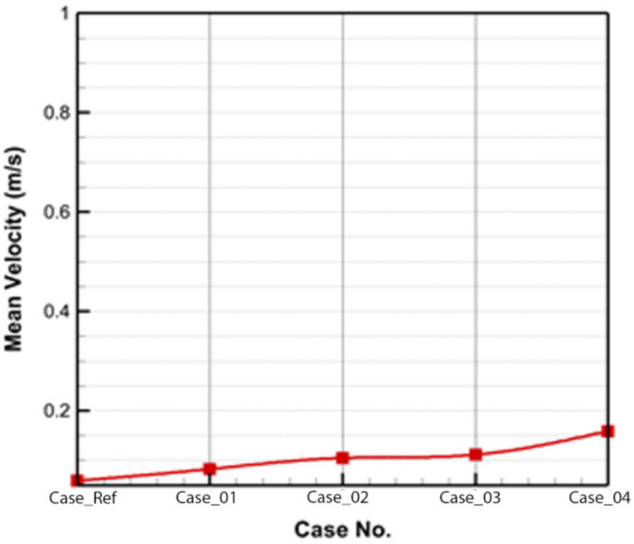


Fig. 13. Changes in the overall mean air velocity in the rooms in samples with Sabat compared to the reference sample. Source: Authors.

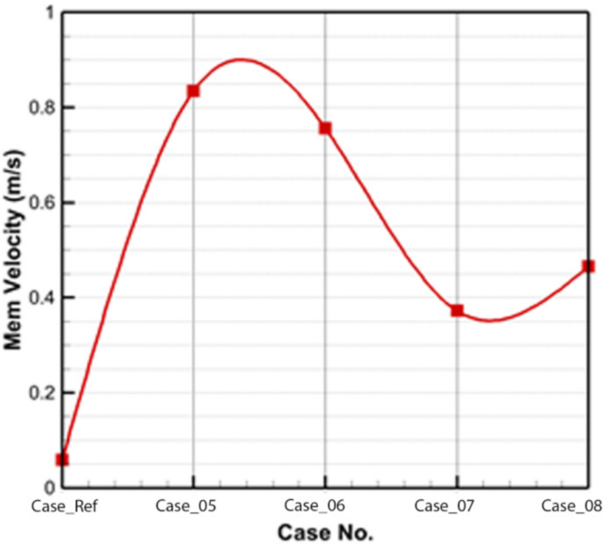
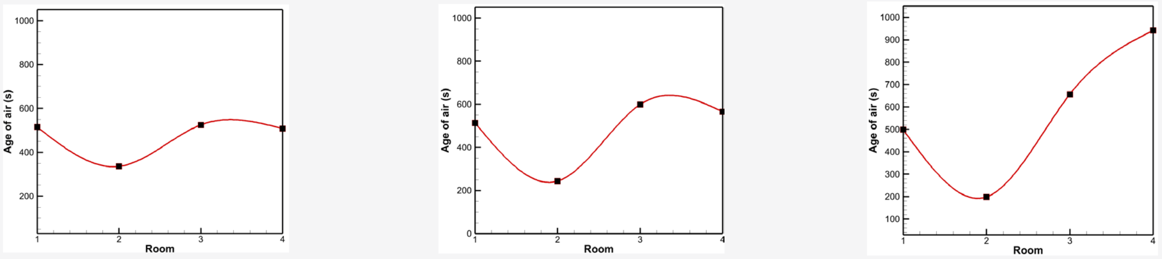


Fig. 14. Changes in the overall mean air velocity in the rooms in samples with windcatchers compared to the reference sample. Source: Authors.



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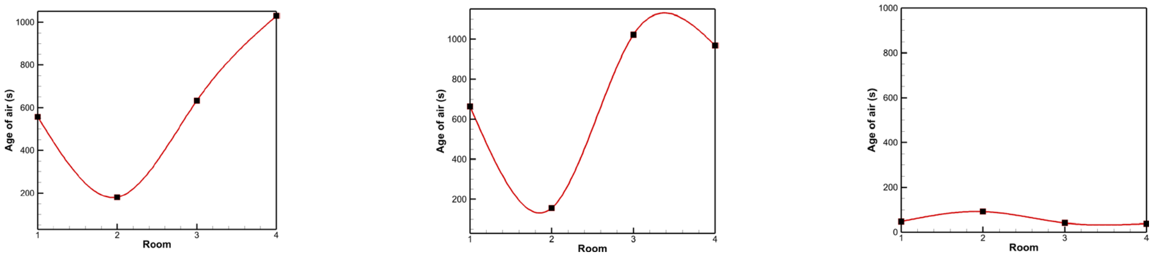

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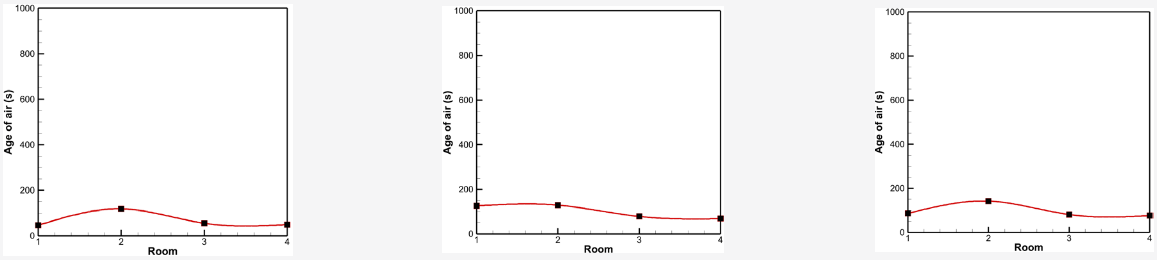

Case- 06 Case- 07 Case- 08

Fig. 15. Changes in air age in the four rooms for each of the case study samples (Number 1 corresponds to room A; number 2 corresponds to room B; number 3 corresponds to room C; and number 4 corresponds to room D.* In the above charts, number 1 corresponds to Room A; number 2 corresponds to Room B; number 3 corresponds to Room C; and number 4 corresponds to Room D). Source: Authors.

air age of this room is lowest in Case_ 04 at 156 seconds and highest in Case_ 01 at an average of 244 seconds among the four samples examined. Regarding the air age values in Case_ 05 to Case_08, the obtained data indicate that, unlike the first four samples, Room B has the highest mean air age compared to the other rooms in each of these samples. In other words, with the addition of a windcatcher to the examined buildings, the air residence time in the B rooms of each building has increased; meanwhile, the D rooms in these buildings have experienced a noticeable decrease in air age compared to the other rooms. The quantitative data for these four samples show that Room B in Case_08, with 142 seconds, has the highest air residence time and Room D in Case_05, with 38 seconds, has the lowest air residence time among the case samples.

Figs 16 & 17, respectively, show the overall mean air age values in the four rooms in Case_ 01 to Case_ 04 and in Case_ 05 to Case_ 08 compared to the reference case. The data related to these charts indicate that from Case_ 01 to Case_04, which is associated with increasing Sabat depth, the overall mean air age has shown an increasing trend; such that the overall mean air age in the rooms in Case_ 01 is the lowest at 481 seconds, and in Case_ 04 the highest at 703 seconds. With this explanation, one can infer that

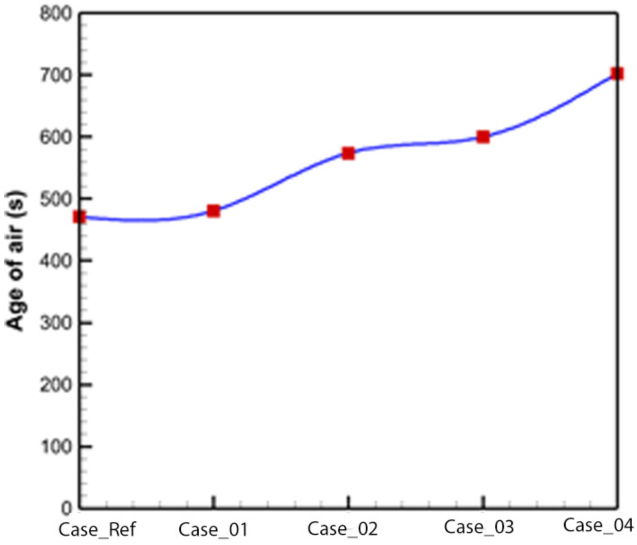

Fig. 16. Changes in the overall mean air age in the rooms present in the cases with Sabat compared to the reference case. Source: Authors.

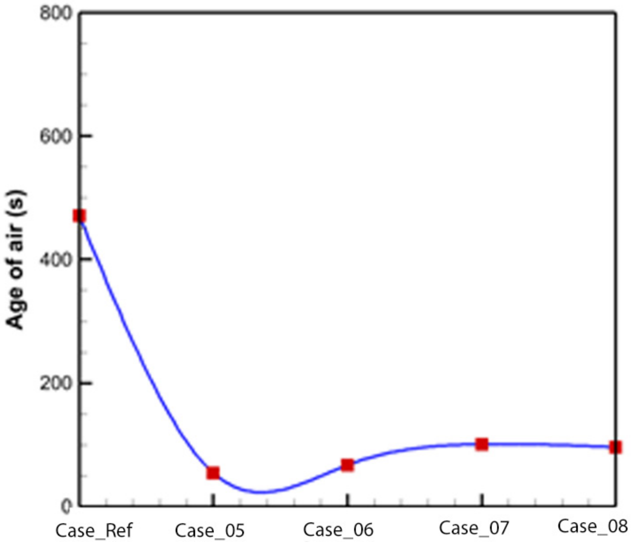

Fig. 17. Changes in the overall mean air age in the rooms present in the cases with windcatcher compared to the reference case. Source: Authors.

with increasing Sabat depth in the case samples, the overall mean air age in the case samples has also increased. In contrast, examining the overall mean air age in Case_ 05 to Case_ 08 shows that Case_05, with 54 seconds, has the lowest overall mean air age, and Case_07, with 101 seconds, has the highest mean air residence time. These results clearly indicate that the placement of ventilation elements relative to surrounding spaces has a large effect on the ventilation quality of each room. On the other hand, increasing the Sabat depth in the first scenario has caused an increase in the overall mean air age (from 481 to 703 seconds), which shows that despite improved conditions in the windward room, the overall ventilation of the building occurred more slowly. These findings are consistent with the classic performance of windcatchers, which provide targeted ventilation in a specific space (Bansal et al., 1994).

- **Analysis of the ventilation effectiveness index**

One of the most important indices for analyzing ventilation performance in a space is evaluating the ventilation effectiveness in that space. This quantity is obtained by dividing the minimum possible time for changing the air within the space by the actual time for changing the air within the room (Awbi, 2002). For this purpose, the Eqs 1 to 3 can be used:

Eq. 1
$$T_m = \frac{V}{Q}$$

Eq. 2
$$T_m = \frac{V}{Q}$$

Eq. 3
$$T_m = \frac{V}{Q}$$

In Eqs 1 to 3, ε is the ventilation effectiveness in the space of interest, expressed as a percentage; T_m is the minimum possible time for changing the air in the space of interest, and T_r is the actual time for changing the air in that space. V denotes the volume of the space of interest, and Q denotes the airflow rate entering or exiting the space of interest. Considering that the dimensions of all rooms in each of the case samples are equal to each other, V is constant in all rooms and is considered equal to 96 cubic meters. The airflow rates entering the rooms can also be extracted from the CFD simulation results; their values for each of the case samples by room are given in Table 1.

Table 1. Values of inlet and outlet airflow rates to each of the rooms present in the case samples. Source: Authors.

Cases	Room A	Room B	Room C	Room D
Case_Ref	0.59	0.61	0.38	1.03
Case_01	0.47	0.46	0.4	0.58
Case_02	0.46	0.47	0.34	0.42
Case_03	0.28	0.27	0.26	0.19
Case_04	0.29	0.17	0.26	0.21
Case_05	1.97	0.39	0.80	1.20
Case_06	0.4	0.18	0.52	0.39
Case_07	0.17	0.18	0.16	0.19
Case_08	0.47	0.29	0.10	1.27

By substituting the above-mentioned values into mathematical Eqs 1 to 3, the ventilation efficiency values for each room in each of the case study samples can be extracted; the results of which are shown in Fig. 18. Also, after averaging the ventilation efficiency across the four rooms in each case, the overall average ventilation efficiency for each of the case study samples was obtained, the results of which can be seen in Fig. 19.

Based on the simulation data, the upward trend in ventilation efficiency from Case_ 01 to Case_ 08 is very clear. This trend can be attributed to the gradual enhancement of the ventilation mechanism from a passive pattern (only Sabat) to a more active and combined pattern (Sabat + windcatcher). In Case_Ref, i.e., the baseline courtyard pattern without any control elements, the ventilation efficiency was only 36%, indicating its inefficiency in the hot and humid climate.

Increasing the depth of the Sabat in Case_ 01 to Case_ 04 increased the penetration and circulation of wind around the courtyard and

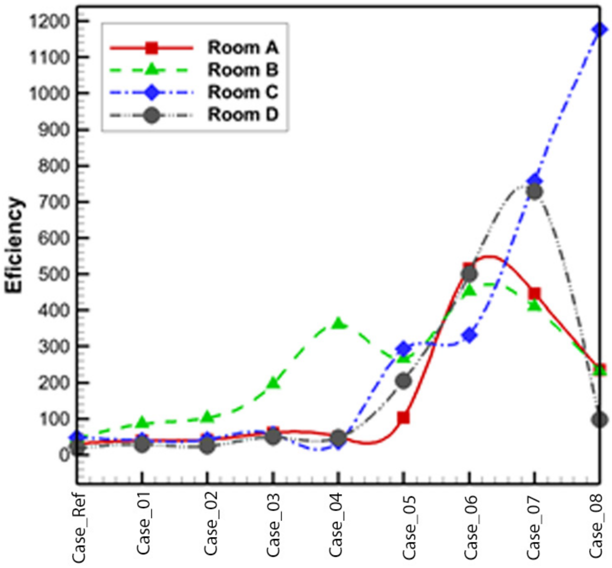

Fig. 18. Ventilation efficiency in the case study samples by room. Source: Authors.

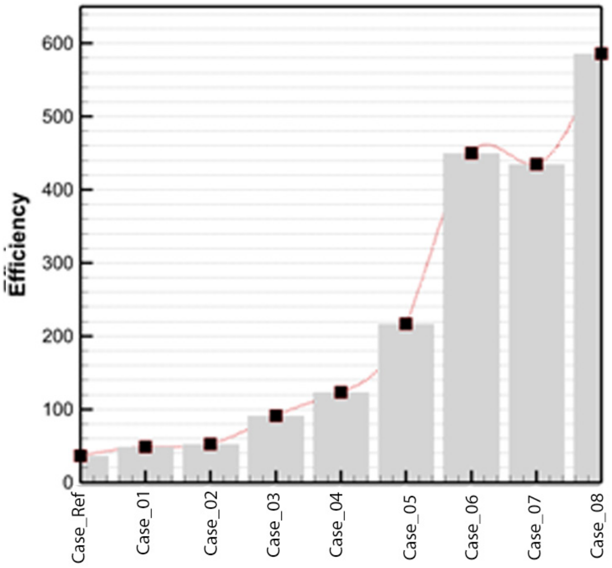

Fig. 19. Overall average ventilation efficiency for each of the case study samples. Source: Authors.

gradually improved efficiency. This trend entered a new stage from Case_ 05 to Case_ 08 with the introduction of the windcatcher, and the airflow pattern changed from one-sided to two-sided. This caused a sharp increase in ventilation efficiency, so that in Case_08the value of 586% was recorded as the highest efficiency. This result clearly emphasizes the role of the windcatcher in creating suction and simultaneously positive–negative pressure and effectively directing the airflow.

Discussion

In the present study, in order to analyze and evaluate the role of windcatchers and Sabats in improving natural ventilation of traditional houses located in the hot and humid climate of Bandar Kong, three main design scenarios were developed and investigated through numerical CFD simulations. These three scenarios are:

1) Using only Sabat with different depths around the central courtyard

2) Using only a windcatcher with varying numbers and orientations of openings

3) Simultaneous use of Sabat and windcatcher in the optimal configuration of each element

The simulations were performed using CFD based on the reference model of a courtyard house without a windcatcher and Sabat (Case_Ref). The objective was to evaluate the performance of each scenario in enhancing ventilation of interior spaces around the central courtyard, based on three key indicators: airflow velocity, air age, and ventilation effectiveness. The results for each scenario are presented as follows:

First scenario: Using Sabat only

Air velocity: Using Sabat in the peripheral space of the central courtyard led to a 40 to 170 percent increase in airflow velocity compared to the reference case. The results indicate that increasing the Sabat depth is directly related to increased air velocity in interior spaces.

Air age: The mean air age in this scenario increased by between 2 and 49 percent relative to the reference sample. This may be due to the creation of more stable recirculating flows caused by the shade and semi-open structure of the Sabat.

Ventilation effectiveness: The obtained data show that ventilation effectiveness increases with greater Sabat depth. This increase is due to improved horizontal airflow and thermal control of the courtyard peripheral environment.

Second scenario: Using windcatcher only

Air velocity: The data indicate that using a windcatcher increased airflow velocity by 12 to 28 times compared to the reference case. The highest air velocities were observed with single-sided windcatchers, which direct flow straight into the interior space.

Air age: This scenario caused a marked reduction in air age compared to other cases. Multi-faced windcatchers, especially the four-sided windcatcher, played an important role in facilitating the exhaust of stale air and improving flow quality.

Ventilation effectiveness: An increase of 6 to 16 times in ventilation effectiveness compared to Case_Ref was recorded. Among these, the four-sided windcatcher showed the most effective performance, as it enables multidirectional and stable ventilation.

Third scenario: Simultaneous use of Sabat and windcatcher

What was examined in the two previous scenarios was the effect of different features of the two elements — Sabat and windcatcher — on indicators affecting ventilation of interior spaces separately. However, in the traditional architecture of Bandar Kong, the simultaneous use of these two architectural elements is clearly visible. Accordingly, in this scenario, the synergistic effect of these two elements was examined in an optimized sample called Case_Fin. This sample included a central courtyard with a Sabat 2. 5 meters deep (as in Case_04) and a four-sided windcatcher above each room (as in Case_08).

Air velocity: The airflow velocity in Case_Fin was 8. 8 times greater than Case_Ref, 3. 2 times greater than Case_04, and 1. 3 times greater than Case_08. This finding indicates the synergistic effect of the combined use of windcatcher and Sabat in increasing natural ventilation.

Air age: The air age in this sample decreased by 85% compared to Case_Ref, by 134% compared to Case_04, and by 5% compared to Case_08, indicating a significant improvement in air circulation and renewal in interior spaces.

Ventilation efficiency: Finally, ventilation efficiency in Case_Fin was recorded as markedly higher — 34. 7 times greater than Case_Ref, 10. 2 times greater than Case_04, and 2. 1 times greater than Case_08. This dramatic increase emphasizes the effective role of an optimized combination of the two architectural elements in enhancing natural ventilation performance.

Conclusion

The present study, aiming to analyze the role of windcatcher and Sabat elements in improving natural ventilation of traditional houses in Bandar Kong, evaluated three key indicators — air velocity, air age, and ventilation efficiency — through three separate and combined scenarios using CFD simulation. The findings show that each of these elements, independently, has a significant effect on improving ventilation of spaces around the central courtyard, but their simultaneous combination produced much more optimal results.

In the first scenario, the Sabat, by increasing velocity and improving horizontal airflow in layers near the central courtyard, led to a relative improvement in ventilation efficiency, although in some cases it also caused an increase in air age, indicating recirculating trapped air and reduced flow renewal. From an architectural perspective, this can be attributed to the Sabat’s role in creating thermal stability and controlling solar radiation.

In the second scenario, the windcatcher — especially in the four-sided form — achieved the highest ventilation efficiency among the single-element scenarios by markedly increasing airflow velocity and significantly reducing air age. This effective performance can be attributed to its vertical structure, multi-directional openings, and the suction and displacement mechanism of fresh air in the interior; features that have been used in the traditional fabric of Bandar Kong to combat humidity and heat of the climate.

Finally, the third scenario, which combined a deep Sabat and a four-sided windcatcher (Case_Fin), showed that an optimized combination of these two traditional elements significantly enhances ventilation performance. In this sample, air velocity improved up to 8. 8 times, air age up to 85%, and ventilation efficiency up to 34. 7 times compared to the reference case. These results indicate a positive synergistic effect between the two elements at both functional and physical levels.

From an architectural standpoint, the study’s findings indicate that the synergy of climate-responsive traditional elements, such as Sabat and windcatcher, not only contributes to effective ventilation of interior spaces but also plays a key role in optimizing energy use and improving thermal comfort in terms of form, shading, and reducing direct heat exchange with the environment. This approach provides a practical model for sustainable architectural design in hot and humid regions.

In conclusion, revisiting traditional elements in contemporary architectural design, supported by quantitative and qualitative analyses such as CFD, can pave the way for developing patterns that are compatible with climate and culture. The present research is a step toward the intelligent revival of indigenous knowledge using modern analytical tools, which can inspire the redefinition of climatic design policies and the revitalization of sustainable architecture in southern Iran. It is recommended that future studies consider simultaneous analysis of thermal comfort indicators such as PMV and PPD, the effect of the position and orientation of windcatchers and Sabats relative to prevailing winds, and seasonal variations in ventilation performance to obtain a more comprehensive model of these elements' behavior.

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