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Wind Catchers (Badgir) of Herat: A Sustainable Cooling Solution for Centuries - Historical, Climatic and Functional Analysis

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Abstract— *Traditional windcatchers in Herat are a key element of climatic architecture in hot, dry regions. They reflect creative human adoption of the environment using renewable energy. This research aims to examine the historical, climatic, and functional features of Herat's one-way windcatcher and discuss the role of these structures in natural ventilation and cooling for residential and public spaces. To achieve this goal, first, historical and architectural sources related to the climate of the region and the windcatchers were reviewed. Then, through field surveys, internal and external measurements were taken in houses with windcatchers in the summer and compared. The result showed an average indoor-outdoor temperature difference of 4 to 10°C during peak summer hours. In addition, using a 3D model of a traditional house and analyzing it with computational fluid dynamics (CFD) software, the performance of the wind catcher on airflow and indoor ventilation was accurately simulated. As a result, the airflow path and its cooling effect for the indoor space were accurately and correctly determined. The findings show that traditional windcatchers in Herat city, with their simple but effective design, provide excellent performance. It also emphasizes that revising and reusing vernacular architecture, such as windcatchers, can be a sustainable and environmentally friendly solution for architecture in hot and dry climates. The research addresses this gap and shows that the traditional cooling and ventilation systems created by the residents of Herat were both practical and appropriate to local climatic conditions.*

Keywords— *Wind Catcher, Traditional Architecture, Sustainable Architecture, Herat Old City*

I. Introduction

Afghanistan was once part of ancient Persia, and this history has left a deep impact on the land and its architecture through Iranian culture, especially that of Greater Khorasan. In eastern Iran and western Afghanistan, traditional houses were commonly constructed with sun-dried mud bricks to adapt to the region's arid climate and to utilize local materials and cultural practices. These buildings were covered with vaulted roofs and curved brick domes. Herat (Figure 1) is located in western Afghanistan and is one of the country's oldest cities; it is located on the historic Silk Road and has been a hub of economic and cultural exchanges from the Far East to Asia Minor for centuries. (19)

Energy consumption of buildings for heating and cooling is one of the most important topics in modern architecture (supply of heating and cooling energy), which is known as the most fundamental challenge facing the world of contemporary architecture. (1) Today, the increasing reliance of buildings on fossil fuels for energy supply has raised significant environmental concerns. For this reason, there has been an increasing interest and desire to utilize renewable energy sources to reduce this dependence and mitigate its negative consequences. Against this backdrop, passive cooling approaches are being reevaluated because of their reduced energy consumption and environmental advantages. This has led to the need to use renewable energies. (2)(3) To achieve this, it is important to be inspired by the methods of the past, who once exploited various methods to maximize the use of energy available in nature using their knowledge and understanding. You would learn that traditional architecture in many arid and semi-arid climates is the best model of sustainable design. The city of Herat is a perfect example, because it has been trained and has knowledge from a climatically rich tradition, and it has vernacular skills. Windcatchers are among such techniques and are an efficient and aesthetic way to achieve natural ventilation and indoor cooling. and its inspiration holds a special place in today's architecture. (4)(5) These clever structures, utilizing the natural flow of wind, directed hot and dry air into the building and, after cooling, delivered cool air to the interior spaces.

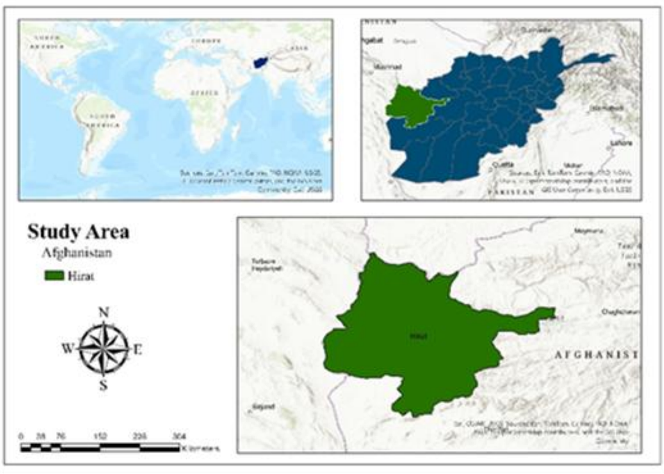

Figure 1. Location of Herat

Windcatchers are generally classified based on several

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aspects. For example, the most important classifications are based on the direction (in which the wind is received and transmitted to the interior), on their plan, on their facade, and on their location in the house plan. (6)

To study the windcatchers in Herat city, we will examine the types of windcatchers in terms of the direction of wind reception and also in terms of the type of its location in the house plan and the plan of the windcatcher itself. Windcatchers are generally divided into one-way, two-way, and four-way windcatchers in different cities of Iran, such as Yazd and Isfahan, which have a very deep similarity with the city of Herat in terms of architecture and history. (2)(6) Researchers have not conducted a comprehensive study on the characteristics of the winds in Herat city, but based on the experience of the people living in the region over many years, it has been determined that the preferred winds in Herat city blow from the north of the city during the hot season, and therefore all the windcatchers in Herat city face north, and therefore the city's windcatchers are one-way. Unlike multi-directional windcatchers, one-way windcatchers have only one opening for the wind to enter the interior space, and the direction of this type of windcatcher is towards the prevailing wind. This means that the efficiency of this type of windcatcher is highly dependent on the prevailing wind direction in the area. This means that if the wind direction changes due to various atmospheric and climatic factors in the area, the efficiency of the windcatcher will decrease. (7) These windcatchers are easier to build than other types of windcatchers due to their simple structure and the small number of components in them, and in Herat city, since the prevailing wind is clearly in the north. (8) This type of windcatcher has excellent efficiency. The excellent use of this type of windcatcher has been in small houses and water tanks due to its simplicity and smaller dimensions.

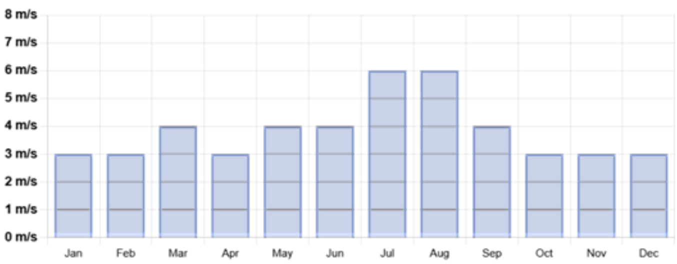

Figure 2. weather-and-climate.com. (2023). Average wind speed in Herat, Afghanistan. Retrieved May 24, 2025

Herat has a semi-arid to arid climate, characterized by low rainfall, high evaporation, relatively high temperatures, and strong seasonal winds. (9) Windcatchers are used only in the summer to ventilate and cool houses. Therefore, Herat's climate is important during this season. Herat's summers are hot and dry, and the average annual temperature in this Afghan province varies. during summer, average daytime temperatures in Herat reach around 40°C, with much higher peaks on particularly hot days. One of the unique features of Herat's climate is the strong summer winds, known as the 120-day winds. These winds blow from the north from early July to September at an average speed of 7.5 meters per second and sometimes up to 25 meters per second. (8)(9) According to statistics from the website weather-and-climate.com (2023), the average wind speed in Herat in July and August is about 6 meters per second (Figure 2).

II. Research Methodology

To better understand the history, structure, and function of windcatchers, a significant number of scientific sources, including a total of 30 articles and 5 specialized books on the architecture of the ancient Khorasan region, and historical studies related to traditional Herat architecture, were reviewed, which collectively provided the theoretical framework for the research. To search for these articles, reputable databases including Google Scholar, Scopus, and Web of Science were used. And also, the keywords used in the search included Wind Catcher, Herat old city, Sustainable Architecture, Traditional Architecture, Herat Climate and etc. After the research, all articles were filtered based on specific inclusion and exclusion criteria so that articles related to the main topic were selected. Then, to fully and accurately analyze the actual performance of Herat windcatchers, A field survey was carried out in six historical houses situated in various parts of the old city of Herat in the summer. Houses were also chosen to represent different forms of building and orientations of the wind-catcher, and also, based on the architectural diversity and geographical distribution in different parts of the old city, a feasible and practical example for field studies should be provided. The reason for choosing this number of houses (six houses) was that it could be a representative example of the historical architecture of Herat, and also provide the possibility of collecting accurate field data, and finally, make it possible to compare the selected examples. Digital thermometers were used to measure the temperatures at two critical nodes: inside (with the wind-catcher functioning) and outside (as close to the walls of the building as possible). (Table 1) The results obtained indicated that the temperature difference between inside and outside the building was between 4 and 10 degrees Celsius. Also, in old-style Herati houses, thistle matter was attached to the inside of the windcatcher opening and kept moist, supposedly adding coolness and moisture to the incoming air. Dry selective windcatchers were tested by using this historical method; moistened thorns were inserted into the windcatcher being tested, and inlets and outlets were covered. The temperature results indicated that this method had the potential to improve the cooling effect, with a decrease in temperature of up to 13 °C. This empirical study validates the performance of this indigenous cooling method.

In this paper, Autodesk Revit was selected as the tool for architectural modeling, given its accurate and precise modeling of the traditional windcatcher. Since it is compatible with simulation tools, it was a good choice for this study. Airflow simulation and temperature distribution were performed using Autodesk CFD. It can be used to simulate natural ventilation and passive cooling performance accurately, and so is appropriate for testing windcatchers adaptive to natural climates. These analyses support the experimental results and show the effect of windcatcher design on ventilation and cooling.

III. HISTORICAL BACKGROUND

The windcatcher has been known throughout history as a traditional structure for ventilation. Finding the exact history of the windcatcher from the remains is very difficult. Because in most buildings, the first signs of destruction occur in the roof and especially in the roof windcatchers. (Figure 4) As a part of the general history of windcatchers, one of the earliest known uses can be traced to the Mochica Indians of Peru. (15) As they used the windcatcher to ventilate their houses. It also existed in the Middle East with various forms and different names (Yarshater, 1989, 368). In Afghanistan, it is known as the term Badgir and Badanhol, in Egypt as the term Malikuf, in Iran as the name Badgi, and in Pakistan as the name Badkhor. (14)(15) Finding the exact history of the windcatcher from the remains is very difficult. Because in most buildings, the first signs of destruction occur in the roof and especially in the roof windcatchers. (Figure 3)

Figure 3. Damage to the roof has caused the complete destruction of the windcatcher in Herat's old city. (Source: K. A. AHMADI)

Herat, located in the Greater Khorasan region, belonged to a broader architectural network of this area. The use of windcatchers in architecture was common in hot and dry regions, including areas such as Yazd and Kerman, which are very similar to Herat in terms of architectural originality. Historical evidence shows that during the Timurid period and later, windcatchers were used in noble houses and public buildings such as mosques and ponds to cool the space and provide natural ventilation. (11)(12)

In the historical context of Herat, especially in old houses and central neighborhoods such as the Khwaja Abdullah Ansari area and Karte Arab, remains of windcatchers can be seen, which were made of local materials such as raw brick and wood. Traditional Herat windcatchers are very similar to Iranian examples of windcatchers. However, they have some special features such as smaller dimensions and better adapted to the design of Herat's enclosed houses. These windcatchers were built in houses with a central courtyard (Figure 5) as well as semi-private spaces.

According to research, the earliest confirmed architectural activity in Herat is assumed to date back to around 441–450 CE, coinciding with the construction of the defensive wall of Gorgan. Over the following two centuries, the fall of the Sassanid dynasty by the Arab powers. Based on the results obtained, researchers assume that the Sassanid emperor Khosrow I built the Herat city wall as a defensive fortification in the late 6th century CE. This may have been part of his reforms after the defeat of the Heptals. (16)

Figure 4. Windcatcher in Ab Anbar in the Yazd region of Iran, 8th century AH Adapted from Mahmoudi & Mofidi Shemirani, 2008.

This suggests that architectural activity in Herat continued for several centuries before the arrival of Islam into the land. Since the Sassanid period is known for its systematic engineering and defensive structures, the presence of strong walls is an indication of a high level of architectural organization. In such a case, Herat, due to its hot and dry summer climate, needed a local solution for cooling and ventilation. Therefore, given the development of architecture during this period, even if we do not have direct evidence of windcatchers, we can raise the possibility of using early forms of climatic measures, such as windcatchers and natural ventilation.

In the Islamic age, particularly from the 9th century onward, Herat flourished as a major cultural and economic center along the Silk Road. In the city, there was a concentration of skilled craftspeople, artists and architects whose innovation in art and architecture paralleled Iran's. The mosques, madrasas and caravanserais in that particular period envisioned during Ghaznavid and Ghorid rule are fine models of climatic wise design. Windcatchers, however, probably also developed into more advanced passive air ventilation systems which were used in domestic and religious architecture. Their purpose wasn't just practical but symbolic – representing an architectural philosophy that promoted a balance of comfort, sustainability and spirituality.

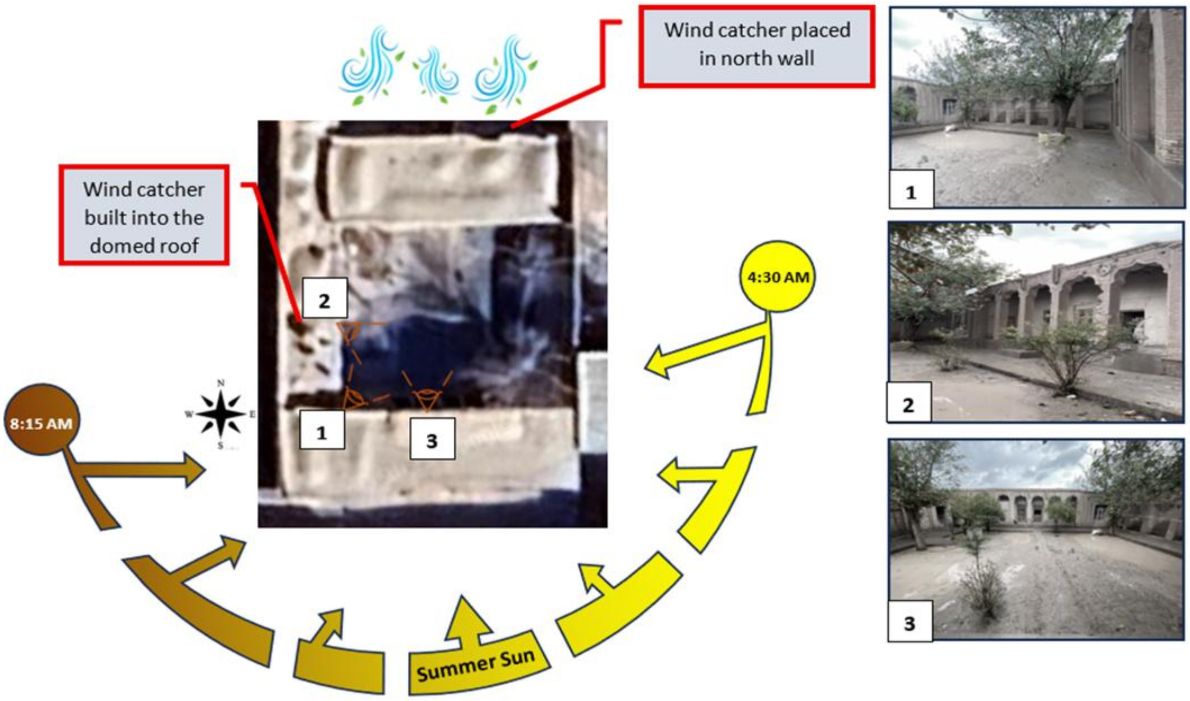

Figure 5. An old house (13) in the old city of Herat, which has a central courtyard and shows the installation of a wind catcher on the north side of the house, and how the wind catchers are placed on the domed roof. (Photograph by K.A. AHMADI 2025)

IV. Architectural Features

To build a windcatcher on the roof of a house, a rectangular cross-section frame is arranged with bricks or adobe prepared from local materials to reach the desired height. Two pieces of wood are used to separate the exterior from the interior in a cross-shaped (X) shape. (Figure 6-a) The depth of the windcatchers varies and ranges from 1 meter to 5.5 meters. The upper part of the windcatchers is made in a trussed shape, which allows the wind to flow enter the space. (Abrar Architecture Group, 2020). After the bricks are stacked, the space between the bricks is sealed with plaster and mortar. The amount of wind inlet is called the spring, and the spring is the distance between the two arranged blades of the wind deflector. The distance between these two blades actually determines the width of the spring of the wind deflector, which is about 30 centimeters.

In traditional house architecture, it was implemented for rooms where it was possible to install a windcatcher on the north side, and for rooms where there were no conditions for installing a windcatcher, it tried to cool and ventilate the interior space by using a windcatcher in the domed ceiling. (Figure 8) As mentioned earlier, the prevailing wind direction in Herat is from the north. (8) This has been recognized by the people living in the region for centuries. Therefore, the windcatchers in this city are generally one-sided. In terms of plan, the windcatchers in Herat are rectangular, which allows for more cold air to enter the interior. As you can see in (Figure 6-a), the windcatcher generally covers 1/3 of the width of the room wall.

In the old city of Herat, windcatchers were generally used for special places such as castles, but in residential houses, these windcatchers had a very simple architecture.

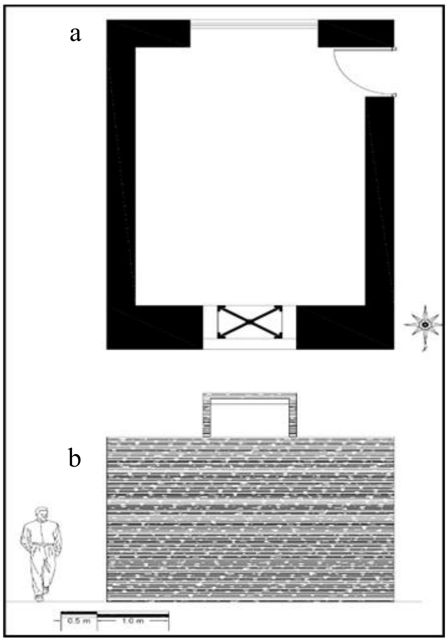

Figure 6-a. The windcatcher plan in residential houses in Herat city is located on the north side of the house, allowing cold air to enter and warm air to exit through a window installed on the south side. (Source: K. A. AHMADI)
Figure 6-b. The north elevation of the house determines the dimensions and placement of the windcatcher in the house. The windcatcher opening on the north side is open, allowing cold northern air to enter the house. (Source: K. A. AHMADI)

The location of windcatchers in the plan of houses in Herat city has been implemented in two ways.

The first case is as shown in (Figure 6-b) in the north wall of the house, which, for all these houses, was installed on the south side of the window, allowing the house to continuously let cold air in from the north and warm air out from the south through the installed window. In the city of Herat, the natural conditions are such that the best light is from the south, and in view of this, houses whose land is longitudinal, that is, north to south, can have the best light by installing a window on the south side. Therefore, these types of houses had the best light and the best ventilation. (Figure 5)

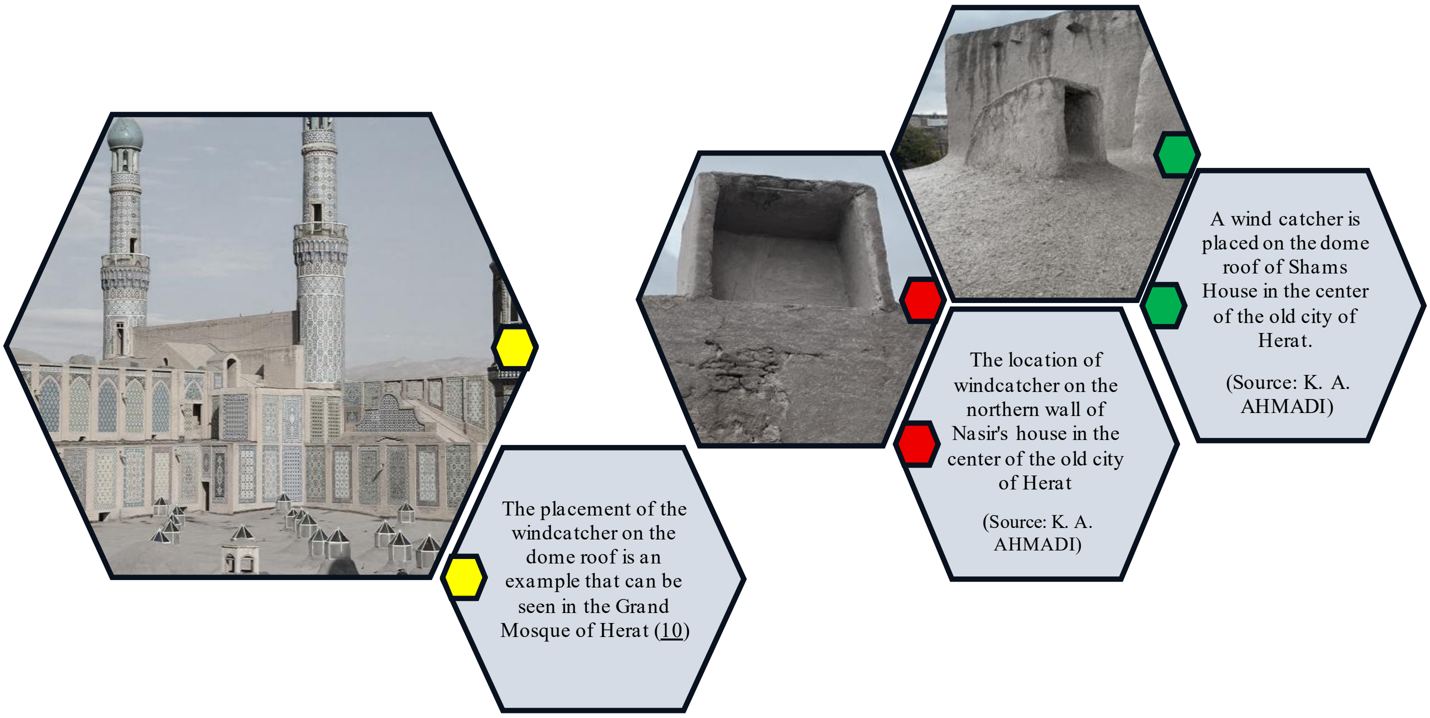

Figure 7. Different types of wind catchers in terms of placement on the house plan in the old city of Herat.

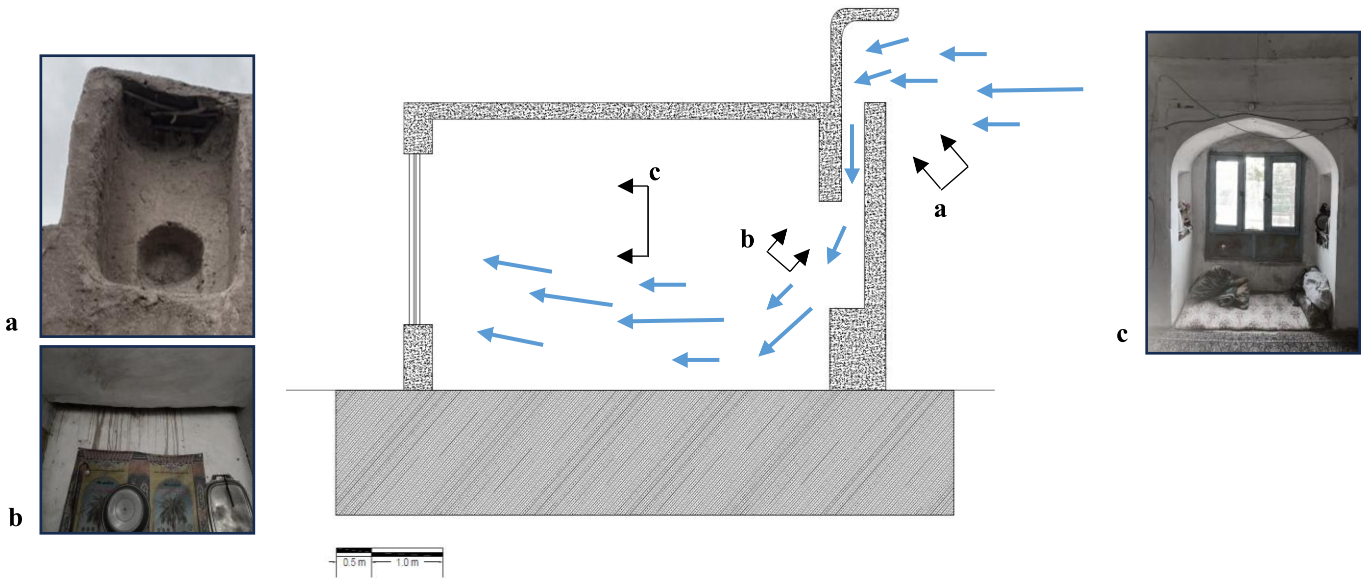

Figure 8. Airflow path inside the house with a windcatcher.
Figure 8-a. windcatcher inlet opening from the outside of the building.
Figure 8-B. Air inlet opening inside the room
Figure 8-c. A window installed on the south side of the room allows the air entering from the wind catcher to exit the room and create passive airflow. (Source: K. A. AHMADI)

The second type of windcatcher placement was in the plan of houses with domes. The windcatcher was installed in the center or next to the dome roof in the central part of the house. This type of windcatcher has also been seen in large spaces.

Examples of it can be seen in the Grand Mosque of Herat and also in most houses in the old city of Herat. (Figure 7)

V. Functionality and Principles

In a study by Dr. Mohammad Reza Ahmadi on the climate of Herat, it is stated: "In traditional Herat houses, the use of windcatchers and central courtyards has caused the temperature of the interior space to be between 8- and 10-degrees Celsius cooler than the temperature of the outside environment on hot summer days" (Ahmadi, 2013, p. 39).

In houses that have a windcatcher on the north wall and a window on the south side, ventilation is adequate, and the air flow entering from the north and exiting from the south creates a continuous air flow. (Figure 8)

As previously mentioned, the effect of the windcatcher in cooling traditional houses in Herat is such that in the summer, the interior of the house is about 8 to 10 degrees cooler than the exterior. Traditional Herat windcatchers generally have a vertical channel that extends above the roof line. (Figure 8) And since the prevailing wind direction in Herat is north (8), the direction of the windcatchers is also north. When the wind enters the windcatcher, it goes down through the vertical channel and enters the interior of the room. (Figure 8) In fact, two factors, namely the difference in temperature inside and outside the building and the pressure difference created by the wind speed, are responsible for the continuation of this air flow. (17)

In addition, the use of traditional building materials such as bricks, mud, and mortar Sarooj for details on Sarooj (see Appendix A) in houses has caused the absorption of heat during the day and its release at night, helping to stabilize the internal temperature. Overall, this intelligent combination and appropriate materials have increased the performance of the windcatcher. To experimentally investigate the performance of windcatchers in several traditional houses, I measured the internal and external temperatures in the summer and compared them. These measurements were made at different times of the day (morning, noon, afternoon, and night).

The results showed that during the hottest hours of the day (around 12:00 to 15:00), this temperature difference was quite noticeable between the indoor and outdoor spaces. On average, the temperature inside the houses with windcatchers was between 4 and 7 degrees Celsius lower than the outdoor temperature. (Table 1) (Figure 9) Therefore, the experiences of this temperature difference are a clear indication of the cooling effect of windcatchers in making the house naturally and sustainably cool without consuming energy.

The mentioned temperature difference between the indoor and outdoor spaces was smaller in the early morning and at night, but was still noticeable. This indicates that even in the absence of strong wind, the thermal storage properties of traditional materials and the residual air flow were effective in maintaining relative coolness.

Here's a representative data set for a summer day in Herat:

TABLE 1. Outdoor and indoor temperatures in houses with windcatchers (Source: K. A. AHMADI)

Time of Day	Outdoor Temp (°C)	Indoor Temp (°C) (with Windcatcher)
6:00 AM	20	18
9:00 AM	26	22
12:00 PM	34	28
3:00 PM	39	31
6:00 PM	37	30
9:00 PM	30	24

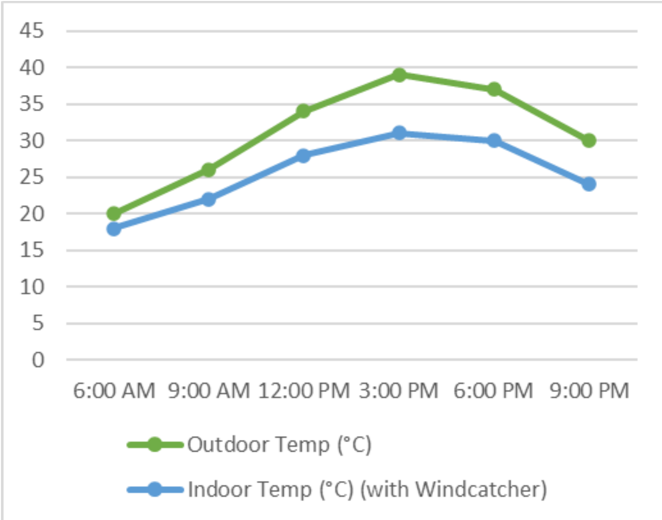

Figure 9. Comparison of outdoor and indoor temperatures in a house with a windcatcher - Herat Climate (Source: K. A. AHMADI)

The above empirical findings confirm the traditional knowledge hidden in vernacular architecture. Therefore, the windcatcher performance experience is not just a theoretical principle, but a very real response and also a very efficient solution to hot climate conditions. In fact, the windcatcher can be considered a climate-responsive architectural element that provides a cool and comfortable environment in a sustainable manner without the need for energy or modern cooling equipment.

In addition to the above-mentioned experimental studies, numerical simulations were performed using Autodesk CFD software to better understand how the windcatcher works and how the airflow is distributed into the interior air. (See Appendix B for additional CFD equations and airflow visualizations) This method allows for a more accurate observation and understanding of the air velocity distribution patterns, how the wind enters the windcatcher, and its effect on the internal ventilation of the house.

The model used is a traditional house with a simple one-way windcatcher facing the prevailing wind in the north, which was designed with Autodesk Revit software and then converted to a format suitable for Autodesk CFD software. Then, in this simulation, the incoming flow was applied at a speed of 7 m/s, based on the wind speed conditions in June and July (8)(9) in Herat city from the windcatcher.

The airflow solution was performed in a steady-state and incompressible manner. The meshing was also done appropriately and with a focus on the wind inlet area and the interior spaces to increase accuracy.

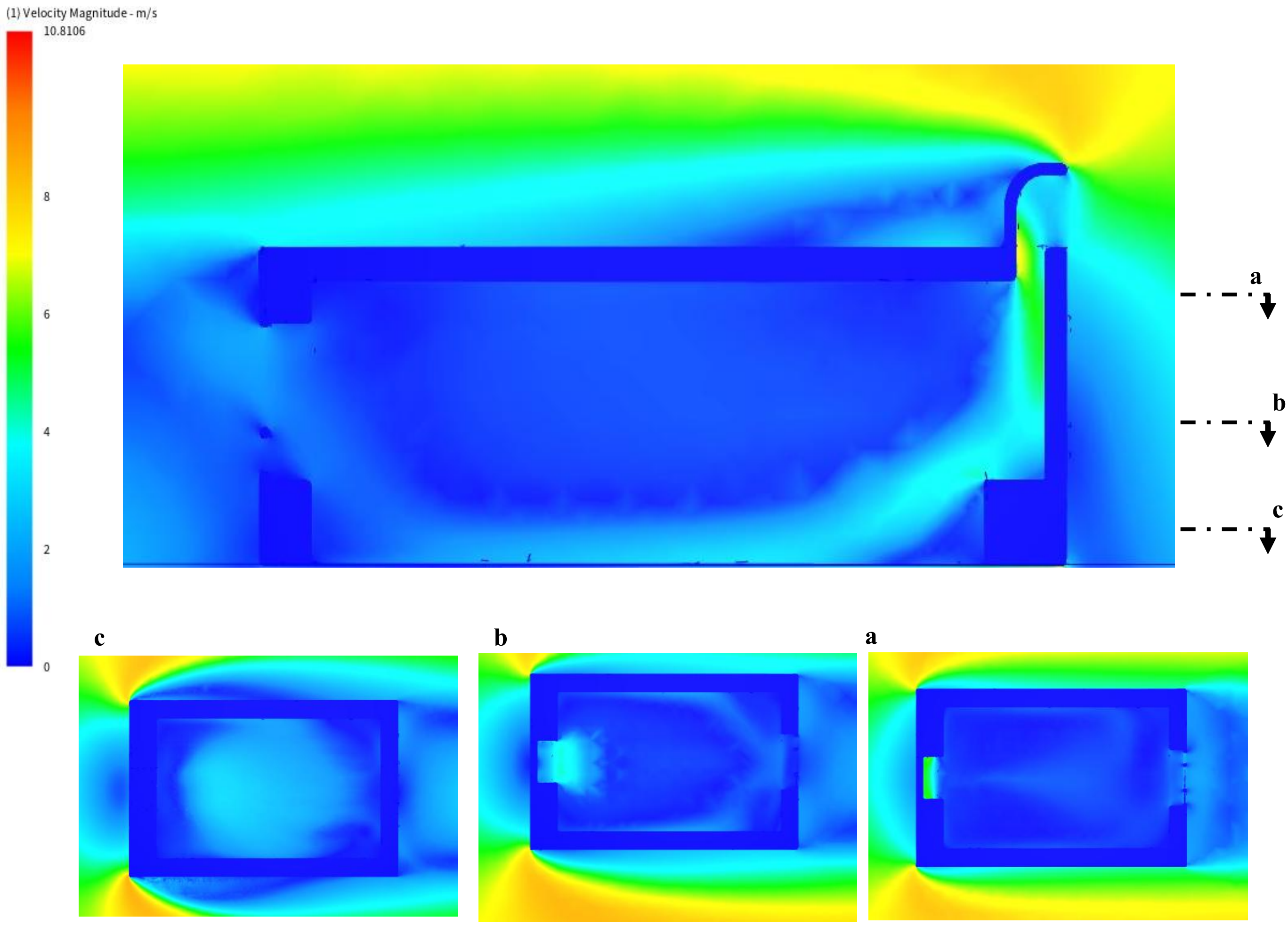

Figure 10. Analysis of the nature and function of wind flow by wind catcher in traditional Herat houses

In (Figure 10), the color map shows the velocity field distribution (velocity magnitude) in m/s. The yellow area above indicates the wind speed outside the building. As soon as this airflow enters the interior space from the wind channel, a drop in velocity occurs and then the airflow spreads widely throughout the interior space (blue and green areas).

As can be seen in (Figure 10), the velocity distribution inside the house is uniform, which indicates effective ventilation. This flow distribution is especially greater in the floor areas, which, given that it is the place where the residents are present, can increase the usefulness of the flow. As previously mentioned, in houses where it is possible to install a wind deflector on the prevailing wind or north side and also on the south side, the presence of a window has created very suitable ventilation for the said space. Here too, the outflow from the window in the opposite direction of the wind deflector has created a continuous air flow, which can create very suitable ventilation for the said space. Also, areas with traveling or very low flow, which are seen in dark blue, are mostly seen in the corners and behind the walls. In the aforementioned image, the air flow inside the house with a wind deflector near the ceiling, at mid-height, and near the floor of the house has been clearly analyzed and displayed. (Figure 10)

According to the details discussed, it was found that one of the most important advantages of traditional windcatchers is that they are passive systems, meaning they do not require anything other than wind energy for their operation. However, traditional windcatchers also have a number of significant disadvantages, the most important of which is that in traditional windcatchers, there is a possibility of dust and insects entering the building through the windcatcher duct, which directly affects the useful performance of the windcatchers. To solve this problem, the indigenous people use a special method. By placing a compressed mass of thistle plants in the windcatcher inlet, they prevent the entry of dust and insects to a significant extent. They also increase the quality of the air entering the space by humidifying the said plant mass, which plays a significant role in reducing the internal temperature after the air enters. Since windcatchers are used for cooling and ventilation in the summer, in the winter, the windcatcher inlet is closed with mud and bricks to prevent cold air from entering the interior during the cold season.

Also, in houses with one-sided windcatchers, having a window opposite the windcatcher entrance opening with dimensions of at least one by one meter can increase the efficiency of the windcatcher. (18) (Figure 11)

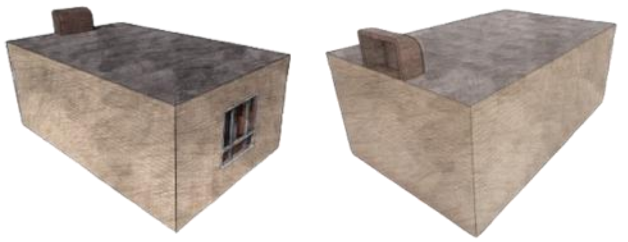

Figure 11. The presence of a window with dimensions of at least one by one meter can significantly increase the performance of one-way windcatchers. (18) dimensions in meter

VI. CONCLUSION

Traditional windcatchers in Herat city represent the pinnacle of wisdom and creativity of local architects in dealing with the challenges of the hot and dry climate of this region. The historical, climatic and functional analysis conducted in this paper showed that such traditional architectural elements are not only suitable environmental solutions to reduce the need for new energy consumption, ventilation and cooling for residential and public spaces, but also a tangible embodiment of the connection between man and nature and the intelligent use of natural forces. Over the centuries, the residents of Herat, with a precise understanding and perception of their local climate and also recognizing wind patterns - especially the prevailing north wind - have creatively designed and implemented windcatchers to exploit the unlimited energy of nature. By designing and creating windcatchers on the north side of houses and installing windows on the south side, they have created the possibility of creating a natural and continuous air flow, and in this way, they have made the most of the natural energies of their environment.

Simulations conducted with Computational Fluid Dynamics (CFD) software also proved that the design of these windcatchers led to the entry of cold air into the interior space, resulting in a noticeable drop in temperature and balanced air distribution in the habitable area, and also created passive ventilation inside the house.

Also, historical analysis also showed that windcatchers were generally accepted, as they had active practical use not only in residential houses, but also in water tanks and mosques, which indicates the extensive empirical and efficiency of these structures over time. Also, the materials used, such as brick, mud, mortar and wood, not only in the construction of the windcatchers but also in the overall structure of traditional houses, were somehow in harmony with the thermal performance and natural ventilation, and by storing heat during the day and releasing it at night, they helped to stabilize the temperature of the indoor environment.

At the end of the comparative study, modeling, thermal performance analysis, and experimental evaluation showed that the traditional Herat windcatchers, while simple, were intellectually complex, climate-oriented, and highly efficient. Reusing such creative patterns in contemporary architecture, especially in designing sustainable houses in hot and dry regions, will not only preserve cultural heritage but also ensure a future in line with the environment and natural resources.

APPENDICES

APPENDIX A. TRADITIONAL BUILDING MATERIALS: SAROOJ

Sarooj is a traditional, water-resistant mortar, primarily used in Afghanistan and Iranian architecture, known for its durability and hydraulic properties. It's an ancient lime-based mortar, historically used in building structures. It is made by combining clay, limestone, and sometimes other ingredients like furnace slag.

APPENDIX B. CFD SIMULATION DETAILS

This appendix includes additional computational fluid dynamics (CFD) results used to analyze airflow distribution inside traditional houses with one-way wind catchers. The equations are provided with brief explanations of the symbols and terms used. (Figure 10) Airflow path lines inside the Herat's traditional house model.

Eq. (B.1) Continuity Equation:

$$\nabla \cdot V = 0$$

Eq. (B.1) represents the conservation of mass. The divergence ($\nabla\cdot$) of the velocity vector (V) is equal to zero, meaning that mass is neither created nor destroyed within the control volume.

Eq. (B.2) Energy Balance Equation:

$$\rho\ Cp\ (\partial T/\partial t + V \cdot \nabla T) = \nabla \cdot (k\ \nabla T)$$

Eq. (B.2) represents the conservation of energy in the system.

- ρ (rho): fluid density
- Cp: specific heat capacity
- $\partial T/\partial t$: change of temperature with respect to time
- $V \cdot \nabla T$: convection term, representing transport of heat by moving fluid
- k: thermal conductivity
- ∇T: temperature gradient
- $\nabla \cdot (k\ \nabla T)$: diffusion term, representing heat transfer due to conduction

A mesh independence check was executed with coarse, medium, and fine meshes. The temperature distributions differed by less than 2% from each other on medium and fine meshes, indicating mesh independence of the simulation. So, this guarantees the capture resolution of CFD results based on the user grid size.

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AUTHOR CONTRIBUTIONS

K.A.A. is primarily responsible for drafting, editing, and revising the paper, He also carried out the entire research process, including the conceptualization of the study, development of the methodology, field data collection, CFD simulations, data analysis, and preparation of the original manuscript draft as well as the final editing. A.M.A. contributed to the writing process by assisting with reviewing, editing, and improving the clarity of the manuscript. S.M.S. provided overall supervision and general academic support during the research.