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Optimizing Passive Cooling Through Wind Flow Analysis in Hot-Humid Climates: A Simulation-Based Study in Lahore

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Abstract- The lack of energy efficient strategies in residential design always leads to heighted indoor discomfort which requires higher energy consumption. Lahore, being a region with a prolonged hot-humid climate, offers a practical solution to enhance indoor comfort conditions and reduce dependence on mechanical systems by utilizing natural ventilation. This study uses a steady-state tool to simulate airflow in a residential building. It analyses different ventilation strategies: including single-sided, cross, and stack ventilation, and aims to identify the most effective approach. The evaluation covers both day and night conditions, considering airflow generated by buoyancy alone and in combination with wind. The results indicated that among the three strategies, stack ventilation showed the highest efficiency, consistently meeting and surpassing the airflow needs for fresh air and cooling. Cross ventilation and single sided ventilation showed promising results with wind assistance. This study offers valuable insights that can help shape future building designs aimed at creating more comfortable, energy-efficient, and environmentally responsible indoor spaces.

Keywords- Passive Cooling, Natural Ventilation Strategies, Wind Flow Rate, Hot and Humid Climate, Wind Driven Ventilation, Cross Ventilation, Stack Effect.

I. INTRODUCTION

In recent years, the design trends of residential architecture in Lahore have leaned heavily towards implying inefficient and excessive unused space while compromising comfortable living environments [1]. As global warming intensifies, the need to adopt sustainable living becomes more urgent [2]. However, the current approach to housing design in the city falls short of aligning with environmental needs and global development goals [3]. Several barriers continue to hinder the adoption of climate-responsive techniques, most notably, limited awareness among builders and homeowners, budget constraints & high upfront costs, user-specific demands, and absence of supporting regulations. These challenges collectively contribute to the dominance of energy-intensive solutions over naturally efficient alternatives [4].

Passive systems, when incorporated as part of a broader integrated building design strategy, serve as a second yet crucial tier of sustainable building design approach in reducing a building's dependency on mechanical systems [5]. For a city like Lahore, characterized by a hot and humid climate for much of the year, residents increasingly rely on air conditioning and mechanical ventilation to cope with thermal discomfort [6]. This dependency is particularly concerning given that a significant portion of population including elder people, females, and children spend most of their time within the confines of their homes [7]. A study shows that elderly people and 62 % of females spend more than 16 hours at home in Lahore [8]. In Pakistan, the residential sector accounts for over 46.5% of the country's total energy consumption, which is projected to rise by 4.5% annually, exacerbating the existing energy crisis [9]. This will be due to the cooling demands surpassing those for heating due to prolonged summers [10].

Given these circumstances, it becomes evident that the early stages of building design are pivotal for energy efficiency of buildings [11]. Integrating passive cooling methods can greatly enhance indoor thermal comfort and air quality by reducing building energy consumption without burdening the electrical grid [12]. According to ASHRAE, thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" [13-14]. While indoor air quality relates to the acceptable concentration of pollutants that do not pose a health risk [15]. Together, these factors form the backbone of healthy housing environments [16].

Some of the most effective passive cooling methods include solar shading, insulation, radiative cooling, evaporative cooling, thermal mass, earth coupling, and induced natural ventilation techniques [17]. Among these, natural ventilation stands out for its key role in removing stagnant, polluted indoor air and help in reducing the indoor particular matter by 80% to 90%, thus providing fresh air circulation that is crucial for health [18-19].

There are various modes through which natural ventilation can be achieved, including single-sided ventilation, cross ventilation, and stack ventilation [20]. Single-sided ventilation is driven by wind pressure fluctuations and thermal buoyancy forces and relies on openings located on a single facade of a room to facilitate air exchange [21]. Cross ventilation occurs, when higher pressure on the windward side and lower pressure on the leeward side create airflow through the building. By placing openings on opposite sides, fresh air is drawn indoors and circulated naturally, improving ventilation and indoor comfort. Stack ventilation works because warm indoor air rises naturally due to temperature differences between the inside and outside environments. When openings are provided at different heights, warm air escapes through the upper opening while cooler outdoor air enters from below, creating continuous natural airflow [22]. Each of these techniques varies in performance based on building orientation, room configuration, and the size and placement of openings [23]. Implementing the right strategy during the design stage can lead to a significant reduction in the need for mechanical systems, thereby conserving energy and enhancing occupant well-being [24].

Early-stage design tools for evaluating natural ventilation are utilized nowadays by researchers and some field experts, which helps in making very quick and strategic designs [25]. A Previous Study employed a quick design tool Optivent 2.0, to explore airflow patterns in a residential setting in Kosovo, during August, the region's hottest month. The study compares two ventilation strategies and proves cross ventilation is far more effective in maintaining thermal comfort [7]. The same tool was applied to support the design of a low-cost school building suited to Indonesia's tropical climate. The study focused on identifying effective passive ventilation strategies early in the design process. It was found that stack effect ventilation was expected to deliver the highest airflow rates, making it the most promising option for maintaining comfort [23]. The CO_2 levels were monitored in school classrooms using data loggers and evaluated ventilation needs through modelling with Optivent 2.1. Its findings showed elevated indoor temperatures and inadequate airflow are associated with increase in pollutant levels [26]. The study also concluded that incorporating cross ventilation and cooling the incoming air with nature-based solutions such as green screens could effectively lower CO_2 concentrations and improve indoor air quality. Although steady-state design tools like OptiVent 2.0 have been widely employed internationally in both professional practice and academic research for analysing natural ventilation performance, its application in Pakistan remains largely unexplored and undocumented.

In the context of this research, this paper aims to evaluate the performance of three natural ventilation strategies i.e., single sided ventilation, cross ventilation and stack effect; applied to a residence located in Lahore, Pakistan. The aim is to simulate the design of the residence during the design process to measure the predicted performance of the natural ventilation and to identify which ventilation mode performs best under specific conditions and orientations to help inform future residential designs. To accomplish this, three different rooms are simulated with varying sizes and positions of inlet and outlet openings across different room orientations by using the steady-state simulation tool Opti vent 2.0. The objectives of this study include:

1. To determine the airflow rates and adaptive thermal comfort acceptability associated with each ventilation strategy implemented in the selected rooms of the case study house.
2. To examine how the performance of these strategies varies throughout the day and to identify which strategy performs best during daytime and night time periods.
3. To compare the ventilation strategies under buoyancy-driven and combined buoyancy- and wind-driven ventilation modes, and to determine the most suitable strategy for improving indoor environmental conditions in the case study house.

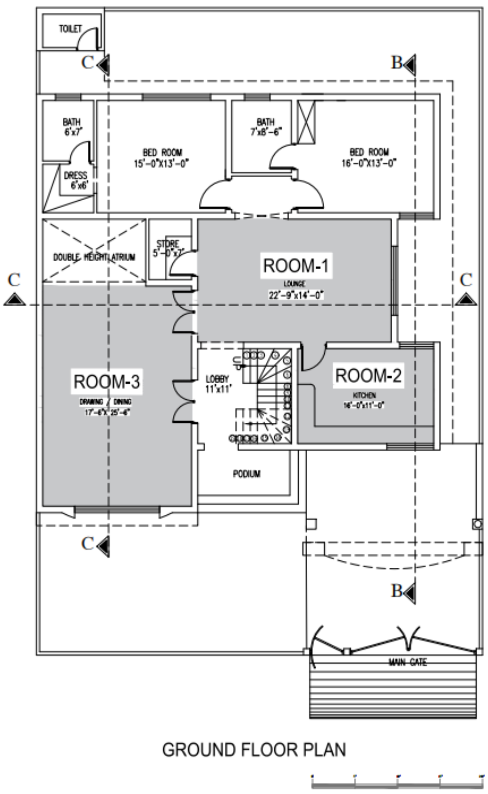
The findings are expected to provide useful insights for architects, planners, and homeowners aiming to create more sustainable and comfortable living environments through data-driven ventilation planning.

II. Methodology

A quantitative study is conducted in this research to assess the natural ventilation potentials of a house. A simple, steady-state tool Optivent 2.0, is used to simulate and generate findings. OptiVent 2.0 is an open source online, user-friendly tool that has been created to assist architects with early design stages in assessing natural ventilation strategies. It is constructed with the help of academic and professional cooperation, and it facilitates the informed decision making by modelling airflow under steady state conditions. The architects have used this tool in a variety of projects in the UK and post graduate students have used it to investigate implications and opportunities of natural ventilation in the various locations. [27]. The tool is limited to simulating one room or space at a time, but this focused approach allows for a clearer understanding of how buoyancy and wind individually influence each natural ventilation strategy. It helps identify which approach performs best under specific conditions.

2.1 Selected Case Study

The selected case is a double-storey House located in the NFC housing society in Lahore. The plans and sections of the house are illustrated in Fig.1 & 2. Based on the natural ventilation strategies, four different rooms were selected to evaluate the ventilation performance. Room 1 is a lounge area on the Ground floor that can accommodate seating for 6 persons. It has a north-facing single-sided window for ventilation purposes. Room 2 is a kitchen area on the ground floor with windows on the east and west-facing walls, which allows cross ventilation in the room. Room 3 on the ground floor is a drawing and dining area that accommodates 6-8 guests at a time. Room 4 on the first floor is a studio workplace used by 5-6 persons. The windows of Room 3 and Room 4 face towards the east, and these rooms have an adjacent atrium that allows natural ventilation through the stack effect. (See highlighted rooms in Fig.1 & 2). These four rooms have different sizes with varying window dimensions, which offers a more realistic approach in the simulation process to evaluate the ventilation performance of a typical house rather than in a uniform or idealized setup. As in most residential designs, room functions, sizes, and orientations naturally vary, and so do their openings. In this way, a more comprehensive assessment of the house's overall design in terms of ventilation performance was conducted.



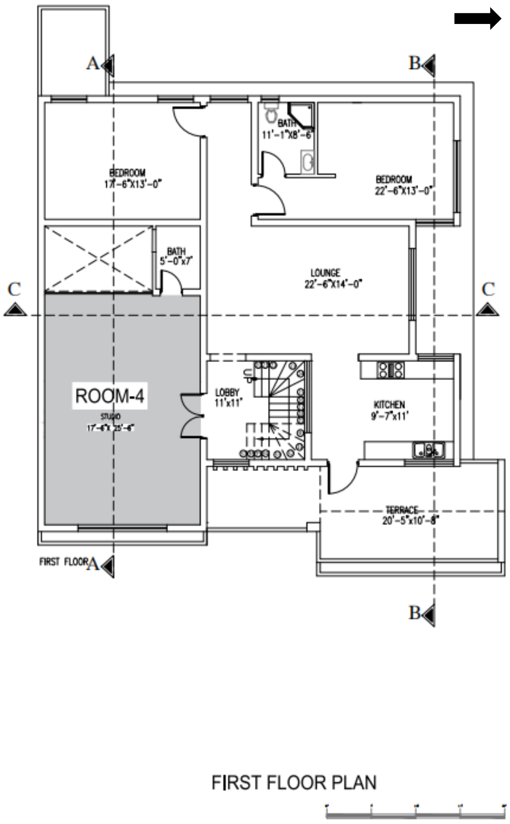
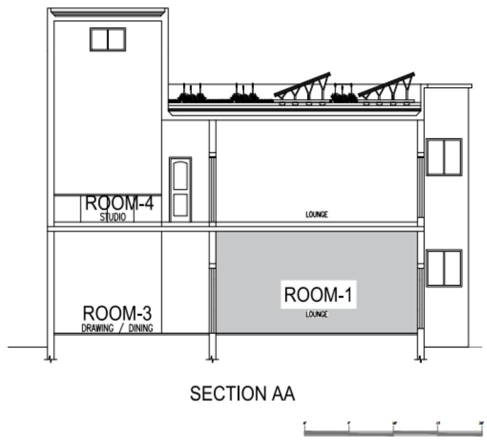
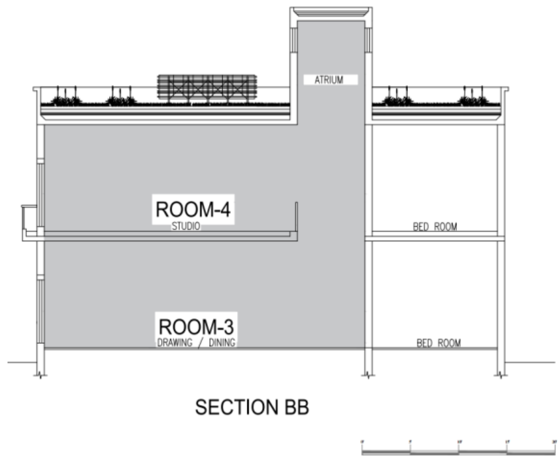


Fig. 1 Plans of Selected House in Lahore, Pakistan





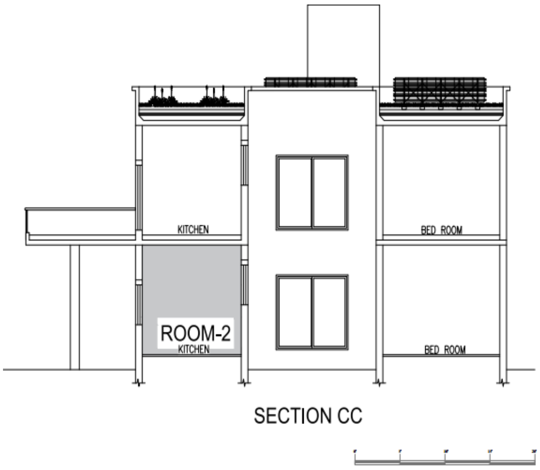


Fig. 2 Sections of a Selected House in Lahore, Pakistan

2.2 Studied Scenarios

This study investigated the three different natural ventilation strategies- single-sided ventilation, cross ventilation, and stack effect ventilation using two different scenarios. The first scenario presents the natural ventilation calculation (air flow rates and adaptive comfort acceptability percentage) of all three strategies during the day, and the second scenario presents the natural ventilation calculation for night. Both scenarios present results in two sub-scenarios: buoyancy-driven and buoyancy & wind-driven.

To perform the simulation, the month of April is selected. It makes sense to evaluate air flow in the house during April in Lahore because the weather is more moderate and realistic for the natural ventilation systems in the house. While in June, people are driven to mechanical cooling, in April, passive cooling methods such as cross-ventilation can be installed in more natural and everyday conditions. This month is representative of how people use their homes, with moderate wind and comparatively mild temperatures, windows open and taking advantage of the outside air for comfort. Furthermore, the Lahore weather data compiled by © WeatherSpark.com [28] indicates that the windier period of the year is from January 21 to July 18 with an average wind speed of more than 5.3 miles per hour (see Fig. 3). April is the windiest month of the year in Lahore with an average hourly wind speed of 6.2 miles per hour. The average temperature of April is 82°F (see Fig. 4). This makes it a more useful and reliable period to study ventilation efficiency, especially when aiming for designs that promote energy-saving and sustainable living in the local climate.

For both scenarios, the data input for construction and material properties used are same. The approximate latitude of Lahore in decimal degrees is 31.5833° N.

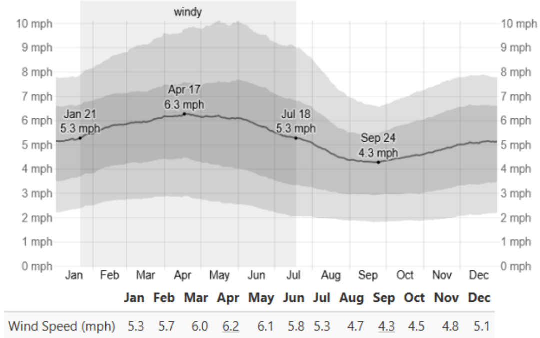


Fig 3. Graph showing the Average Wind Speed recorded for the month of April, 2025 in Lahore, Image Source: © WeatherSpark.com

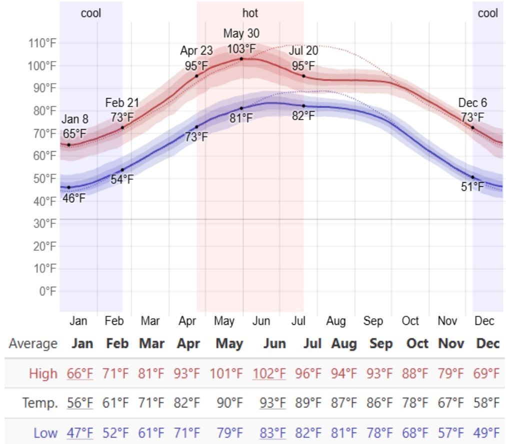


Fig 4. Graph showing the Average High and Low temperatures recorded for the month of April, 2025 in Lahore, Image Source: © WeatherSpark.com

In this case study, burnt brick walls with sandstone facing, reinforced concrete slabs, and transparent double-glazed windows are used as construction members. Shading proportion for windows was selected as 20% due to their coverage with overhangs. The solar transmittance factor of the double-glazed window is 0.6 according to the study [29]. The surface absorptance of white colored wall is 0.5 as per standardized values mentioned in the Optivent tool. The U value of the brick wall is calculated by using a U value calculator based on BS EN ISO 6946:2017 standards [30] and the external surface transmittance of a 230mm brick wall is 3.15 w/m^2. K [31]. The sizes of the openings vary but effective aperture in all openings was kept 50%.

III. Results and Discussion

The various modes through which natural ventilation can be achieved, including single-sided ventilation, cross ventilation, and stack ventilation were analyzed by steady-state tool Optivent 2.0. The details of each mode and the results are discussed in the following sections 3.1 - 3.3.

3.1 Single Sided Ventilation:

As is shown in the Table-1, the area of the room-1 is 28m² and the volume is 98m³. The inlet z1 is 1.5m high above the ground level.

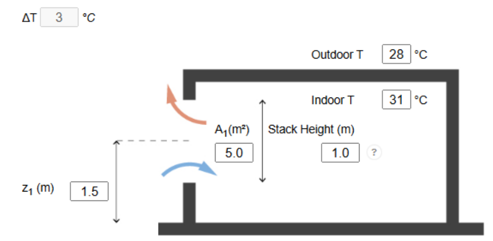
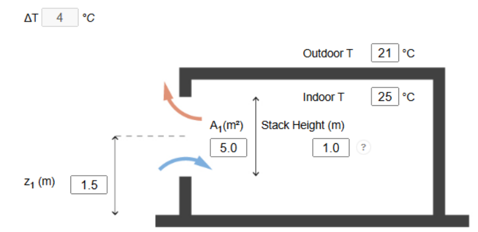
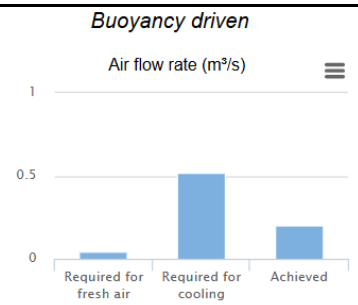
3.1.1 Single Sided Ventilation in Daytime

The temperature difference between the internal and external air temperature is 3°C as per dependency of the buoyancy driven ventilation on the air temperature difference. As per the graph shown for air flow rate (Table-1), the air flow rate required for fresh air is 0.04 m³/s and for cooling is 0.52 m³/s. In buoyancy driven mode, the achieved air flow rate is 0.23 m³/s, which means that the room-1 fulfil the requirement of fresh air, but the air flow rate is not sufficient to cool the interior environment. While the buoyancy and wind driven mode show the achieved air flow rate of 0.62 m³/s which is greater than the required airflow rate for fresh air and cooling. Hence, Buoyancy driven single sided ventilation of room-1 is predicted to maintain 80% acceptability limits according to ASHRAE standard 55-2013. The adaptive comfort band shows 90% acceptability limits, when the air flow is driven by buoyancy effect and wind.

3.1.2 Single Sided Ventilation in Nighttime:

To check the performance of the single sided ventilation via window in room-1 at night, the temperature difference between the internal and external air temperature is kept 2°C as per dependency of the buoyancy driven ventilation on the air temperature difference. The graph for air flow rate in Table-1, shows that the air flow rate required to supply fresh air in room is 0.04 m³/s and for cooling is 0.39 m³/s. In buoyancy driven mode, the achieved air flow rate is 0.23 m³/s , which means that the room-1 fulfil the requirement of fresh air, but the air flow rate is not sufficient to cool the interior environment. While the buoyancy and wind driven mode show the achieved air flow rate of 0.46 m³/s which is greater than the required airflow rate required for fresh air and cooling. Buoyancy driven single sided ventilation of room-1 is predicted to maintain 90% acceptability limits according to ASHRAE standard 55-2013. The adaptive comfort band shows 80% acceptability limits, when the air flow is driven by buoyancy effect and wind. It is projected that there will be good thermal comfort in room-1 with single sided ventilation during the day with buoyancy and wind driven flow rates, while the comfort zone will be around lower compatible range at night.

Table 1: Summary of Input Parameters and Outcomes for Room-1 Single-Sided Ventilation in Daytime and Night time Conditions;
Source: The Authors

<table>
<tr><td colspan="3">Scenario-1</td></tr>
<tr><td colspan="3">Time: Day
Duration: 12 hr
Orientation: North facing Window
Wind Speed: 3 m/s</td></tr>
<tr><td colspan="3">Airflow data Input and Building Geometry</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">Scenario-2</td></tr>
<tr><td colspan="3">Time: Night
Duration: 12 hr
Orientation: North facing Window
Wind Speed: 2 m/s</td></tr>
<tr><td colspan="3">Airflow data Input and Building Geometry</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td>Cell Dimensions</td><td>Area</td><td>Exposure</td></tr>
<tr><td>Height (m) 3.5</td><td>Floor Area (m²) 28</td><td>No exposure though roof</td></tr>
<tr><td>Width (m) 7.0</td><td>Volume (m³) 98</td><td>Only North facing Wall Exposure</td></tr>
<tr><td>Length (m) 4.0</td><td></td><td></td></tr>
<tr><td colspan="3">Buoyancy driven Air Flow Rate & Adaptive Comfort Band</td></tr>
<tr><td colspan="3">
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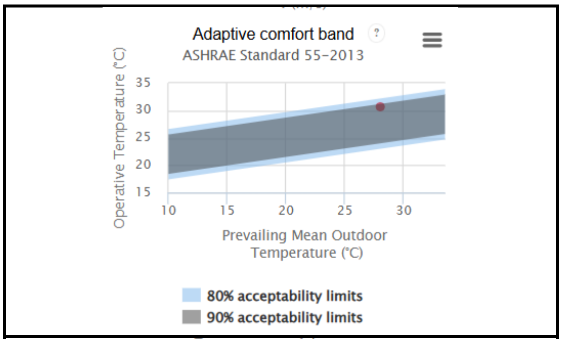
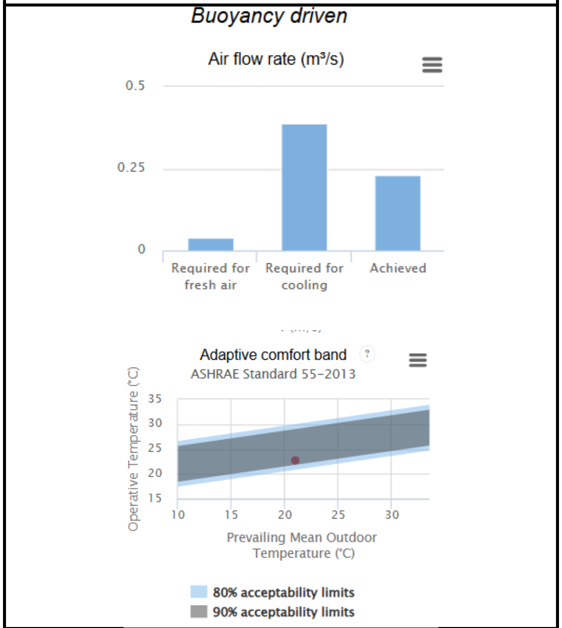
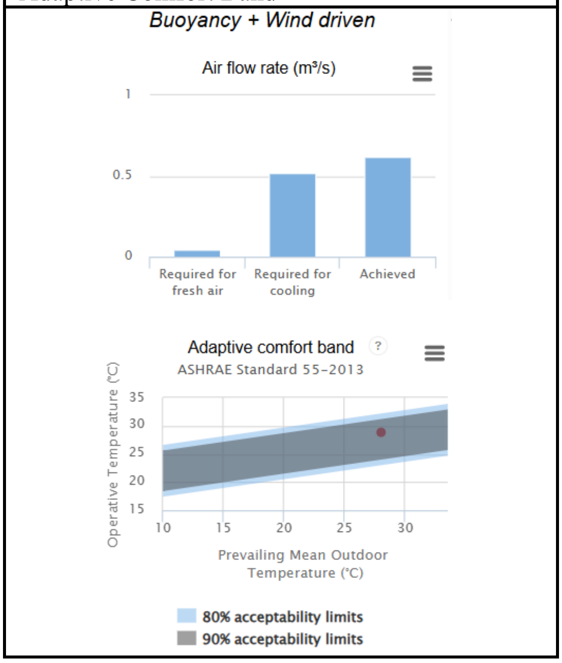
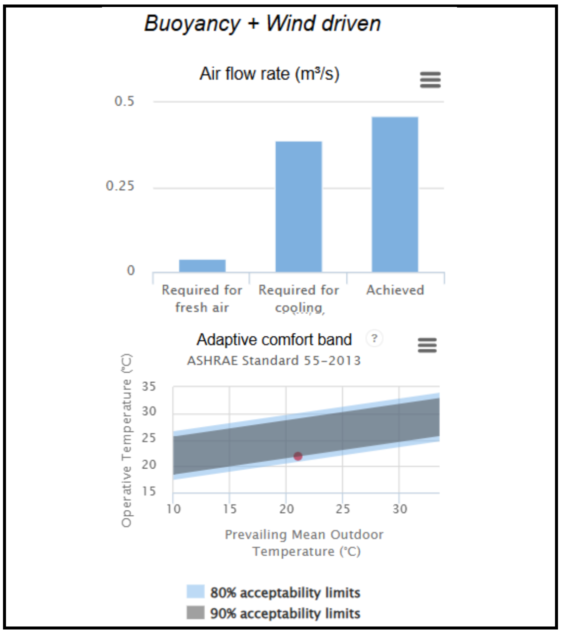




Buoyancy + Wind driven Air Flow Rate & Adaptive Comfort Band





3.2 Cross Ventilation:

As is shown in the Table-2, the area of the room-2 is 16.8 m^2 and the volume is 58.8 m^3. The inlet z1 is 1.5m high above the ground level and the stack height from the midpoint of inlet to the midpoint of outlet is at 1m.

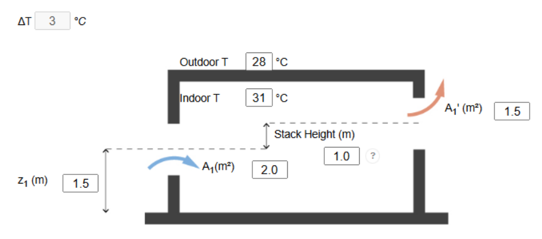
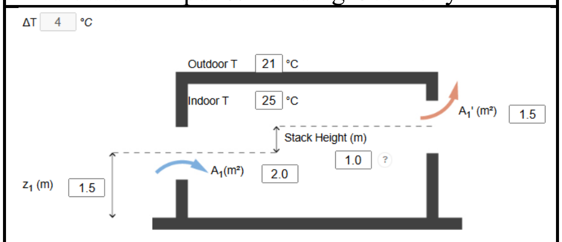
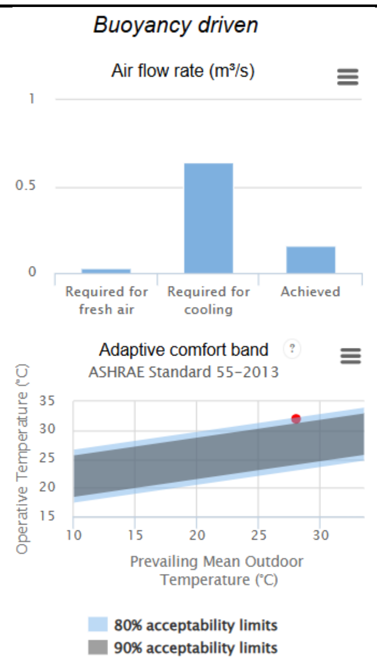
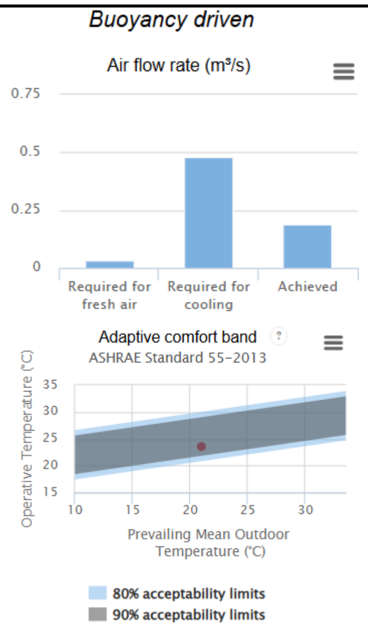
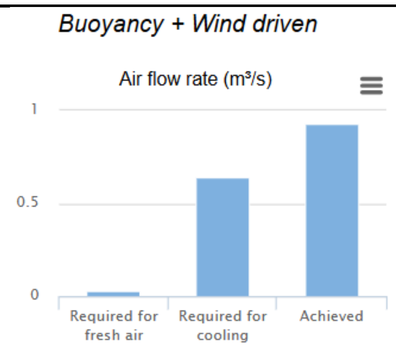
3.2.1 Cross Ventilation in Daytime

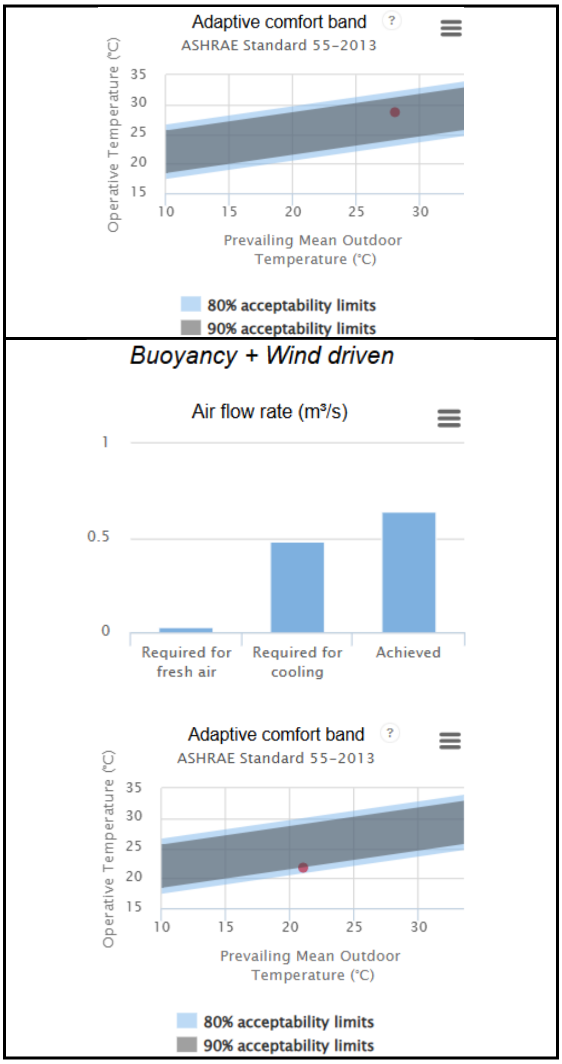
The temperature difference between the internal and external air temperature is 3°C as per dependency of the buoyancy driven ventilation on the air temperature difference. The simulation input for buoyancy-driven ventilation shows an achieved air flow rate of 0.16 m^3/s, which exceeds the required fresh air flow rate of 0.03 m^3/s, but remains insufficient to meet the cooling requirement of 0.64 m^3/s. Thus, buoyancy alone does not satisfy the thermal comfort criteria for active cooling during the day. In contrast, the combined buoyancy and wind-driven ventilation mode achieves an air flow rate of 0.93 m^3/s, which exceeds both the required fresh air and cooling rates. According to ASHRAE 55-2013 adaptive comfort standards, the room is projected to maintain 90% acceptability limits under this ventilation strategy. The adaptive comfort band analysis confirms that the airflow achieved via buoyancy and wind effectively maintains thermal comfort, making cross ventilation a viable passive strategy for daytime cooling in Room-2. Furthermore, when wind-assisted airflow is present alongside buoyancy, the conditions are predicted to fall within the 80% acceptability range of the adaptive comfort model.

3.2.2 Cross Ventilation in Nighttime

Then, the performance of cross ventilation was evaluated again for night time conditions, for which the wind speeds were reduced to 2 m/s and the window orientation remained east. The buoyancy driven air flow rate is higher, at 0.19 m^3/s, which is of course sufficient for the required fresh air rate (0.03 m^3/s), but is still not enough for the cooling requirement (0.48 m^3/s). This suggests that buoyancy-driven night ventilation is not completely efficient in cooling during the night. But when the buoyancy and wind-driven cases are combined, the air flow rate achieved is 0.64 m^3/s, which is well above the fresh air and cooling flow rate requirement. Based on the ASHRAE 55-2013 it can be seen that this strategy and buoyancy driven mode delivers 90% adaptive comfort acceptability at night, and for buoyancy and wind driven mode it is 80% acceptability. The results indicate that the low speed night wind, combined with cross ventilation, can remarkably improve the indoor comfort in Room 2

Table 2: Summary of Input Parameters and Outcomes for Room-2 Cross Ventilation in Daytime and Night time Conditions; Source: The Authors

Scenario-1		
Time: Day Duration: 12 hr Orientation: East facing Window windward, West facing window leeward Wind Speed: 3m/s		
Airflow data Input & Building Geometry		
		
Scenario-2		
Time: Night Duration: 12 hr Orientation: East facing Window windward, West facing window leeward Wind Speed: 2m/s		
Airflow data Input & Building Geometry		
		
Cell Dimensions	Area	Exposure
Height (m) 3.5	Floor Area (m^2) 16.8	No exposure though roof
Width (m) 4.8	Volume (m^3) 58.8	East, West and North facing Wall Exposure
Length (m) 3.5		
Buoyancy driven Air Flow Rate & Adaptive Comfort Band		
		
		
Buoyancy + Wind driven Air Flow Rate & Adaptive Comfort Band		
		



3.3 Stack Effect Ventilation:

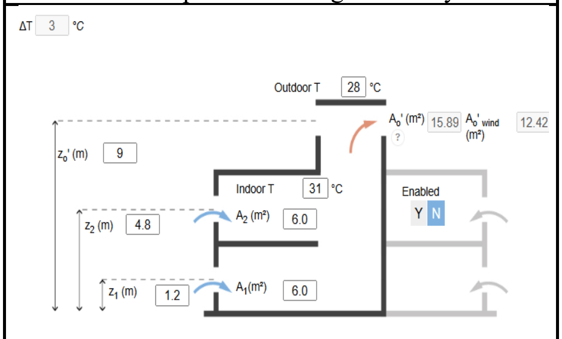
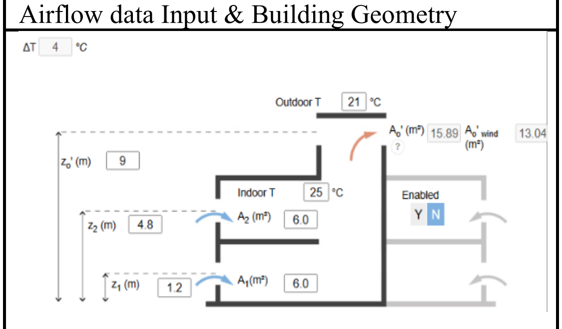
3.3.1 Stack Effect Ventilation in Daytime

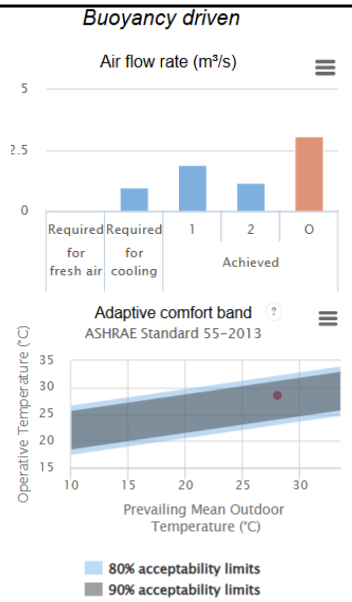
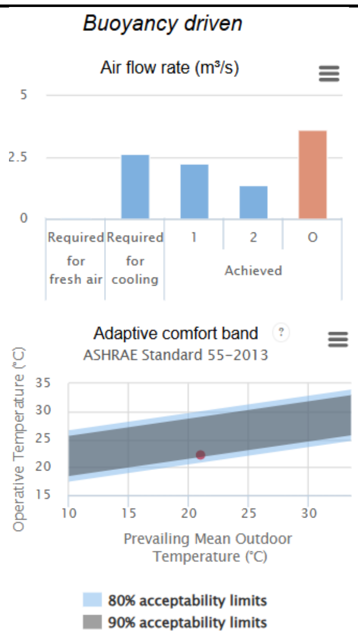
The necessary air volume of fresh air for Room-3 and Room-4 is 0.05 m³/s, and the air volume of cooling is 0.98 m³/s which is much higher. The individual rates of air-flow that were obtained in Room-3 and Room-4 were 1.93 and 1.17 m³/s respectively, with a combined outlet (O) air-flow rate of 3.10 m³/s under buoyancy-driven conditions. The results indicate that the fresh air requirement and cooling are met in both rooms. It means that during the day, the vertical ventilation stack can supply fresh air, and fulfil the cooling function, which reflects the effectiveness of the vertical ventilation stack and proves that fresh air and cooling can be met by buoyancy. With the assistance of wind, the airflow is greatly enhanced to 4.34 m³/s in Room-3, 4.06 m³/s in Room-4 and 8.39 m³/s out of the outlet. These are much higher than fresh air and cooling needs. For both sub-scenarios (buoyancy driven and buoyancy and wind driven), these rooms are expected to maintain comfort zone for 90% acceptability limits as per ASHRAE standards. This suggests that ventilation in a stack effect configuration ensures passive cooling during the day.

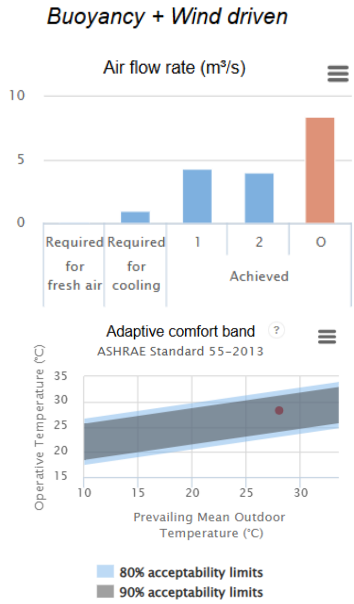
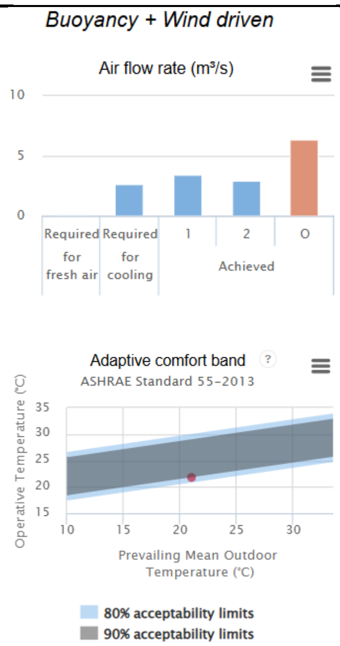
3.3.2 Night Stack Effect Ventilation: in Nighttime

The airflow requirement for cooling during the night increases to 2.67 m³/s, while the required fresh air flow rate remains at 0.05 m³/s. Under buoyancy-driven conditions, Room-3 achieves an airflow of 2.26 m³/s, and Room-4 achieves 1.37 m³/s, with a total outlet airflow of 3.63 m³/s. This indicates that the requirements for only fresh air are fulfilled in both rooms. In buoyancy and wind-driven mode, the airflow rates further improve, reaching 3.43 m³/s (Room-3), 2.93 m³/s (Room-4), and 6.36 m³/s at the outlet. These values exceed the ventilation thresholds comfortably. In both sub-scenarios (buoyancy-driven and buoyancy & wind-driven mode), these rooms are predicted to maintain comfort zones on 80% acceptability limits according to ASHRAE standards.

Table 3: Summary of Input Parameters and Outcomes for Room-3 & Room 4 Stack Effect in Daytime and Night-time Conditions; Source: The Authors

Scenario-1
Time: Day Duration: 12 hr Orientation: East facing Window Wind Speed: 3m/s
Airflow data Input & Building Geometry

Scenario-2
Time: Night Duration: 12 hr Orientation: East facing Window Wind Speed: 2m/s
Airflow data Input & Building Geometry


Cell Dimensions	Area	Exposure
Height (m) 7.3	Floor Area (m^2) 52.47	Roof not directly exposed (covered with roof garden & solar panels)
Width (m) 9.9	Volume (m^3) 383.03	Only East-facing Wall Exposure
Length (m) 5.3		
Buoyancy driven Air Flow Rate & Adaptive Comfort Band		
		
		
Note: In the above graph, Bar-1 represents the Airflow rate of Room 3 and Bar -2 represents the air flow rate of Room-3, while O represents the net airflow rate.		

Buoyancy + Wind driven Air Flow Rate & Adaptive Comfort Band



3.4 Comparative Performance of Natural Ventilation Strategies

Based on a comprehensive analysis of the data, Fig. 5 indicates that all three ventilation methods can deliver the necessary airflow rates for cooling, both during the day and at night, when indoor air movement is influenced by combined buoyancy and wind forces. Among these, stack ventilation consistently outperforms the others, as it provides airflow levels that significantly exceed the cooling requirements under both buoyancy-only and combined buoyancy-wind conditions, during the day time. However, during the night, the assistance of mechanical airflow is necessary to achieve the desired thermal cooling effect.

This highlights stack ventilation as the most dependable and effective strategy, offering consistent air circulation and enhancing indoor thermal comfort in warm weather conditions when the average outdoor temperature is 28°C in Lahore. When comparing single-sided ventilation with cross ventilation, the latter demonstrates superior performance in achieving the airflow rates needed for effective cooling, as further illustrated in Figure 5. It is also evident that all ventilation strategies achieve up to 80% and 90% of the acceptability limits of comfort, both during the day and night at different scenarios in the warm weather conditions in Lahore.

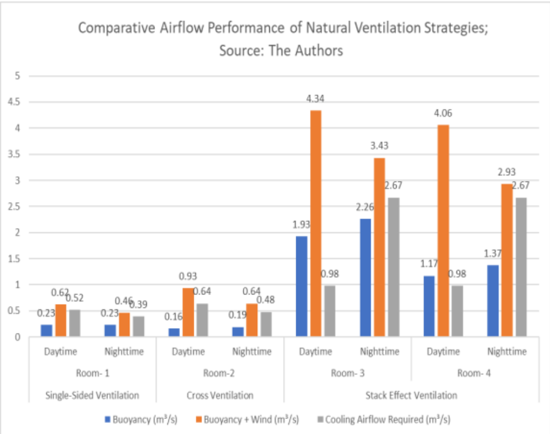


Fig 5. Bar Graph illustration for the comparative airflow performance of Natural Ventilation Strategies.

IV. CONCLUSION

The residential design was analyzed in current study, with three modes of ventilation i.e., single sided, cross ventilation and stack effect to select the best option to meet natural ventilation requirements in hot humid climate regions. The results prove that none of the strategies can achieve effective cooling during night time when relying solely on buoyancy driven wind flow. Desired thermal cooling effect is achieved when combined buoyancy and wind driven ventilation is available. Effective reliance on buoyancy-driven airflow is achievable only during the daytime when the design incorporates a stack effect ventilation strategy, which enables sufficient air movement without the need for external mechanical assistance. Incorporating stack-driven strategies can drastically reduce dependency on mechanical cooling and contribute to sustainable thermal comfort in hot humid regions such as Lahore during warm weather conditions.

V. RECOMMENDATION

The stack effect ventilation strategy is particularly pertinent during the summer months when temperatures often exceed 40°C. Future research could extend this study by evaluating the performance of the same residential design under these extreme conditions, providing insights into further design enhancements. Such investigations would be invaluable for architects and the construction industry, offering guidance during the design development phase to create energy-efficient buildings that are less dependent on mechanical systems.

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