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Adaptive Ventilation Strategies and Their Impact on Operative Temperatures in a Warm and Humid Climate

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Abstract: This study investigates this dynamic in the Kanchanjunga apartment, designed for natural ventilation. The research evaluates the effect of air pollution on indoor thermal temperatures and explores the potential benefits of adaptive ventilation strategies. Two models were analyzed: night ventilation and a temperature-dependent modulation profile. Both rely on opening windows during periods of better outdoor air quality and closing them during peak pollution times. Results indicate that adaptive strategies reduce the duration when indoor temperatures exceed 30°C. Among the tested strategies, the temperature-dependent modulation profile was most effective across various spaces effective in maintaining comfort, as discomfort temperatures were only observed to exceed the comfort zone by 25% annually in some areas. These results emphasize the importance of not only designing for natural ventilation but also optimizing and adapting designs based on varying external conditions, such as air quality and temperature.

Keywords: Natural Ventilation, adaptive ventilation, Pollution, Passive Cooling, Thermal Comfort

1. Introduction

In Mumbai, urbanization has led to severe air pollution with particulate matter PM2.5 concentration was found to 52 µg/m^3, which is 2.6 times above the acceptable limit set by WHO of 20 µg/m^3(AQI, n.d). Air pollution contributes to millions of deaths annually, primarily in the Asia-Pacific region Only in India, this represents 1.6 million in 2019 (BBC News, 2022). Confronted with these alarming figures, a pressing question emerges as sustainable architects, how can we design buildings that harness the benefits of natural ventilation without compromising indoor air quality due to external pollutants? While natural ventilation serves as an efficient cooling method in such environments, it poses a notable challenge. In contrast, active ventilation systems, though ensuring cleaner air, can significantly boost energy consumption, further intensifying pollution from greater fossil fuel use. Solely relying on natural ventilation in high-pollution areas might not be a sustainable strategy for ensuring occupants' health and well-being. Nevertheless, optimizing designs to minimize thermal temperatures can pave the way for reduced energy consumption, striking a balance between sustainability and health (Tenorio†, 2002).

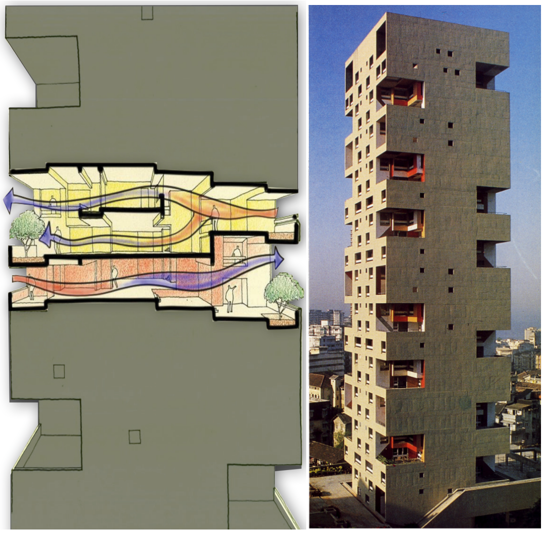


Figure 1: Kanchanjunga Apartment. Image Mondal, P. (n.d.), identity housing. (2009).

In urban landscapes facing housing deficits, high-rises are often the answer, but achieving effective ventilation remains a hurdle. However, Kanchanjunga Apartments sets a benchmark with its high-rise form, leveraging innovative stack-effect for natural ventilation through its unique staggered design, hence was chosen for this study.

2. Context

The Kanchanjunga Apartment by Charles Correa was designed to rely on natural ventilation, the building stands 84 meters tall and houses 32 apartments of varying typologies. The building enjoys a coastal location near the Arabian Sea oriented east west to captures sea breezes. Merging traditional Indian verandahs with modern design, garden terraces encircle the building, shielding it from sun and rain. Strategic level differences were designed to facilitate stack ventilation for better airflow and cooling effect. The structure is made mostly of concrete with a whitewashed stucco finish (Pagnotta, 2023).

Mumbai's climate fluctuates between 17.7°C and 33.7°C, maintaining a relative humidity of 60% to 90%. The city's AQI, per IqAir's report, is marked at 163, designating it as "unhealthy." Predominant pollutants include PM2.5, PM10, SO2, CO, and ozone (IQAiR, n. d., Stranger, Et al.2008). The highest levels of pollution are found during summer and winter months due the atmospheric characteristics that make difficult to dissipate pollutants. The most polluted time span from 8am to 4pm, peaking at 1pm, with vehicular emission, construction, and fossil fuel burning as the main contributors .

3. Scope and Research methodology

This study focuses on a high-rise residential building to address its core research questions. We aim to determine the optimal balance between passive and active cooling techniques, particularly in light of varying air quality challenges. Our approach utilizes both static and dynamic simulations. Static simulations are employed to understand the building's existing stack ventilation system. In contrast, dynamic simulations are crucially deployed to assess the effectiveness of natural ventilation in providing cooling solutions.

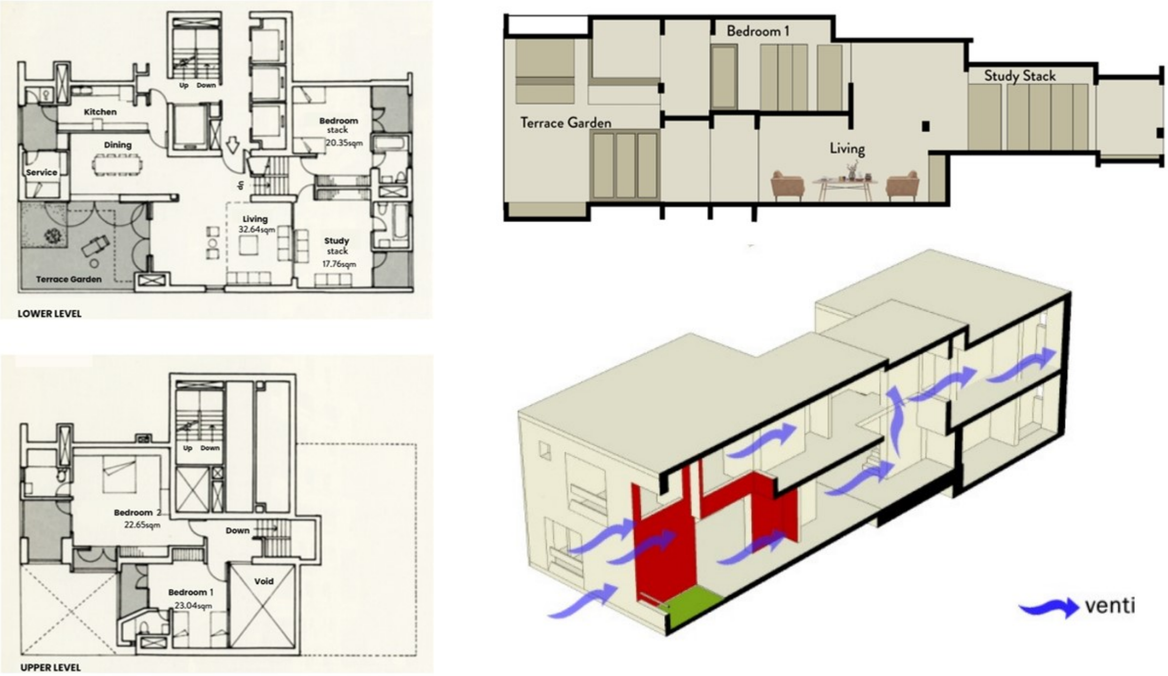


Figure 2: Unit A detailed floor plan and Section (Archsociety)

The study focused on a typical 3-bedroom unit ‘A’ under 4 different scenarios, differentiated by elevation and orientation. Blocks 1 and 3 are set at a lower elevation (+4.5m to +9m). Block 1 faces northeast, whereas Block 3 has a different orientation. In contrast, Blocks 2 and 4 sit at a higher elevation (+66.5m to +69.5m); Block 2 has a southwest orientation, and Block 4 another direction.

The study targeted bedrooms and the living room for potential AC installation. At the lower level (either 4.5m or 66.5m), the living room, with a height of 6m, covers 32.64 m^2 and has a WWR of 24.2%. 1.5m above, the bedroom stack measures 20.35 m^2 (WWR 13.5%) and the study stack 17.76 m^2 (WWR 10.6%). At 3m higher, Bedroom 1 is 20.04 m^2 (WWR 14.4%), and Bedroom 2 is 22.65 m^2 (WWR 18.9%). All rooms have a height of 3m, with the exception of the living room which stands at 6m

IESVE Analysis conducted in three key phases:

This research harnesses two primary methodologies: Computational Fluid Dynamics (CFD) analysis and thermal dynamic building simulations using IESVE software. The CFD analysis, was done to comprehend airflow patterns and velocities within the unit, emphasizing the building's existing stack ventilation system. On the other hand, the thermal dynamic building simulations were performed to explore multiple scenarios (detailed in Table 1) concerning the building's thermal performance and ventilation efficiency, particularly when air conditioning is used in rooms with prolonged occupancy.

4. Assumptions:

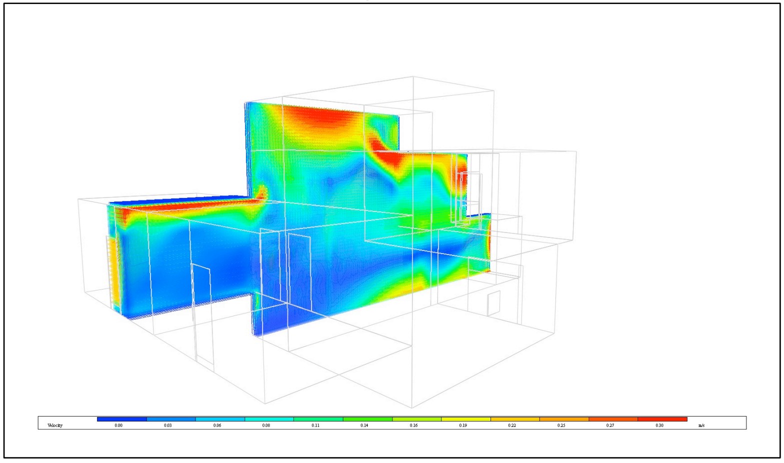
Table 1 show the assumption made for the simulations:

Air Quality	The air quality is deemed to be between "good" and "moderate" from the end of May to mid-September. For the remainder of the year, the air quality is assumed to be "poor" from 8 a.m. to 6 p.m. Derived from AQI data (IQAiR, n. d.).
Weather Data	Mumbai weather file from the IWEC database
Lighting Gains	Determined via IESVE analysis 8.37 (W/m2/100 lux)
Comfort Range	18-30°C (India Model of Adaptive Comfort, IMAC)
Structural Properties	Exterior walls U-value: 2.6 W/m^2 K, Ceiling/floor of RCC structure U-value: 3.07 W/m^2K
Occupancy Profiles & Equipment Duration	The living room was assumed to be occupied by 5 people and a varying profile of occupancy was created, the bedroom was assumed to be occupied by 2 people at a time while
Air Infiltration	0.25 arch, an achievable low rate for modern construction, to minimize outdoor pollution infiltration during times of poor air quality. (Etheridge, 2014)
Window Opening Assumptions	
Case 1	Windows consistently closed
Case 2	Original design with persistent open doors and windows
Case 3	Night-time cooling; windows open from 20:30 P.M. to 7 A.M.
Case 4	Modulating profile for window operations based on the temperature being between 20-30 °C and closed during low air quality time.

5. Results and discussions

The results are discussed in 2 parts terms of static stimulation Computational Fluid Dynamics (CFD) techniques and dynamic stimulation from IESve.

5.1.1 Ventilation Analysis



A CFD analysis was done using IESVE for the interior of the building on 18 may at 20:30pm, which was the date and time of maximum ventilation air flow inside the unit as per IESVE MacroFlo external ventilation data Figure 3 illustrates the airflow pattern on a clear upward movement of air from the lower levels to the higher levels, hence indicating that the stack ventilation system is functioning effectively as per the original design intent. In terms of air velocity the analysis suggests that most parts of the unit's air velocity levels were found to be within permissible range of 0.4-0.8m/s (Girin, 2021)However, there were certain regions where the velocity was significantly higher, at about 0.30 m/s[13], indicating a little faster airflow. However, these locations were typically at the ceiling level, which can maximize cooling effect while not causing discomfort due to high speed.

5.1.2 Thermal Analysis

Outdoor temperatures exceeded 30°C for 55.5% of the time, peaking at 40°C. In Case 1, with closed windows, temperatures surpassed 30°C between 91.1% and 96.1% of the time.
For Case 2, the bedroom stack was hottest, exceeding 30°C 35.2% of the time, while the coolest was the living room stack's R3003 at 31.6%. The study stack's R1001 peaked at 40.29°C. In Case 3, discomfort was highest in the bedroom stack's R3003 at 61.7% and lowest in the living room's R1001 at 36.5%. Temperature peaks ranged from 38.08°C in the study stack's R1001 to 37.39°C and 37.58°C in bedroom 1's stacks. In Case 4, the bedroom stack's R1001 was the hottest, with temperatures exceeding 30°C 38.5% of the time, while the coolest was bedroom 2's R3003 at 25.1%. The temperature range was between 37.9°C in the study stack's R1001 and 37.5°C in bedroom 2's R3003.

In Unit 1 (NE, lower level), living room temperatures increased by 3.2% from Case 2 to 3 and decreased by 5.1% to Case 4. The bedroom stack decreased by 20% and 28.9% across Cases 2 to 3 and 2 to 4, respectively, while the study stack had a slight 0.7% improvement in Case 3 but dropped 9.9% in Case 4. Unit 2 (SW, lower level) saw a 0.9% living room temperature rise from Case 2 to 3, followed by a 7.4% drop to Case 4. The bedroom and study stacks had varied temperature reductions across the cases, except for a 1.1% rise in Bedroom 2 from Case 2 to 3. For Unit 3 (NE, higher level), living room temperatures increased 4.5% from Case 2 to 3 but fell 4% by Case 4. The bedroom and study stacks had minor reductions, with the exception of Bedroom 2's consistent 0.5% drop across Cases 3 and 4.Lastly, in Unit 4 (SW, higher level), living rooms rose 2.9% from Case 2 to 3 and declined 5.6% by Case 4. The bedroom and study stacks mostly saw reductions, barring a 0.8% improvement in Bedroom 2 during Case 3.

6. Conclusions

The study underscores that, while natural ventilation can improve thermal comfort—most notably observed in scenario 4—it doesn't wholly eliminate the issue of rising indoor temperatures. Approximately 37% of the time, temperatures climbed beyond 30°C, indicating a pressing need for mechanical ventilation during these periods. The Computational Fluid Dynamics (CFD) analysis further complicates the issue of cooling, revealing challenges with introducing an air conditioning system in the living room. The current stack ventilation design hinders efficient cold air distribution, leading to higher energy consumption and reduced cooling efficiency.

Adding a modulating temperature-dependent window opening mechanism does help to solve the problem. However its success is based on the orientation of the room at its worst, occupants could experience discomfort 37% of the time, and even in the most favorable scenarios, discomfort levels linger at 25.1%. This concern is exacerbated by temperature extremes reaching up to 37.9˚C.

This data illustrates the multifaceted challenges in securing optimal thermal comfort in such architectural configurations. The observed effectiveness of natural ventilation in scenario from scenario 1 to scenario 2 is laudable, but it's evident that in certain rooms, the introduction of mechanical ventilation becomes indispensable. The consistency in temperature fluctuations, irrespective of unit orientation, underlines potential hurdles in realizing efficient cooling—especially in living areas with their inherent stack ventilation designs, as highlighted by Lundgren-Kownacki et al. (2018).

To best address these concerns, a hybrid approach might be optimal. This would entail integrating adaptive ventilation strategies with mechanical cooling and incorporating air filtration systems, ensuring pollutant ingress is effectively managed.

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