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The effect of single-channel wind tower on air flow and cooling of the building

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Extended Abstract

Introduction

Passive cooling systems are essential for sustainable architecture, particularly in regions with high cooling demands. The windcatcher, a traditional architectural element prevalent in the Middle East and North Africa, offers a proven, energy-free method for natural ventilation and temperature moderation. Its principle relies on capturing cooler, higher-velocity winds at an elevation and channeling them into a building's living spaces, often enhanced by evaporative cooling from water sources. While historically effective, optimizing its design for contemporary construction requires a detailed understanding of how specific parameters influence its thermal and aerodynamic performance. This study undertakes a numerical investigation to systematically quantify the impact of three critical variables—windcatcher height, ambient wind speed, and the integration of a heat-absorbing surface—on the cooling capacity and ventilation rate of a single-channel windcatcher system. The goal is to provide actionable data that bridges traditional passive cooling wisdom with modern engineering design principles.

Methodology and Numerical Approach

The research employed a rigorous Computational Fluid Dynamics (CFD) methodology to simulate the complex airflow and heat transfer phenomena. A three-dimensional computational model was constructed, representing a scaled (1:10) residential building unit equipped with a single-channel windcatcher. The building geometry included defined interior spaces and walls with standard brick thermal properties (conductivity of 0.15 W/m·K). The analysis was performed using the finite volume-based solver ANSYS Fluent. The governing equations for mass, momentum, and energy conservation were solved for a turbulent, incompressible flow. The Renormalization Group (RNG) k-ε turbulence model was selected for its accuracy in handling flow separation and recirculation, coupled with standard wall functions. The pressure-velocity coupling was resolved using the SIMPLE algorithm, with second-order upwind discretization schemes for momentum and energy to enhance solution accuracy. The Boussinesq approximation was applied to model the natural convection effects due to density variations caused by temperature differences. A structured, non-uniform mesh was generated, with significant refinement near the windcatcher walls, the building envelope, and the heat-absorbing surface to resolve critical boundary layers and gradients accurately. A mesh independence study was conducted to ensure the results were not sensitive to further grid refinement. The boundary conditions were defined as follows: a velocity inlet with specified speeds (3, 5, 8 m/s) and ambient temperature at the domain's windward side, a pressure outlet at the leeward side, and no-slip, constant-temperature conditions for the sun-exposed external walls (313.15 K). The key parametric studies included:

1. **Windcatcher Height:** Three total heights were analyzed: 4.5 m, 5.5 m, and 6.5 m from the ground.
2. **Ambient Wind Speed:** Inflow velocities of 3, 5, and 8 m/s were tested.
3. **Heat-Absorbing Surface:** The effect of a cooled surface at the base of the windcatcher channel was simulated by applying constant heat flux conditions of 0 (baseline), 50, 100, and 200 W/m², representing the cooling effect of an evaporating water pool or a thermally active plate.

Key Findings and Results

The simulations yielded quantitative and visual data (contours and velocity vectors) that clearly delineated the influence of each parameter on system performance, measured by average indoor temperature reduction and induced mass flow rate.

1. Impact of Windcatcher Height:

Increasing the height of the windcatcher had a consistently positive effect. As the height rose from 4.5 m to 6.5 m, the average temperature in the living space decreased from approximately 301.76 K to 300.25 K. Concurrently, the induced ventilation rate (outlet mass flow) increased by about 35%, from 1.38 kg/s to 1.81 kg/s. This improvement is attributed to two factors: access to stronger wind velocities at higher elevations and the introduction of ambient air that is less influenced by ground-level heat gain.

2. Impact of Ambient Wind Speed:

The ambient wind speed proved to be a primary driver of performance. Under a constant windcatcher height (4.5 m), increasing the inlet velocity from 3 m/s to 8 m/s reduced the indoor temperature by roughly 1.5 K (from 302.32 K to 300.82 K). More dramatically, the ventilation rate increased by over 75%, from 1.05 kg/s to 1.84 kg/s. Higher speeds not only force a greater volume of air through the system but also enhance convective heat removal from the building's thermal mass.

3. Impact of the Heat-Absorbing Surface:

The integration of a cooling surface at the windcatcher's base significantly enhanced its *cooling* capacity, albeit with a minor trade-off for *flow* rate. Compared to the baseline model (no cooling surface), applying a heat flux of 200 W/m² further reduced the indoor temperature by about 1.14 K. This simulates the powerful evaporative cooling effect of traditional windcatchers. However, this cooler, denser air created a slight flow resistance, causing the mass flow rate to decrease marginally from 1.38 kg/s to 1.19 kg/s. This indicates that while the *quality* (temperature) of the air improves substantially, the *quantity* is slightly reduced, yet the overall cooling effect (enthalpy change) is greatly beneficial.

4. Overall Cooling Potential:

A critical comparative finding was the absolute benefit of the windcatcher system. The model predicted that, under the studied conditions, the presence of the windcatcher could lower the interior temperature by up to 11°C compared to a scenario with no induced ventilation. This highlights its profound potential for passive climate control.

Conclusions

This numerical investigation conclusively validates the single-channel windcatcher as a highly effective passive cooling and ventilation strategy. The study provides a clear quantitative framework for designers:

- **Height is Advantageous:** Taller windcatchers perform better, though structural and aesthetic constraints will define practical limits.
- **Site Wind Matters:** The system's efficacy is directly proportional to the available wind resource, underscoring the need for careful site analysis.
- **Evaporative Cooling is Highly Effective:** Integrating a cooling surface, replicating traditional water pools, dramatically improves thermal comfort despite a negligible impact on airflow volume.

The research demonstrates that optimizing these parameters allows windcatchers to meet significant portions of a building's cooling load without mechanical assistance. The findings are directly applicable to sustainable architectural design in hot, arid, and even temperate climates, promoting energy conservation and resilience. Future work could explore multi-directional windcatchers, integration with other passive systems (e.g., thermal mass), and year-round operation including heat recovery for colder seasons. This study successfully translates an ancient bioclimatic solution into a quantifiable modern engineering asset.

Keywords: wind deflector, air conditioning, building cooling, numerical study

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