Integrating Statistical Wind Analysis and CFD Modeling for Greenhouse Design in Hammond, Indiana

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Background

Greenhouses are essential in modern agriculture as they provide controlled environmental conditions for crop production (Shamshiri et al., 2018). However, their lightweight structural materials are vulnerable to wind pressure and uplift forces (Kim, 2017; Wang 2021). As global climate change intensifies and extreme weather occurs more frequently, the need for wind-resilient agricultural design has become a matter. Engineers must understand how wind effects interact with greenhouse structures to reduce failure and ensure structural stability.

Our research focuses on analyzing wind flow effects on agricultural buildings, particularly greenhouses, through computational fluid dynamics (CFD) combined with statistical analysis of wind characteristics in Hammond, Indiana, where Purdue University Northwest is located. Dominant wind characteristics were identified through statistical methods such as Weibull and Rayleigh distributions, and the data were visualized through automated Python Programming to reveal yearly, seasonal, and monthly trends.

These dominant wind characteristics were used as inputs for 2D CFD simulations, and the pressure coefficient (C_p) was applied to evaluate the wind pressure distribution across the greenhouse structure. By testing various geometric parameters, including roof type and slope, the analysis examined how wind interacts with different designs under different boundary conditions. Motivated by the question, "What if we built a greenhouse in Hammond?" our research integrates statistical wind analysis and CFD modeling to provide insights into structural performance, wind resistance, and optimal greenhouse design for local environmental conditions.

Purpose and Objectives

The purpose of our research was to determine the optimized structure of a greenhouse against local wind conditions in Hammond. Thus, we 1) Identified dominant wind characteristics, such as wind speed, using statistical methods, 2) Integrated wind characteristics as boundary conditions for CFD simulations, 3) Tested multiple greenhouse geometries, including roof type, shapes, and slope to evaluate wind pressure distributions, and 4) Provided optimized design insight of wind-resilient and structurally efficient greenhouse buildings.

Methods / Procedures

Wind data were collected from two authoritative databases, WRDB and the Indiana Mesonet. Hourly and 5-minute resolution data were processed using Python to clean, organize, and visualize wind characteristics. Weibull and Rayleigh distributions were applied to identify dominant wind speeds and directions, including critical parameters k and c, for each distribution in 2020, as well as yearly, seasonal, and monthly data. To visualize the characteristics of wind conditions, Weibull Probability Density Function (PDF) for wind speed was used by Python's matplotlib library, clarifying the central tendency of wind distribution, allowing for an intuitive understanding of wind patterns.

ANSYS/FLUENT 2024 was used to conduct 2D steady-state CFD simulations. We used the most representative greenhouse structure (Kim, 2017) with a wall height of 3.5 m, a roof type of either gable or arched, a width of 8 m, and roof slopes of 20°, 25°, and 30°. The CFD domain was size to ensure realistic bluff-body external aerodynamics simulation based on a study by Wang (2021), preventing artificial boundary effects and allowing appropriate development of upstream and downstream flow. Considering H is the ridge height, we set upstream length of 5H, downstream length of 15H, and vertical domain height of 5H. Only the roof pitch was varied in the third study to isolate its influence on wind pressure (Wang, 2021). C_p values provided a visualization of the relative wind pressure distribution and differences, and an understanding of regions of high wind pressure and suction, identifying the structural stress.

Results

The dominant wind characteristics of Hammond, Indiana, were determined for use as boundary conditions in the CFD simulation. Analysis of 2020 wind data revealed the prevailing wind direction was from 181.41° (south), with a dominant annual speed of 3.29 m/s, a mean wind speed of 3.88 m/s, a peak probability density of 0.206, and a probability of wind speed between 3.0–3.5 m/s of 10.27%. Seasonal and monthly trends provided additional details for realistic simulation conditions and were visualized through automated Python code.

The CFD results demonstrated geometry significantly affects wind pressure distribution. In particular, the 25° roof structure showed strong changes in C_p value at the roof windward slope, especially near the transition between wall and roof, where strong negative C_p values indicated suction effects causing uplift forces and reduced structural stability.

Varying roof slopes illustrated different peak C_p values. For instance, a 25° roof had C_p values ranging from +14.8 (stagnation) to -26.9 (leeward suction), while the 30° roof ranged from +13.9 to -14.8. In summary, the 20° gable roof produced the smoothest pressure distribution with suction zones evenly spread, reducing localized stress. The 30° gable roof showed stronger suction on the leeward side and ridge line, creating uplift risks. The arched roof displayed smooth flow across the roof but concentrated suction forces at the crest, producing the highest negative C_p values. Overall, the 20° geometry demonstrated the most balanced pressure distribution and reduced suction extremes, making it the most stable design.

Conclusion

Our research investigated the wind flow effects on greenhouse structures in Hammond, Indiana, and it involved the integration of statistical wind analysis and computational fluid dynamics. The primary objective was to evaluate how varying geometric parameters, such as roof slope, influence wind pressure distribution under local Hammond wind conditions. The study suggests that careful geometric design, particularly roof slopes, can significantly reduce the risk of wind damage while improving structural reliability. The results are directly applicable to engineers and agricultural practitioners seeking to design efficient, wind-resistant greenhouses. The 20° gable roof, which exhibited balanced pressure distribution, offers a practical guideline for future constructions in Hammond and similar regions. Furthermore, the methodological framework, combining environmental statistics with computational modeling, can be applied to other agricultural buildings, supporting climate-resilient design strategies in rural development.

Our simulations were limited to 2D steady-state flow; however, the use of statistically validated wind parameters significantly enhanced the realism and relevance of the aerodynamic results, supporting optimized greenhouse design tailored for wind resilience in the Hammond region. The 2D, steady-state approach limited the ability to capture corner effects, lateral wind loads, and the variations in wind direction, as steady wind conditions were assumed. Future work will extend the simulations to 3D modeling to capture corner effects and lateral wind loads, incorporate unsteady CFD to capture guests. We will use varying geometry conditions, add ventilation, and hanging edge, and consider greenhouse grouping instead of a single span greenhouse structure to study the "shield effect."

References

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