Revista Ciência Agronômica, v. 57, e202696451, 2026
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

RESEARCH ARTICLE
ISSN 1806-6690

Predicting aerodynamic coefficients in pitched roof greenhouses using computational fluid dynamics[1]

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ABSTRACT - Wind action represents one of the main causes of damage to the structural and cladding elements of greenhouses. Its complexity posits that standardized aerodynamic pressure coefficients are limited and that greater comprehensiveness and accuracy can be achieved via computational fluid dynamics (CFD). Hence, this study analyzed the pressure coefficients used to design pitched-roof greenhouses obtained via computational simulations, and verified discrepancies in relation to standardized values. CFD modeling was employed across 18 scenarios to simulate the distribution of pressure coefficients (Cp) in greenhouses with height-to-span ratios (h/s) of 0.41 and 0.63. k-ε, k-ω, and k-ε RNG turbulence models were evaluated for Reynolds numbers ranging from 1.2×10^4 to 1.2×10^8. The distributions of the external pressure coefficients were similar for these turbulence models. Main discrepancies regarding the technical standards concerned lower Cp values than those standardized for leeward walls and roof of greenhouses with h/s equal to 0.63, and the inversion of coefficients from pressure to suction in the windward roof zone across all evaluated scenarios. CFD simulation provided extensive detailing for the pressure coefficients and identified critical discrepancies; thus, its use and further development in future research might contribute to the structural safety of greenhouses.

Keywords: Wind action. Fluid mechanics. Pressure coefficient.

INTRODUCTION

Agricultural construction technology faces the challenge of designing protected environments that improve growing conditions, boost production efficiency and keep costs affordable for farmers (Kwon *et al*., 2016; Laktionov *et al*., 2023). Within this scenario, greenhouses represent a solution undergoing global expansion (Liu *et al*., 2024). These structures typically consist of lightweight metal frames covered with glass or plastic film, allowing sunlight to pass through while protecting crops from adverse weather conditions and pests (Soriano; Shiguemoto; Vieira Neto, 2024).

Considered one of the main causes of greenhouse damage and collapse, wind is a key factor in defining structural loading (Bronkhorst *et al*., 2017; Ha *et al*., 2014; Richardson, 1986). In low-rise buildings, under 15 m in height, wind effects are critical due to intense pressures generated on roof surfaces, associated with flow separation at the edges, eaves, and ridges (Bianchin; Braun, 2025). Wind action must therefore be considered alongside other acting loads, such as self-weight, cladding/covering and equipment, to ensure structural safety (Jiang *et al*., 2021).

Pressure coefficients (Cp) for the structural design of greenhouses are defined by standards such as EN 13031-1 (European Committee for Standardization, 2019). However, these coefficients are limited to certain types of construction and their values differ from those measured in more complex structures (Fouad; Mahmoud; Nasr, 2018; Wang *et al*., 2021). Such cases call for experimental determination of aerodynamic coefficients even though wind tunnel tests are expensive, time-consuming, and subject to practical limitations.

Given these limitations, computational fluid dynamics (CFD) constitutes a promising alternative for evaluating the aerodynamic behavior of greenhouses (Fouad; Mahmoud; Nasr, 2018; Kim; Lee; Kwon, 2017; Kuroyanagi, 2017; Wang *et al*., 2021). CFD simulation allows estimating the wind-structure interaction considering turbulence effects and pressure distribution on the surfaces (Ntinas *et al*., 2017). Due to the complexity of fluid-structure

DOI: 10.5935/1806-6690.v57e202696451
Section Editor: Profa. Mirian Cristina Gomes Costa - mirian.costa@ufc.br
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Received for publication in 20/02/2026: approved in 13/07/2026
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interaction, however, further studies are needed to improve turbulence models, particularly in structures with varied shapes and high Reynolds numbers (Soriano; Shiguemoto; Vieira Neto, 2024; Uematsu; Takahashi, 2020). Additionally, no universally superior model for all types of flows exists (Lee; Wahab, 2019).

Considering the existing gaps regarding the limitations and accuracy of standard-based pressure coefficients for greenhouses, this research contributes to bridge this gap by presenting results from CFD simulations using the k–ε, k–ω and k–ε RNG turbulence models. Based on EN 13031-1 parameters (European Committee for Standardization, 2019), the ability of these three turbulence models to predict external pressure coefficients was evaluated. Given the complex distribution of dynamic wind pressure, CFD analysis proved highly valuable, as it captured aerodynamic phenomena not addressed in technical standards, such pressure coefficient inversion within the same windward zone.

MATERIALS AND METHODS

We defined the geometric parameters of the studied greenhouses to meet the EN 13031-1 standards (European Committee for Standardization, 2019), which are required for obtaining the pressure coefficients of the structure planes. Figure 1 presents the parameters, in which H represents the total height of the greenhouse; *he*, the height below the gutter; and *s*, the structure's span. EN 13031-1 groups pressure coefficients by the *h/s* ratio in which the characteristic height *(h)* is calculated as *0.75H*, but with a value greater than or equal to *he*.

For a greenhouse with an he/s ratio of 0.3, we adopted a span of 8 meters, a column height of 2.4 meters and a roof slope of 26°; with 5 modules of 3.6 meters each, this results in a greenhouse length of 18 meters. Greenhouses with a he/s ratio of 0.6 were simulated using these same dimensions, except for the column height, which was set to 4.8 meters. Height-to-span (he/s) ratios equal to 0.3 and 0.6 resulted in h/s ratios equal to 0.41 and 0.63, respectively.

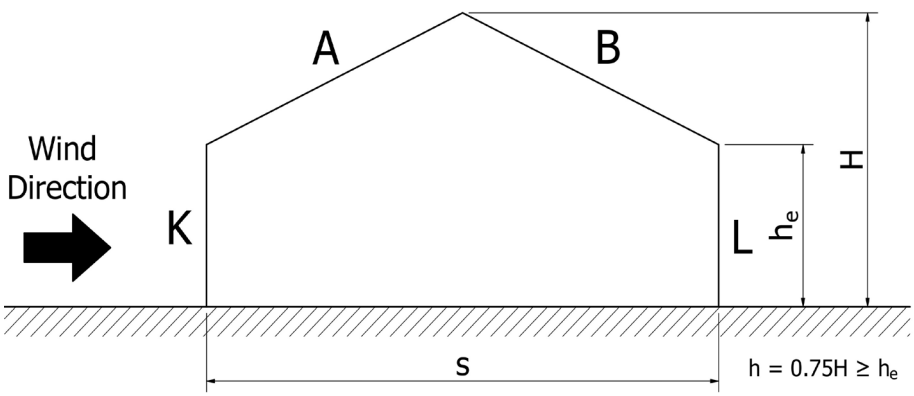
Aerodynamic coefficients corresponding to the wind direction perpendicular to the ridge are identified by zones of the greenhouse geometry: on the walls, the windward side (zone K) and the leeward side (zone L); on the roof, the windward side (zone A) and the leeward side (zone B). In this wind direction, an analysis of the pressure coefficients reveals marked differences between the various building parts (walls or roof) and between the windward and leeward sides. In contrast, when the wind blows parallel to the ridge, the pressure coefficient tend to remain constant or vary only slightly for the wall and roof zones, as set out in EN 13031-1 (European Committee for Standardization, 2019) and corroborated by CFD simulations performed by Ha *et al*. (2014). Nonetheless, structural design should not neglect the wind action parallel to the ridge.

The roof slope was defined based on structural optimization research for greenhouses with 20° and 26° roofs (Vieira Neto; Soriano, 2016, 2017), which concluded that steeper slopes result in lower stresses on the structural elements of the roof. Additionally, this configuration provides better environmental conditions (Zghal *et al*., 2025) due to the increased internal volume of the greenhouse, promoting the ascent and expansion of hot air, thereby reducing the thermal load in the crop zone.

2.3 Computational simulation

An unstructured mesh with refinement applied near the analyzed geometry (Figures 2A and B) was used, following Kim, Lee, and Kwon (2017) and

Figure 1 - Geometric parameters for determining the pressure coefficients in wall (K and L) and roof (A and B) zones, with wind blowing perpendicular to the ridge, for a greenhouse with span (*s*), total height (*H*), height beneath the gutter (he) and characteristic height (*h*)



Rico-Garcia *et al*. (2011). The mesh for the model with an h/s ratio of 0.41 consisted of 40,133 elements and 9,175 nodes, whereas the mesh for the greenhouse with an h/s ratio of 0.63 comprised 23,412 elements and 5,260 nodes. Mesh independence tests were conducted by applying refinements of 50% and 100% to the number of elements automatically generated by the software; a maximum difference of 5% was observed between the different meshes, in accordance with Autodesk (2019) guidelines.

Regarding the control volume and properties of solid and fluid materials, all simulations used the same boundary conditions. All structures were treated as rigid, with steel used for their components, and air was modeled using the fluid properties listed in Table 1—values corresponding to the Autodesk CFD software defaults.

The control volume used dimensions larger than those of the simulation models found in the literature (Ha *et al*., 2014; Kateris *et al*., 2012; Ntinas *et al*., 2017) and strategies suggested by Autodesk (2019), while adhering to conditions ensuring that its side walls provided a no-slip condition, the inlet flow entered the domain at a constant velocity, and the outlet boundary allowed the fluid to leave the domain without distortion and at zero pressure.

Figure 2 - Unstructured mesh applied in numerical simulations. A) in all control volumes. B) refinement near the greenhouse

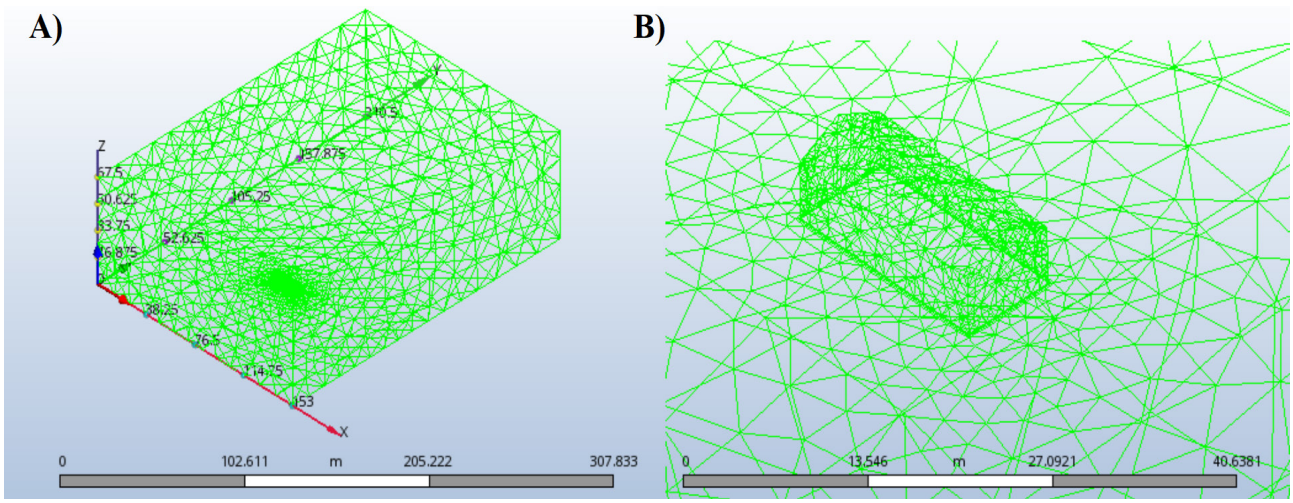


Table 1 - Thermophysical properties of fluid (air) and solid (steel) set as boundary conditions in Autodesk CFD software

Material	Property	Value	Unit
Fluid: Air	Density	1.20473	kg m^{-3}
	Viscosity	1.817×10^{-5}	Pa s
	Conductivity	0.02563	W $(m\ K)^{-1}$
	Specific heat	1004	J $(kg\ K)^{-1}$
	Ct/Cv	1.4	ad.
	Emissivity	1	ad.
	Control volume wall roughness	0	m
	Temperature	19.85	°C
Solid: steel	Density	7833	kg m^{-3}
	Specific heat	465	J $(kg\ K)^{-1}$
	Electrical resistivity	1.7×10^{-7}	Ohm m
	Emissivity	0.3	ad.
	Greenhouse coating roughness	0	m
	Temperature	19.85	°C

In which: Ct/Cv – coefficient of adiabatic expansion; Ct – thermal capacity at constant pressure; Cv – thermal capacity at constant volume

The dimensions of the computational domain surrounding the greenhouse were determined based on the height from the base to the ridge (*H*), resulting in a distance of *10 H* at the flow inlet (from the start of the control volume to the windward wall) and an equal distance at the greenhouse sides; *9 H* above the greenhouse; and *20 H* from the leeward wall to the flow outlet (Figure 3). Greenhouse geometries and control volumes were modeled using Autodesk AutoCAD 2026 software.

The Navier-Stokes flow equations were solved by applying the three turbulence models (k-ε, k-ω and k-ε RNG) into the Autodesk CFD 2026 software. The adopted convergence criteria were based on the stabilized variables TKE (Turbulent Kinetic Energy), TED (Turbulent Energy Dissipation), velocity components (Vx, Vy, Vz), and pressure. The equation residuals reached values on the order of at least 10^{-8}, ensuring the numerical consistency of the obtained solutions, which, according to Curi *et al*. (2017), satisfy the minimum residual value of 10^{-4}.

For each h/s ratio and each turbulence model, simulations were conducted across three the Reynolds number (Re) (Table 2), corresponding to wind speeds ranging from calm conditions to the gale category on the Beaufort scale (Ahmad *et al*., 2017). Based on the gale category, effects that may be significant for the structural safety analysis are highlighted.

For all combinations of turbulence models and Reynolds numbers, pressure coefficients in each wall or roof zone were calculated by averaging the values obtained at points positioned 10 cm from the modeled geometry (Rico-García *et al*., 2011); the spacing between consecutive points was 30 cm, and 20 segments were generated within that interval. For example, 320 pressure coefficient values were generated along the 4.8 m-high column for calculating the arithmetic mean.

Figure 3 - Configuration of the control volume generated around the structure, using the total height of the greenhouse (H) as a reference

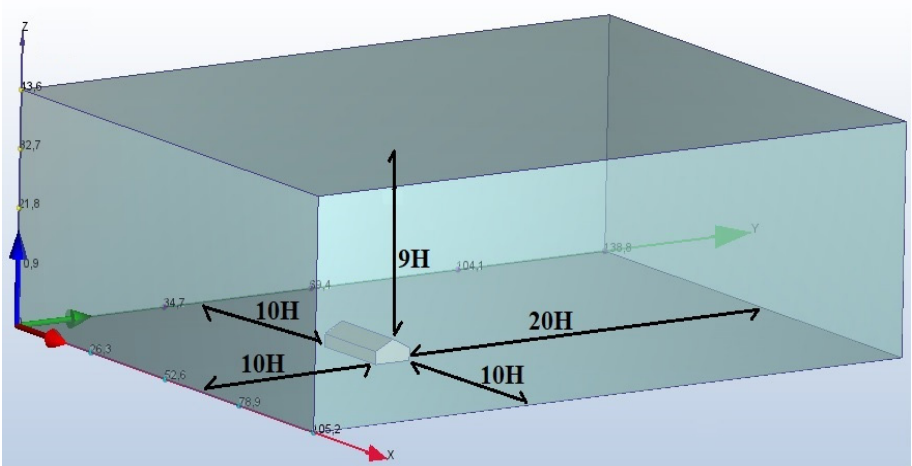


Table 2 - Simulation scenarios grouped by the relation between characteristic height and greenhouse span (h/s), Reynolds number (Re), wind speed (v) and turbulence model. Scenarios A1 to A9 represent an h/s ratio of 0.41. Scenarios B1 to B9 represent an h/s ratio of 0.63

Scenario	Re	v (m s^{-1})	Turbulence model
		h/s = 0.41	
A1	12,000	2.67×10^{-3}	k-ε
A2			k-ω
A3			RNG
A4	1,200,000	2.67×10^{-1}	k-ε
A5			k-ω
A6			RNG
A7	120,000,000	26.72	k-ε
A8			k-ω
A9			RNG

Continuation Table 2

	h/s = 0.63		
B1	12,000	1.78×10^{-3}	k-ε
B2			k-ω
B3			RNG
B4	1,200,000	1.78×10^{-1}	k-ε
B5			k-ω
B6			RNG
B7	120,000,000	17.81	k-ε
B8			k-ω
B9			RNG

h/s = height (h) to span (s) ratio for pressure coefficients

Data analysis employed a combinatorial arrangement between two geometric relations (h/s = 0.41 and 0.63), three Reynolds numbers (1.2×10^4, 1.2×10^6 and 1.2×10^8) and three turbulence models (k–ε, k–ω and k–ε RNG), totaling 18 scenarios. Cp values extracted point-by-point were tabulated and evaluated descriptively and compared against the European standard EN 13031-1 values. Additionally, wind flow dynamics were qualitatively evaluated using the pressure fields and velocity vectors generated in the CFD simulations.

RESULTS AND DISCUSSION

Mean pressure coefficients obtained from CFD simulations, considering wind incidence perpendicular to the ridge, illustrate the pressure distribution patterns across the greenhouse wall and roof zones as a function of Reynolds number and the turbulence model employed (Figures 4A and 4B). Analysis of the 18 simulated scenarios indicated positive pressure coefficients in Zone K (windward wall) under all analyzed conditions, characterizing overpressure. Negative pressure coefficients in Zones L (leeward wall) and B (leeward roof) indicate suction in these structural regions. This general distribution pattern is consistent with the aerodynamic behavior predicted by EN 13031-1 (European Committee for Standardization, 2019).

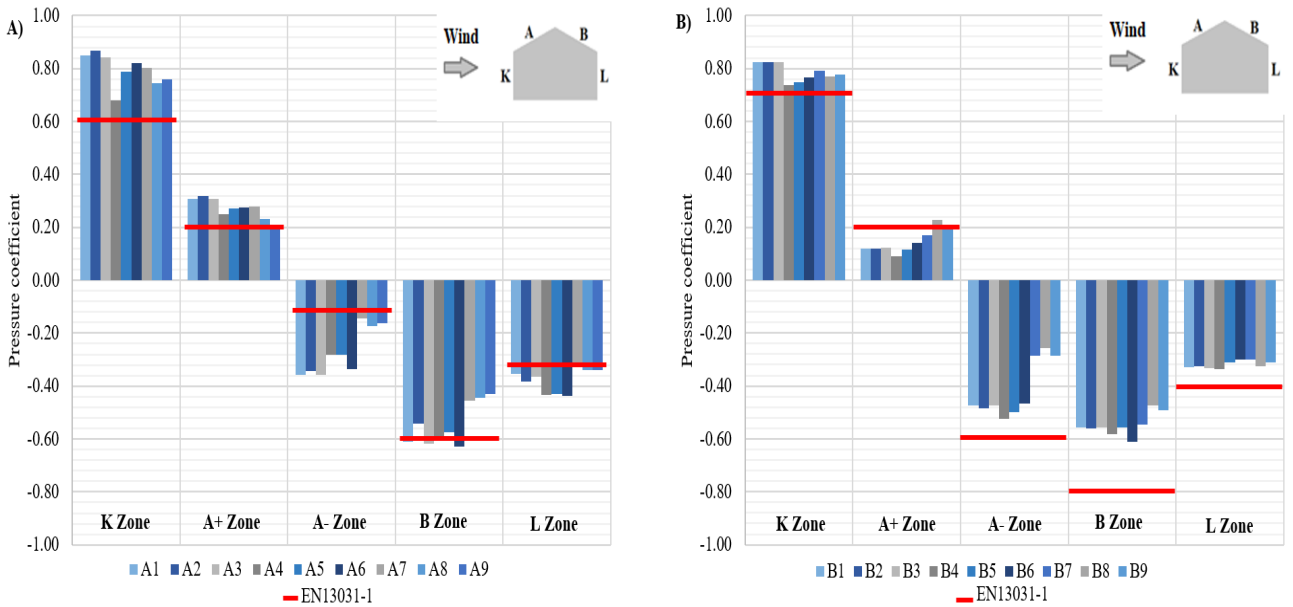
In Zone A, corresponding to the windward roof panel, the CFD simulation results showed behavior distinct from that described by EN 13031-1 (European Committee for Standardization, 2019). For both ratios (h/s = 0.41 and h/s = 0.63), in the direction from the eaves to the ridge, the pressure coefficients are initially positive (overpressure) and then become negative (suction), characterizing a subdivision of this roof zone.

Although the EN 13031-1 standard (European Committee for Standardization, 2019) does not explicitly present this subdivision of Zone A, for the analyzed geometries, alternating Cp values are prescribed: +0.20 or −0.13 (for h/s = 0.41) and +0.20 or −0.62 (for h/s = 0.63). Applying a single average value does not appear to adequately represent the aerodynamic effects across the entire roof length, because the cladding material (plastic film) has low stiffness, and its behavior can be significantly affected by wind action.

In such a context, Kateris *et al*. (2012) recommended subdividing the roof zones as a strategy to better represent the variability of pressure coefficients. Additionally, Tominaga *et al*. (2015) highlighted that the Cp distribution on the windward roof slope is strongly influenced by the roof pitch, with suction predominating at slopes below 26° and positive pressure at slopes above 36°, reinforcing the need for a more detailed analysis of this structural region.

For the leeward roof slope (Zone B) and h/s = 0.41, the mean pressure coefficients obtained via CFD for the two lowest Reynolds numbers were close to the Cp = −0.61 value prescribed by EN 13031-1 (European Committee for Standardization, 2019). This demonstrates good agreement between the numerical results and the standard's recommendation across all three turbulence models. However, as the Reynolds number increased, the suction decreased, yielding Cp values approximately 27.8% lower (absolute value) than those indicated by the standard. The h/s = 0.63 configuration exhibited the largest discrepancies relative to the normative values, as the simulations yielded a mean pressure coefficient value on the order of −0.55. This value is lower than the Cp of −0.80 recommended by EN 13031-1 (European Committee for Standardization, 2019) for zone B, yet similar to the results obtained by Tominaga *et al*. (2015), who reported a mean Cp of −0.5 with slight variation due to roof slope. Similarly, Lewei *et al.* (2013) reported coefficients around −0.50 for this structure zone when studying greenhouses referenced by the Chinese technical standards.

Figure 4 - Pressure coefficients on the walls (Zone K and Zone L) and on the roof (Zone A and Zone B). A) Characteristic height-to-span ratio h/s=0.41, with CFD simulations (A1 to A9) and the European standard (EN13031-1) values. B) Characteristic height-to-span ratio h/s=0.63, with CFD simulations (B1 to B9) and the European standard (EN13031-1) values



The highest suction intensities in zone B were found near the ridge (Kateris *et al.,* 2012; Kim; Lee; Kwon, 2017). A convergence trend of Cp values was observed from the intermediate region to the leeward ridge around −0.55, a behavior also identified by Kateris *et al*. (2012) and Tominaga *et al*. (2015). Overall, these results concerning Zone B indicate that European normative values may be more conservative for certain greenhouse geometric configurations.

In Zone K (windward wall), the pressure coefficients obtained via CFD simulations, considering the three turbulence models and different Reynolds numbers analyzed, ranged from +0.68 to +0.87 for the h/s = 0.41 ratio and from +0.74 to +0.92 for h/s = 0.63. These values proved to be higher than those recommended by EN 13031-1 (European Committee for Standardization, 2019), which establishes Cp values of +0.64 and +0.70 for the respective geometric ratios. Similar results are reported in the literature, albeit with some variations associated with geometry and flow conditions. Kwon *et al*. (2016), in their evaluation of single-span greenhouses, reported mean Cp values of up to +0.67 on the windward wall.

In turn, Tominaga *et al*. (2015), based on wind tunnel tests and CFD simulations of pitched-roof greenhouses, observed significantly higher pressure coefficients in this zone, reaching values close to +1.0 near the gutter, which is a region characterized by intense flow deceleration and pressure buildup. Adopting an intermediate approach, Lewei *et al*. (2013), based on the Chinese standard for greenhouses, applied Cp = +0.80 for the windward wall. Considering the mean values obtained in this study, the greenhouse with an h/s ratio of 0.63 exhibited pressure coefficients closest to those reported in standards and experimental studies, indicating better alignment with available technical references.

Regarding Zone L (leeward wall), for the h/s = 0.41 ratio, the pressure coefficients obtained via CFD showed good agreement with the Cp value of −0.34 prescribed by EN 13031-1 (European Committee for Standardization, 2019), demostrating consistency between the numerical results and the normative recommendation. For the h/s = 0.63 ratio, the Cp values differed by an average of 20.2% from the normative coefficient of −0.40, regardless of the turbulence model adopted. These numerical results are close to the coefficients in the order of −0.30 reported by Tominaga *et al*. (2015) for pitched-roof greenhouses, indicating that an increase in the h/s ratio does not necessarily induce a proportional increase in suction along the leeward wall.

Ntinas *et al*. (2017) and Vieira Neto and Soriano (2020) attribute the suction effects in Zone L to the formation of vortices downstream of the building, resulting from flow separation at the ridge, as also observed in this study. This aerodynamic behavior reinforces the combined influence of greenhouse geometry and flow regime on determining pressure coefficients in this zone.

Preliminary analysis of the flow regimes further indicates that under high turbulence, the boundary conditions tend to stabilize, reducing abrupt variations in the flow separation points. Given this behavior and seeking to evaluate critical design conditions, we analyzed the distribution of pressure coefficients for a Reynolds number of 120,000,000 in greater depth in the following section, focusing on the roof zones of the greenhouse.

Distribution of pressure coefficients for Re=120,000,000

This section discusses the global aerodynamic effects on Cp distribution for a Reynolds number of 120,000,000, with associated wind speeds (Table 2) falling into the gale category on the Beaufort scale. For the greenhouse with an h/s ratio of 0.41, the pressure distributions obtained from the CFD simulations are presented for each turbulence model (Figures 5A, B, and C), corresponding to the main views of the windward and leeward walls. Both quantitative and qualitative analysis indicate the occurrence of maximum overpressure on the windward wall and maximum suction on the side wall near the windward wall edge, as well as a pressure coefficient inversion near the windward gutter. Overall, the turbulence models exhibit similar patterns in pressure coefficient distribution. CFD simulation results for greenhouses with an h/s ratio of 0.63 (Figures 6A, B, and C) show similar behavior regarding the distribution of aerodynamic coefficients.

Position of the pressure coefficient inversions resulting from the turbulence model for Re = 120,000,000

Figure 7 highlights zone A, which shows the variations in aerodynamic coefficients along the length (Lr) of the sloping roof surface as a function of the h/s ratios and turbulence models. For the h/s ratio of 0.41, with reference to the edge formed by the roof and wall planes, the inversion point occurs within a range of 0.75 m (k-ε model) and 1.33 m (k-ω model). For the h/s ratio of 0.63, this inversion point lies between 0.88 m (k-ε model) and 1.20 m (k-ω model). Figure 7C highlights these regions of pressure coefficient inversion as the inversion position (x) relative to the length (Lr). For both h/s ratios, the k-ω model tends to predict inversion points further away from the gutter compared with

Figure 5 - Cp distribution for greenhouses with a characteristic height-to-span ratio h/s=0.41 and Re=120,000,000, shown in perspectives highlighting the windward and leeward walls. A) k-ε turbulence model. B) k-ω turbulence model. C) k-ε RNG turbulence model

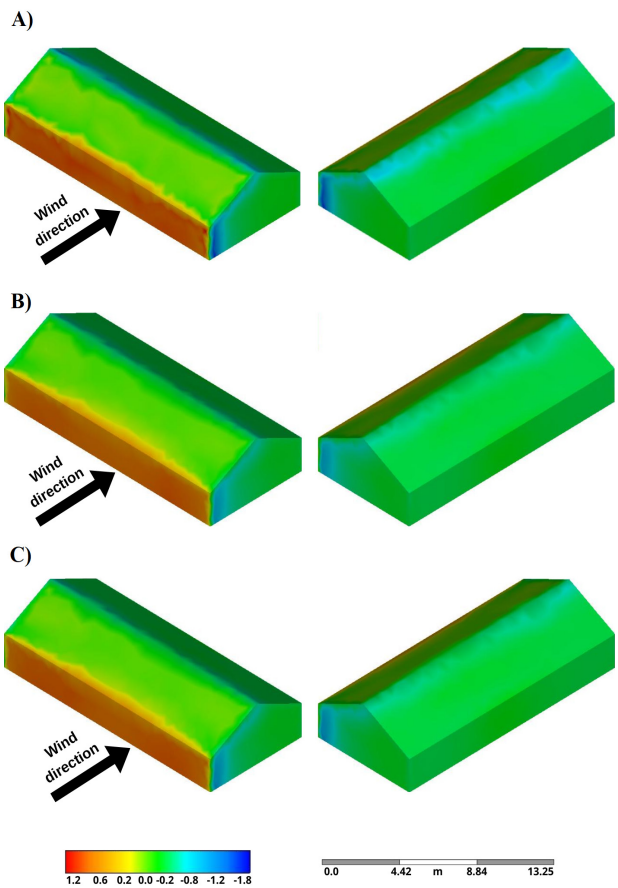
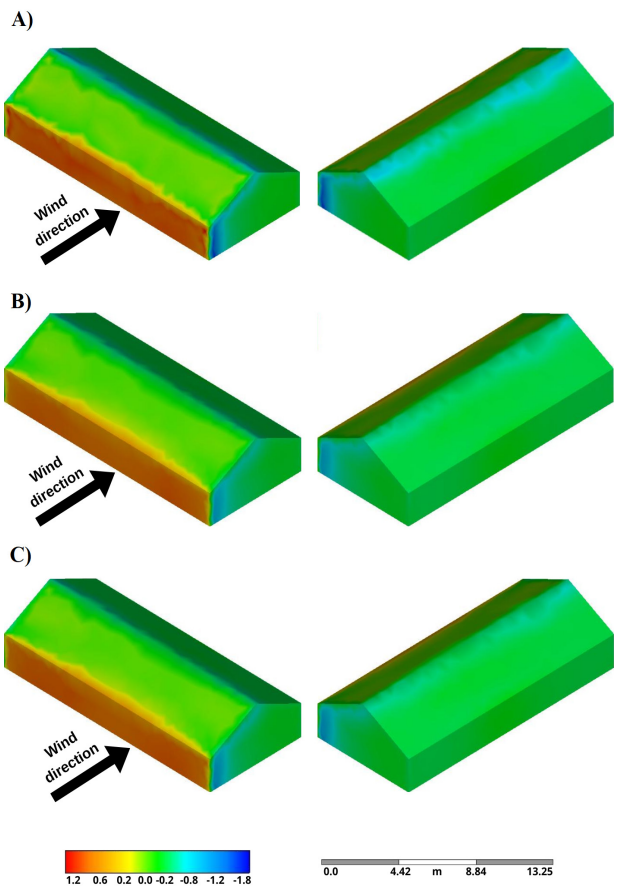
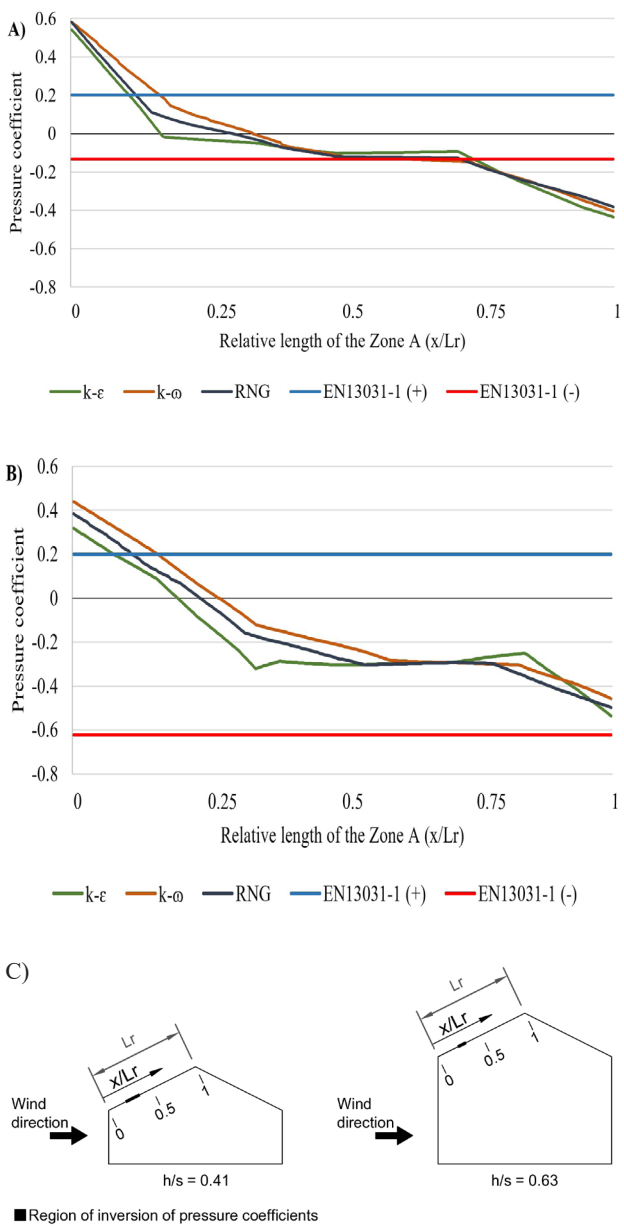


Figure 6 - Cp distribution for greenhouses with a characteristic height-to-span ratio h/s = 0.63 and Re = 120,000,000, shown in perspectives highlighting the windward and leeward walls. A) k-ε turbulence model. B) k-ω turbulence model. C) k-ε RNG turbulence model



the k-ε model, which can be attributed to the k-ω model's greater sensitivity in near-wall regions and boundary layers (Wilcox, 2006).

Figure 7 – Distribution of pressure coefficients (Cp) in Zone A, with Reynolds number Re = 120,000,000 and the turbulence models k-ε, k-ω and RNG. A) Greenhouse height-to-span ratio (h/s) of 0.41. B) Greenhouse height-to-span ratio (h/s) of 0.63. C) Representation of the region where the pressure coefficients were inverted along the windward roof plane, in relation to the position (x) and length (Lr) of the roof plane



The EN 13031-1 standard (European Committee for Standardization, 2019) establishes pressure coefficient values for the windward roof area of agricultural greenhouses, highlighting the need for special consideration of this surface in the structural design. The numerical results indicate that all three turbulence models predict an inversion of the pressure coefficient along the roof in this region, regardless of wind speed, which is consistent with the flow complexity described in the EN 13031-1 standard (European Committee for Standardization, 2019) covers both overpressure and suction conditions; notably, the highest h/s ratio (0.63) exhibits a wider range of Cp values, transitioning from 0.20 to −0.622 (Figure 7B) and indicating more severe aerodynamic loads on the roof. Conversely, for the lowest h/s ratio (0.41), Figure 7A, the variation in pressure coefficients was less pronounced, ranging between 0.20 and −0.133, indicating a more moderate aerodynamic behavior in this geometric configuration.

Kwon *et al*. (2016) and Kim, Lee, and Kwon (2017) observed similar results. Through experimental studies in a wind tunnel and CFD modelling of pitched-roofed greenhouses with an h/s ratio of 0.29, they identified a distribution pattern for the pressure coefficients characterized by positive values in the windward region closest to the gutter, followed by high negative values in the mid-roof and near the ridge. They also emphasized that the central section of the greenhouse (from which we obtained our results) exhibits the highest suction values and is, therefore, considered a critical zone from a structural perspective.

Discrepancies observed among the fluid dynamics models, as well as their deviations from normative values, underscore the need for further research, including experimental analysis. Future refinements to the computational models must also account for the aeroelastic behavior of flexible greenhouse cladding materials.

CONCLUSIONS

1. All three turbulence models (k-ε, k-ω and k-ε RNG) yielded a similar response pattern, indicating that the turbulence model has minimal impact on the prediction of wind flow and its effects on pressure coefficients. However, the three turbulence models investigated confirm the hypothesis that critical differences exist between their results and standardized values, demonstrating that CFD simulation is an important tool for obtaining pressure coefficients;

2. The CFD prediction of pressure coefficients proved that the windward roof surface requires special structural consideration, as the three turbulence models indicated pressure coefficient inversion along its length regardless of wind speed. This roof region is subject to both overpressure and suction conditions, with the highest h/s ratio (0.63) yielding a larger variation in Cp values, thereby evincing more severe aerodynamic effects on the roof structure.

ACKNOWLEDGMENTS

The authors thank Espaço da Escrita – Pró-Reitoria de Pesquisa – UNICAMP – for the language services provided.

DATA AVAILABILITY STATEMENT

The research data is available only upon request to the corresponding author.

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