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# ENVIRONMENTAL COMFORT OF GREENHOUSES ASSOCIATED TO PARAMETERS OF STRUCTURAL SHAPE

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**ABSTRACT:** The aim of this work was to evaluate the thermal comfort efficiency by energy and mass balance for normalized greenhouses with pitched roof and in arch roof, with variation of the shape parameters. The data for analysis were generated by the application of analytical models in eight situations of each type of greenhouse, defined by variations of the greenhouse parameters: span, height of gutter, slope of the roof and height of the arched roof. In addition, fully closed models with low density polyethylene and side openings were evaluated. The analysis of the different models showed that the comfort conditions concerning the different times of obtaining the climatic data close to 6 h for the winter and 15 h for the summer are more susceptible to the variations of the ratio between the parameter's height and span. These shape parameters were shown to be strategic for the efficiency of greenhouse projects, since they directly affect summer heat reduction and winter heat retention and affect environmental humidity for protected crops.

**Keywords:** protected crops, pitched roof, arched roof, energy balance, mass balance.

# CONFORTO DO AMBIENTE DE ESTUFAS AGRÍCOLAS ASSOCIADO AOS PARÂMETROS DE FORMA DA ESTRUTURA

**RESUMO:** Este trabalho teve como objetivo avaliar a eficiência de conforto térmico pelo balanço de energia e massa para estufas agrícolas normalizadas com coberturas em duas águas e em arco, com variação dos parâmetros de forma. Os dados para análise foram gerados com aplicação de modelos analíticos em oito exemplares de cada tipo de estufa, definidos por variações dos parâmetros de largura da estufa, altura de pé direito, inclinação do telhado e altura do arco do telhado. Além disso, foram avaliados os modelos totalmente fechados com polietileno de baixa densidade e com aberturas laterais. A análise dos diferentes modelos mostrou que as condições do conforto concernentes aos diferentes horários de obtenção dos dados climáticos próximo das 6 h para o inverno e das 15 h para o verão são mais susceptíveis às variações da razão entre os parâmetros altura e vão. Esses parâmetros de forma mostraram-se estratégicos para a eficiência dos projetos de estufas, pois afetam diretamente a redução do calor no verão e a retenção do calor no inverno, além de afetarem a umidade do ambiente para o cultivo protegido.

**Palavras-chaves:** cultivo protegido, telhado duas águas, telhado em arco, balanço de energia, balanço de massa.

## 1 INTRODUCTION

The technology for the construction of environments for protected crops has a lot of challenges in the sense that the designs of environments can provide greater productive efficiency in smaller cultivated areas.

The quality of the production is generally ensured by the control of temperature, humidity, radiation, $CO_2$ and optimal conditions of fertility and plant health. Under these aspects, the greenhouse is a modality of protected cultivation that allows the production of different crops, with partial

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or total modification of the internal environmental conditions.

In Brazil, standardization for the manufacturing of greenhouse structures occurred with the publication of the Brazilian Standard of Regulation NBR 16032 (ABNT, 2012). This standardization considers two structural forms for designs: pitched roof and arched roof. In the evaluation of roof slope effects, with angles ranging from 20° to 26°, the fixation of the slope at 26° is a strategy that reduces stress in the roof structural elements, besides increasing the greenhouse volume (VIEIRA NETO and SORIANO, 2016, 2017).

In the world, there are great trends of conceptions of larger and taller models of greenhouses, according to the evaluation of Von Elsner et al. (2000a). Particularly in tropical countries, the implementation of higher greenhouses favors environmental comfort, which is due to the greater inertia of the environment in response to external changes.

For the evaluation of comfort in greenhouses, the mathematical models proposed by Hellickson and Walker (1983), ASHRAE (1978) and Albright (1990) consider parameters of temperature and indoor humidity. Costa, Leal and Carmo Júnior (2004) compared these mathematical models with the results of a network of sensors to obtain the temperature and internal humidity of the greenhouse. The authors concluded that the models are adequate for estimating the data, since the calculated mean values were not significantly different from the values obtained with sensors.

Crop production in greenhouses, as reported by Ahemd, Al-Faraj and Abdel-Ghany (2016) and Baxevanou et al. (2018), is influenced mainly by radioactive and convective transfer processes, through photosynthesis and transpiration, which, associated, directly affect the growth and development of the plants. According to Costa, Leal and Carmo Júnior (2004), the energy balance method makes it possible to determine atmospheric scale demand at hourly intervals and at smaller intervals, thus being a versatile, accurate and less expensive alternative compared to other methods.

In this context, the objective of this study was to evaluate, through the balance of energy and mass, efficiency in greenhouse comfort considering the shape parameters of the structure according to the NBR 16032 (ABNT, 2012).

## 2 MATERIAL AND METHODS

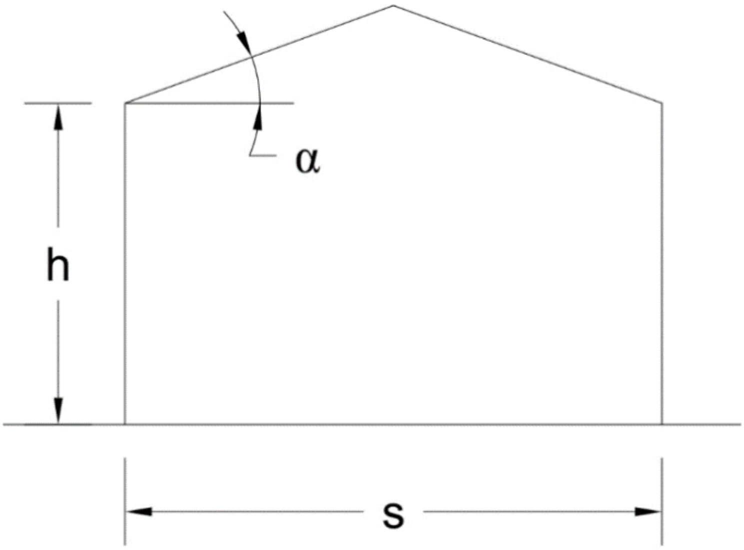
In this work, we studied the two main commercial shapes of single-span greenhouses: arched roof and pitched roof (commercially known as Poly House and Poly Venlo, respectively).

For the evaluation of the models treated by NBR 16032 (ABNT, 2012), the relationships of the structural shapes were organized so that the extreme values of height and span were used.

### 2.1 Pitched roof shape

For pitched roof models, the angles of slopes of the roof (α) were considered within the limits set by NBR 16032 (ABNT, 2012), ranging from 20° to 26°, and the extreme ratios of column height (h) per span (s), with values of 0.3 and 0.6. Eight models of pitched roof greenhouses were simulated, according to Figure 1 and Table 1, which illustrate the structural form of the models and the dimensions used in the calculations.

**Figure 1**. Structural shape of pitched roof and parameters of variation shape




h: column height; s: span; α: slope of the roof.

**Table 1.** Parameters considered for simulation of pitched roof models.

| Parameter | Model | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1-A** | **1-B** | **2-A** | **2-B** | **3-A** | **3-B** | **4-A** | **4-B** |
| h (m) | 1.92 | 2.40 | 1.92 | 2.40 | 3.84 | 4.80 | 3.84 | 4.80 |
| s (m) | 6.40 | 8.00 | 6.40 | 8.00 | 6.40 | 8.00 | 6.40 | 8.00 |
| h/s | 0.30 | 0.30 | 0.30 | 0.30 | 0.60 | 0.60 | 0.60 | 0.60 |
| α (°) | 20 | 20 | 26 | 26 | 20 | 20 | 26 | 26 |

h: column height; s: span; α: slope of the roof.

## 2.2 Arched roof shape

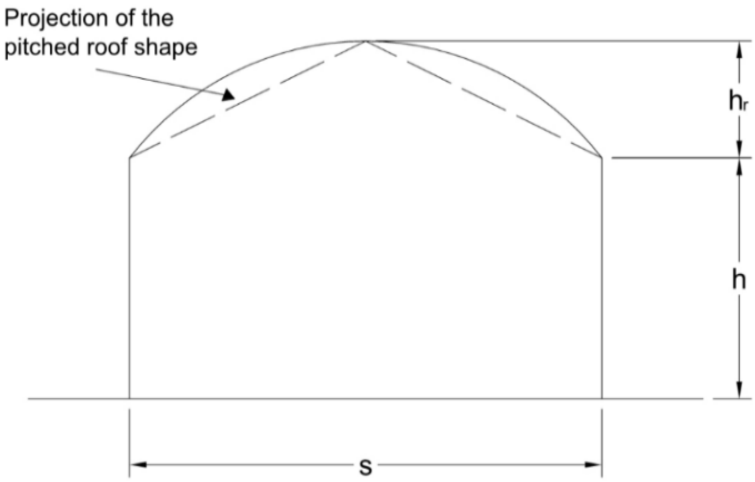
By the Brazilian standard NBR 16032 (ABNT, 2012), for arched roof models, the admitted ratio of the column height and span parameters is $0.4 \geq h/s \geq 0.6$. However, for purposes of comparison between the models we adopted values identical to those used for the pitched roof model, i.e., h/s = 0.3 and 0.6, which resemble the arched roof model.

The height of the arch, defined by hr, is indicated by NBR 16032 (ABNT, 2012), having values in relation to the span (s), which are $hr/s \geq 0.2$ and $hr/s < 0.2$. In order to compare the shapes of pitched roof and arched roof, for the fixation of the height of the arched greenhouses, the projection of the ridge of the pitched roof form was used (Figure 2), and thus the arch was obtained by the three points of the projection of the pitched roof shape (column height-ridge-column height).

For the projection of the ridge with roof inclined planes of 20°, it was possible to obtain the height hr of the arch, for which the relation $hr/s < 0.2$ is established by NBR 16032 (ABNT, 2012). Similarly, for the roof angle equal to 26° it was possible perform the calculations with the ratio $hr/s > 0.2$. Thus, the total heights obtained (h + hr) for the arched greenhouses were equal to the total heights of the pitched roof models.

Analogously to the pitched roof structural form, eight arched roof models were simulated, with different heights and span, maintaining the dimensions obtained in pitched roof models, according to Figure 2 and Table 2.

**Figure 2**. Arched roof shape and variation parameters compared to pitched roof shape




h: column height; s: span; $h_r$: height of arc roof.

**Table 2**. Parameters considered for simulation of arched roof models.

| Parameter | Model | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1-A** | **1-B** | **2-A** | **2-B** | **3-A** | **3-B** | **4-A** | **4-B** |
| h (m) | 1.92 | 2.40 | 1.92 | 2.40 | 3.84 | 4.80 | 3.84 | 4.80 |
| s (m) | 6.40 | 8.00 | 6.40 | 8.00 | 6.40 | 8.00 | 6.40 | 8.00 |
| h/s | 0.30 | 0.30 | 0.30 | 0.30 | 0.60 | 0.60 | 0.60 | 0.60 |
| $h_r$ (m) | 1.16 | 1.45 | 1.57 | 1.95 | 1.16 | 1.45 | 1.57 | 1.95 |
| $h_r$/s | <0.20 | <0.20 | >0.20 | >0.20 | <0.20 | <0.20 | >0.20 | >0.20 |

h: column height; s: span; α: slope of the roof; $h_r$: height of the arched roof.

## 2.3 Mathematical models for environmental comfort

The calculation considering the energy and mass balance aims implicitly to estimate the values of temperature and internal relative humidity of the greenhouses, respectively. In this analysis, climatic data for the city of Campinas (State of São Paulo, Brazil) were used, with a historical period of 20 years (1988 to 2008), according to the meteorological data of the Center for Meteorological and Climatic Research Applied to Agriculture (CEPAGRI, 2013).

According to CEPAGRI, historically the average maximum temperature for Campinas is 298.45 K and the average minimum is 291.25 K.

### 2.3.1 Energy balance

In the calculation of energy balance, due to the established conditions of the greenhouses, we used the balance method proposed by Hellickson and Walker (1983) and ASHRAE (1978), whereby we obtained the difference between the gain and loss of sensible heat. The energy balance was simulated with the data of winter and summer (obtained approximately at 6 a.m. and 15 p.m., respectively), and for each of these seasons the greenhouse was considered to be either open or closed.

The average of three consecutive months with higher dry bulb temperatures was assumed as 'summer', and the average three consecutive months with lower dry bulb temperatures was classified as 'winter'. Equation 1 for the energy balance proposed by the Hellickson and Walker (1983) is:

$$Qrad + Qequ + Qaqu + Qresp = Qcnd + Qpis + Qven + Qinf + Qrtc + Qfot + Qsl \quad (1)$$

Where Qrad (W) is sensible heat from the sun – radiation, Qresp (W) the sensible heat of respiration of the plant, Qcnd (W) the sensible heat conduction of the structure, Qpis (W) the sensible heat transferred from the ground to the perimeter, Qven (W) the sensible heat of ventilation air (natural or mechanical), Qrtc (W) the heat of thermal reirradiation to the sky, Qfot (W) the sensible heat used for photosynthesis, Qsl (W) the sensible heat converted to latent heat inside the internal environment.

The energy balance terms were defined according to Equations (2) to (11):

$$Qrad = \zeta \cdot I \cdot Ap \quad (2)$$

Where ζ is the transmittance of the covering material (low density polyethylene equal to 0.92), I (W $m^{-2}$) the intensity of local solar radiation, Ap ($m^2$) the floor area of the greenhouse.

$$Qresp = Qfot \cdot 10\% \quad (3)$$

$$Qfot = Qrad \cdot 3\% \quad (4)$$

$$Qven = Qsv + Qsl \quad (5)$$

$$Qsv = V \cdot \rho_{ar} \cdot Cp \cdot \Delta T \quad (6)$$

$$V = Vv \cdot Ea \cdot A_{abert} \quad (7)$$

$$Qsl = E \cdot Fc \cdot Qrad \quad (8)$$

Where V ($m^3$ $s^{-1}$) is the wind flow, Cp (1006 J $kg^{-1}$ $K^{-1}$) the specific air heat, ΔT (K) the difference between the internal temperature Ti and the external temperature Te, $\rho_{ar}$ (kg $m^{-3}$) the air density, Vv (m $s^{-1}$) the wind speed, Ea the efficiency of the openings (0.35), $A_{abert}$ ($m^2$) the opening area; E the ratio of evapotranspiration and solar radiation (0.5), Fc the cultivation factor (crop area/floor area = 1.0).

$$Qcnd = U \cdot A_{cob} \cdot \Delta T \quad (9)$$

Where U (6.8 W $m^{-2}$ $K^{-1}$) is the global transfer coefficient of the covering material, $A_{cob}$ ($m^2$) the contour area for plastic of the greenhouse.

$$Qpis = F \cdot Per \cdot \Delta T \quad (10)$$

Where F is the perimeter factor (1.15), Per (m) the perimeter of the covered greenhouse.

$$Qrtc = \varepsilon_{sup} \cdot \gamma_T \cdot \sigma \cdot Ap\,(Ti^{\,4} - \varepsilon_{ar}\ Te^4) \quad (11)$$

Where $\varepsilon_{sup}$ is the emissivity of the internal surface (0.85), $\gamma_T$ the thermal transmittance of long-wave cover material (0.80), σ (5.678 $10^{-6}$ $Wm^{-2}$ $K^{-4}$) the constant of Stephan Boltzmann, $\varepsilon_{ar}$ the apparent emissivity of the atmosphere (tabulated by Hellickson and Walker (1983) depending on the temperature of the dew point of the sky = 0.837).

In the energy balance equation, due to the particularities of the study, the following parameters were not considered, since their exclusion did not cause interference in the results of all simulations: Qequ (W) the heat from sources of thermal energy from motors, equipment, lighting, people, etc., Qaqu (W) the sensitive heat of heating system, Qinf (W) the sensitive heat of involuntary infiltration through cracks.

From these equations and with the organized climatic data, internal temperatures were estimated for the greenhouses, both in the closed and open construction situations approximately at 15 p.m. (in summer), as well as in the closed and open at 6 a.m. (in winter) approximately. The closed structure is composed of low-density polyethylene cover. About open greenhouse conditions, total openings on the sides were considered, without the presence of covers or screens.

### 2.3.2 Mass balance

The mass balance to estimate the relative humidity of the greenhouses was applied by the model proposed by Albright (1990). Due to the boundary conditions adopted, the mass balance for the open greenhouse models resulted in equal internal humidity values for all the models, since both the openings areas and the external environmental conditions are the same from one model to another.

The calculation method can be applied without the presence of a specific crop, because in the situation of the open greenhouse, evapotranspiration of plants should be considered due to the latent heat. This factor was considered invariable, with no plant presence, since the results would be the same for the models. For this purpose, the evaluation of internal humidity was defined only in the condition of closed greenhouse, according to Equation 12.

$$Uri = \frac{100}{Apm + Acont}\left(Apm + \frac{Acont \cdot \rho_{se}}{\rho_{si}}\right) \quad (12)$$

Where Uri (%) is the internal relative humidity, Apm ($m^2$) the wet floor area, Acont ($m^2$) the contour area of the greenhouse, $\rho_{se}$ (kPa) the steam saturation pressure associated with external climatic conditions, $\rho_{si}$ (kPa) the steam saturation pressure associated with internal environment temperature and external relative humidity.

The energy balance equations proposed by Hellickson and Walker (1983) and ASHRAE (1978), and the mass balance equations proposed by Albright (1990) were applied to each greenhouse model in order to verify the respective levels of comfort, as well as their adequacy to the region of Campinas – SP.

In the calculation for each situation – summer (open or closed) and winter (open or closed) – all the parameters of the energy and mass balance equations were obtained, with exception of conditions where they are negligible or inconsiderable, or there is no possibility of the existence of the parameter, as in the following cases:

Open construction in summer (OS): Qequ = Qaqu = Qcnd = 0;

Closed construction in summer (CS): Qequ = Qaqu = Qven = 0;

Open construction in winter (OW): Qrad = Qequ = Qaqu = Qcnd = Qfot = Qsl = 0;

Closed construction in winter (CW): Qrad = Qequ = Qaqu = Qfot = Qven = Qsl = 0.

## 2.4 Climate data

The climatic data for the city of Campinas were obtained through the meteorological station of the CEPAGRI (2013), in 20-year intervals ranging from June 1988 to October 2008. The averages for each month are presented in Table 3.

**Table 3.** Climatic data for the city of Campinas for a period of 20 years, from 1988 to 2008.

| Month | DBTmax mean (K) | DBTmin mean (K) | RH 6 a,m, (%) | RH 15 p,m, (%) | Insolation ($h \cdot day^{-1}$) | Solar radiation[1] ($W \cdot m^{-2}$) | Wind velocity ($m \cdot s^{-1}$) | Wind direction (°) |
|---|---|---|---|---|---|---|---|---|
| Dec | 302.8 | 292.3 | 75 | 47 | 6.2 | 739.6 | 4.75 | 213 |
| Jan | 302.9 | 293.0 | 78 | 57 | 6.2 | 723.4 | 4.17 | 227 |
| Feb | 303.2 | 293.1 | 78 | 54 | 6.7 | 745.3 | 3.79 | 211 |
| Mar | 303.1 | 292.8 | 73 | 50 | 6.3 | 733.3 | 4.63 | 212 |
| May | 298.7 | 287.7 | 75 | 46 | 6.6 | 607.2 | 3.88 | 193 |
| Jun | 298.0 | 286.1 | 75 | 43 | 6.3 | 595.9 | 3.24 | 224 |
| Jul | 298.0 | 285.4 | 73 | 41 | 6.0 | 590.7 | 3.17 | 204 |
| Aug | 300.4 | 287.0 | 67 | 36 | 6.5 | 675.6 | 3.70 | 209 |

[1]Average values at approximately 15 p.m. for the summer months and at 6 a.m. for the winter months. DBT max. mean: average dry bulb temperature of the maximum; DBT min. mean: average dry bulb temperature of the minimum; RH: Relative humidity.

**Source:** CEPAGRI (2013).

Table 4 shows the average values of the three most critical months of each season. Three months with the highest average of dry bulb temperature and three other months with the lowest average were selected to represent the summer and winter seasons, respectively. The selected quarterly periods are shown in Table 4, with which the other factors of the mass and energy balance equations were calculated.

**Table 4.** Averages of climatic data for the city of Campinas[1].

| Average of 3 months | DBT max, mean (K) | DBT min, mean (K) | RH (%) | Insolation ($h \cdot day^{-1}$) | Solar radiation ($W \cdot m^{-2}$) | Wind velocity ($m \cdot s^{-1}$) | Wind direction (°) |
|---|---|---|---|---|---|---|---|
| D, J, F | 302.97 | 292.8 | 55.00 | 6.37 | 736.10 | 4.24 | 217.00 |
| *J, F, M* | *303.07* | *292.97* | *53.67* | *6.40* | *734.00* | *4.20* | *216.67* |
| M, J, J | 298.23 | 286.40 | 74.33 | 6.30 | 597.93 | 3.44 | 207.00 |
| *J, J, A* | *298.00* | *286.17* | *71.67* | *6.27* | *620.73* | *3.37* | *212.33* |

[1] the values in italic have been selected for the calculations, based on the highest temperature in the summer and the lowest in winter. DBT max. mean: average dry bulb temperature of the maximum; DBT min. mean: average dry bulb temperature of the minimum; RH: Relative humidity.
**Source:** CEPAGRI (2013).

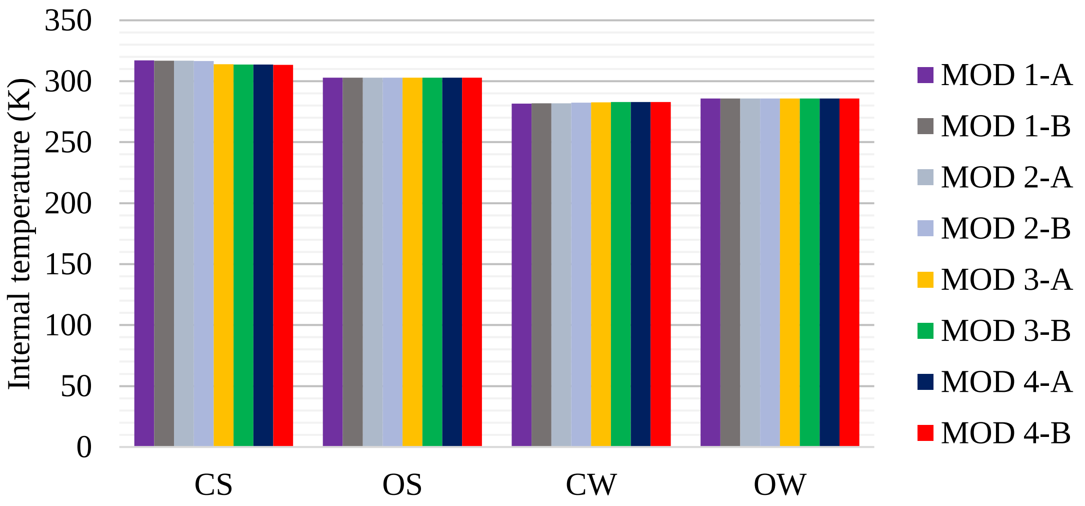
## 3 RESULTS AND DISCUSSION

### 3.1 Environmental conditions of pitched roof greenhouses

The increase in volume due to the greater height of the pitched roof greenhouse produces the effects on environmental comfort determined from the energy balance solving the Equations (1) to (11), that are shown in Figure 3.

The internal temperature values compared between the models were very close, especially those belonging to the same h/s ratio and because of the boundary conditions and models with single span are the same.

**Figure 3**. Internal temperatures resulting from the energy balance of pitched roof greenhouses




CS: closed construction in summer; OS: open construction in summer; CW: closed construction in winter; OW: open construction in winter.

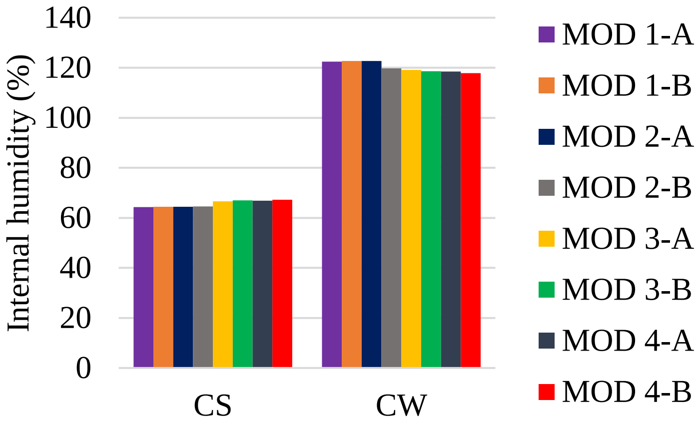
The benefits resulting from the increase of greenhouse volume are evidenced by the decrease of the temperature up to 4 K, because of the increase in the h/s ratios of 0.3 to 0.6, in the condition of closed construction in summer (CS). For the closed construction in winter condition (CW), greenhouses with larger volumes were more efficient in the retention of heat under colder conditions, resulting in a difference of 1 K, with the increased h/s ratio of 0.3 to 0.6.

As the boundary conditions for the models were the same, and the dimensions of the models were not proportional, in the energy balance for the conditions of open construction in summer (OS) and winter (OW), the internal temperature values were similar for all simulations, resulting in temperatures of 303.15 K and 285.95 K, in summer and winter, respectively.

The highest internal temperature was obtained in MOD 1-A with CS condition, with a value of 317.25 K, equivalent to 14.16 K above the external temperature.

By mass and energy balances, the increase in the h/s ratio (from 0.3 to 0.6) for the models analyzed by Equation (12), i.e., model 1 to model 3 and model 2 to model 4, resulted in significant differences of the order of 3% in the gain in the internal humidity, both for the simulation in the closed summer condition and for the closed winter condition, according to Figure 4.

**Figure 4**. Internal humidity resulting from the mass balance for pitched roof greenhouses




CS: closed construction in summer; CW: closed construction in winter.

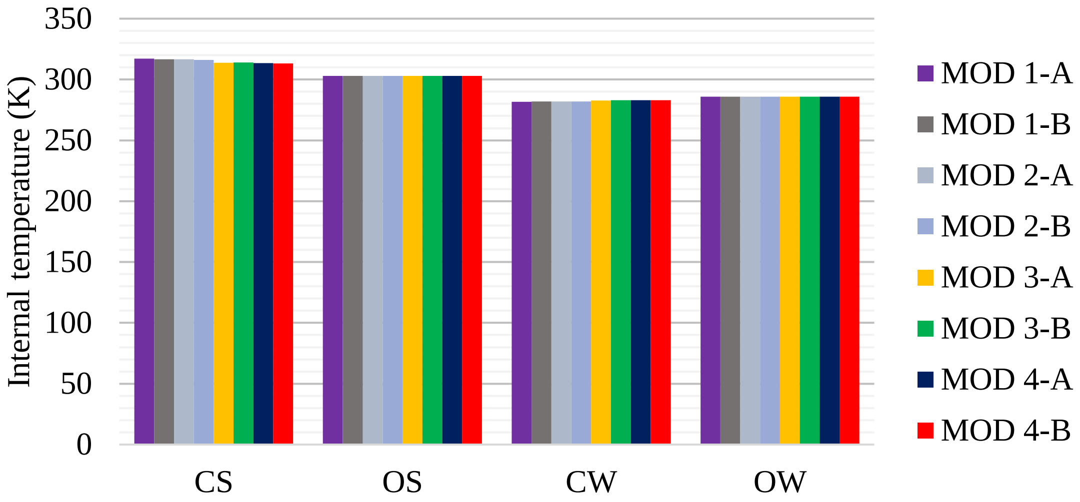
In the hypothesis of the determination of internal humidity in the open greenhouse conditions, due to the boundary conditions, the values would be the same or similar, mainly because the method employed used as reference the mass flow due to the evapotranspiration of the cultures. Therefore, this case was not verified.

The internal relative humidity values above 100% are consistent with the supersaturation condition, in which the external saturation pressure is greater than the internal saturation pressure. This case of supersaturation is undesirable for cultivation, because this is one of the phenomena responsible for the condensation of water vapor inside greenhouses.

### 3.2 Environmental conditions of arched roof greenhouses

The analysis of energy balance to determine the internal temperatures (Figure 5) of the arched roof greenhouses were performed by solving the Equations (01) to (11) and produced results similar to those obtained for pitched roof greenhouses.

**Figure 5.** Internal temperatures resulting from the energy balance of arched roof greenhouses




CS: closed construction in summer; OS: open construction in summer; CW: closed construction in winter; OW: open construction in winter.

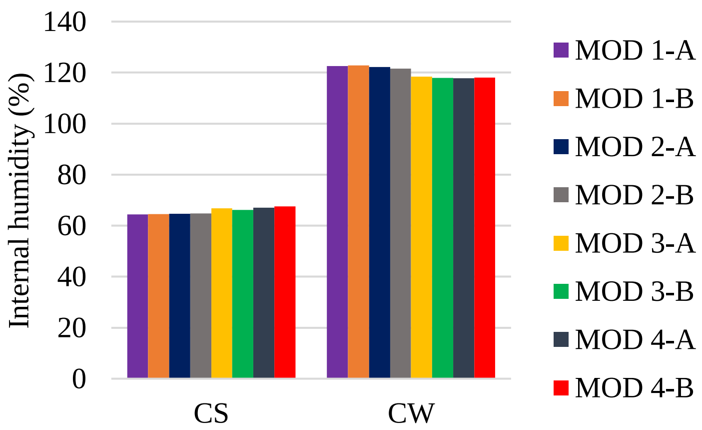
For the closed summer condition, the highest temperature gradient resulted from the increase in the h/s ratio (0.3 to 0.6) and, this variation caused a temperature decrease of 3 K.

The higher heat retention capacity of the larger greenhouses, in the closed winter condition, took place with a temperature gradient of 1 K on average. This result is desired in a cold situation and significant for some crops that are sensitive to changes in temperatures.

The highest internal temperature was obtained in MOD 1-A with CS condition, with a value of 317.05 K, equivalent to 10.98 K above the external temperature.

The results of the mass balance calculated by Equation (12) and shown in Figure 6 were similar to those of pitched roof greenhouses under the same conditions, and we highlight that the increase in the h/s ratio, ranging from 0.3 to 0.6, produced an upward variation of 3% on average in internal humidity in the summer. In winter, this same increase in the h/s ratio caused a decrease in the internal humidity content, also of the order of 3%.

**Figure 6.** Internal humidity resulting from the mass balance for arched roof greenhouses




CS: closed construction in summer; CW: closed construction in winter.

In the arched roof models, in four situations the humidity was above 100%, whereas for the pitched roof model we observed this condition in three situations. The condensation in greenhouses covered by plastic film can change the energy balance coefficients, since the latent heat is released and the heat increases inside them, according to the radiation indexes (VON ELSNER et al., 2000b).

### 3.3 Comparative analysis between pitched roof and arched roof models

Given the variations of the shape parameters defined for the two models of greenhouses addressed by NBR 16032 (ABNT, 2012), Table 5 presents the results of the comfort simulations of a comparative analysis for both models. In the case of simulations with variations of the slope of the roof, despite the differences found in the volumes of the models, we conclude that the thermal comfort conditions are similar. This result can be attributed, mainly, to the fact that this study considered models with the same dimensional characteristics and single span.

**Table 5**. Synthesis of the results of the simulations for pitched roof and arched roof greenhouses.

| Simulated condition | Pitched roof | Arched roof |
|---|---|---|
| Increasing the roof slope from 20° to 26° with h/s ratio = 0.3 | - Increase of 7.5% in volume; - Variation in energy balance with temperature difference below 1 K; - Non-significant variation in mass balance. | - Increase of 10% in volume. - Variation in energy balance with temperature difference below 1 K; - Non-significant variation in mass balance. |
| Increasing the roof slope from 20° to 26° with h/s ratio = 0.6 | - Increase of 4.3% in volume; - Non-significant variation in energy and mass balance. | - Increase of 6% in volume; - Non-significant variation in energy and mass balance. |
| Increasing the h/s ratio from 0.3 to 0.6 with slope of the roof equal to 20° or 26° | - Increase of 40% in volume; - Significant reduction of internal temperature in the summer up to 4 K and retention of heat in winter up to 1 K; - Increase of indoor humidity in the summer around 3%; - Reduction of internal humidity in the winter around 3%. | - Increase of 40% in volume; - Significant reduction of internal temperature in the summer up to 4.4 K and retention of heat in the winter up to 1.1 K; - Increase of indoor humidity in the summer around 3%; - Reduction of internal humidity the in winter around 3%. |

In the case of the simulations varying in h/s ratio, the higher reduction in internal temperature in summer was observed for the arched roof model, in relation to the pitched roof model, whose difference was equal to 0.4 K. Also, regarding the variation of internal temperature and humidity, these parameters are more sensitive with the variation of the h/s ratio than with the variation of the roof slope.

The microclimatic changes inside agricultural greenhouses tend to present behavior according to the results obtained in this research, i.e., higher temperatures inside the greenhouse in conditions of high external temperatures and lower internal temperatures in conditions of lower external temperatures (ZHOU et al., 2017).

Finally, the volumes of the arched models were the largest in all the situations in which the roof slope was varied, which is due to the projection of the arched roof in relation to the pitched roof. Concerning the commercial production scale, this result is representative in terms of ambience, because the temperature values resulted in lower values for summer conditions, a condition that is desired in tropical countries.

## 4 CONCLUSIONS

For the models of pitched roof and arched roof greenhouses, in respect to the form parameters evaluated, we verified that the variation of the h and s ratio can produce the most significant effects for the environment comfort.

The benefits obtained by increasing the h/s ratio from 0.3 to 0.6 are quantified by reducing the temperature by up to 4 K for pitched roof greenhouses and 4.4 K for arched roof greenhouses (CS condition) and, by retention of 1 and 1.1 K for the models in pitched and in arched roof models, respectively, (condition of CW).

For both conditions, CS and CW, internal humidity gain was obtained up to 3%. However, the shape of the arched roof, due to the increased volume provided, presented the best environmental conditions for most models, with lower temperature up to 0.4 K in summer and higher temperature up to 0.1 K in winter. These observed situations favour efficiency in vegetable cultivation in countries with tropical climatic characteristics.

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