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*Article*

# Development and Application of a Crossed Multi-Arch Greenhouse in Tropical China

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**Abstract:** Deep analysis and demonstration of the developed crossed multi-arch greenhouse were conducted from the perspectives of conceptual design, architectural and structural design, functional design, loading parameters, and structural internal forces. The results show that the crossed multi-arch greenhouse combines the ventilation area between the floor-standing round-arch greenhouse and the unsuitable operation area under the arch bars into one to form a multi-span crossed arch structure with good ventilation and heat dissipation, land savings, and fine mechanical behaviors. The main arch structure uses 32.4% less steel and 25% less foundation volume than the control greenhouse under the same load, which can save about CNY 10,184.00/667m$^2$ of investment according to the current cost level. In the meantime, ventilation simulation analysis of the developed crossed multi-arch greenhouse was carried out using the software Design Builder. A comparison shows that, under the condition of no wind and breeze (1 m/s) in summer, the setting of the ventilation channel has obvious advantages for the heat dissipation of the greenhouse, and the average temperature is about 2 °C lower than that of the greenhouse without a ventilation channel; under the breeze condition, the temperature in the crossed multi-arch greenhouse is more evenly distributed than that of an ordinary round-arch greenhouse with ventilation channels. Considering the greenhouse function, building cost, using effect, and other evaluation factors, the crossed multi-arch greenhouse can meet the production environment requirements of tropical coastal areas (rain protection, sunshade, and ventilation), with obvious structural advantages, good typhoon resistance, and low construction costs, which is a preferable choice of greenhouse type.

**Keywords:** vegetable greenhouses; multi-arch greenhouses; arch cross type; resistance to the typhoon



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## 1. Introduction

Tropical areas have frequent typhoons and rainstorms with high temperatures, high humidity, and long durations of heat. The summer and autumn seasons are not suitable for open-air planting, but greenhouse facilities can provide a rain-proof, protected cultivation environment for crops, which becomes the main production method for summer and autumn off-season production in tropical areas [1,2]. The round plastic arch greenhouse has a simple structure, low cost, and wide application in China, which is one of the main greenhouse structures applied in the Hainan region. Ventilation and rain are the main considerations for Hainan greenhouses. However, due to the roll film window setting, round plastic arch greenhouses cannot be closed in time when a sudden rainfall occurs, and the crops inside the greenhouse can be damaged as a result [3]; conversely, a closed roof causes poor ventilation and heat accumulation problems, and many greenhouses in Hainan have been abandoned due to this reason, resulting in the adverse social impact of field desolation. Moreover, many greenhouses could be blown down, as they are not strong enough to resist typhoon weather, causing large amounts of property losses [4–9]. Therefore, greenhouse facilities in the tropics require special attention to rain, ventilation, and typhoon resistance. However, the dilemma in the process of solving these problems is that a better wind resistance requires a higher cost of the greenhouse, making it hard to recover the investment cost, whereas simple, lower-cost greenhouses do not have the ability to resist strong wind. Some greenhouses even have to sacrifice their functions of protecting the crops (such as not being rain-proof, no shade, poor ventilation, etc.) to reduce the building cost.

Driven by this market demand, the crossed multi-arch greenhouse was developed. This greenhouse type can fully absorb the advantages of various greenhouse structures, with function as the major consideration, i.e., suitable for local climate conditions [10] and meeting the requirements of storm prevention, ventilation, cooling, shading, and other functions, while developing reasonable structural forms, improving the wind resistance of the structure, and using less steel for the main structure, thus reducing the building cost without sacrificing function.

## 2. Development Idea

### *2.1. Evolution of the Round Arc Greenhouse Structure*

The arch bar of the floor-type round-arch greenhouse structure (Figure 1a) has a good mechanical performance and an easy-to-install structure [11]. However, there are also problems such as the difficulties in using and operating the area below shoulder height in the greenhouse or between greenhouses. Thus, an upright side wall type single arch greenhouse structure (Figure 1b) was developed during real production. This structure solves the problem of shoulder space use. To further improve the land use and make full use of structural materials, a multi-span round-arch greenhouse structure (Figure 1c) was developed [12–15]. This structure is spacious and has a high land use rate, which is being gradually developed into a major structural form of the current multi-span plastic greenhouse [16].

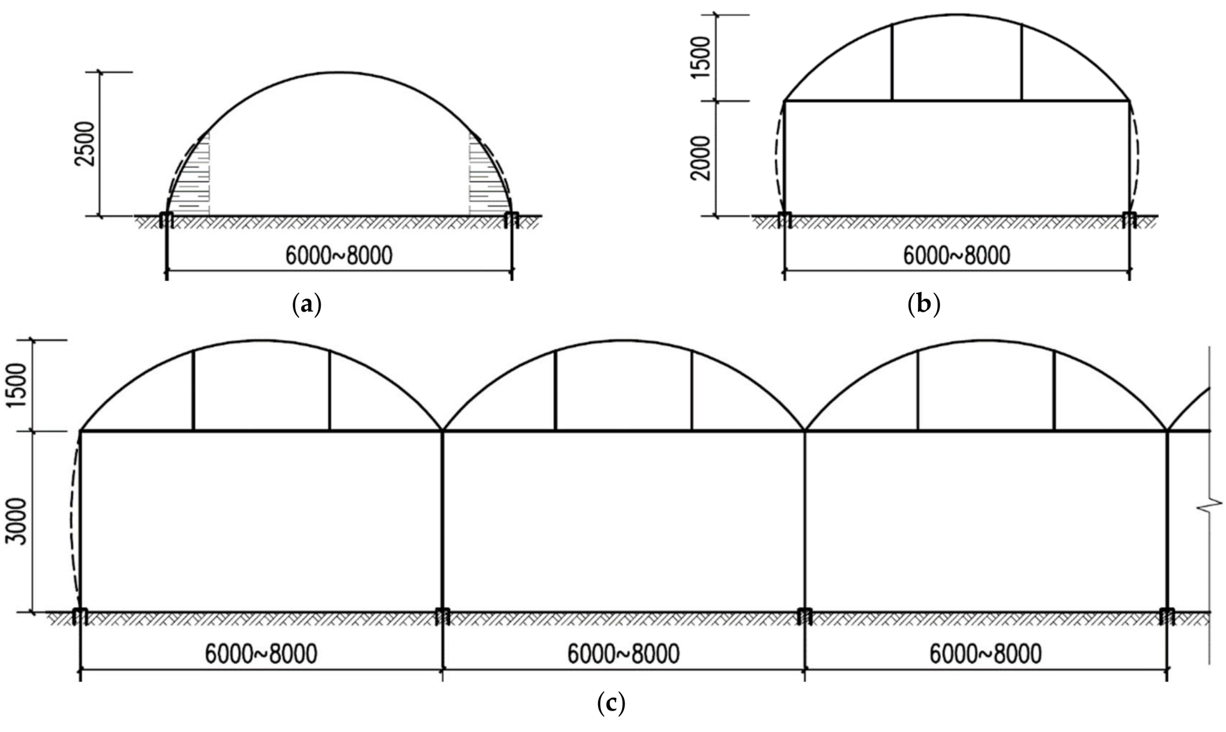



**Figure 1.** Evolution of the round-arch greenhouse structure (unit: mm). (**a**) Floor-type round-arch greenhouse structure; (**b**) Upright side wall type single arch greenhouse structure; (**c**) Multi-span round-arch greenhouse structure.

When the multi-span round arch plastic greenhouse is used in tropical areas such as Hainan, it has ventilation and rain protection problems. For example, when a sudden rainstorm occurs in summer and autumn, the roll film ventilation mechanism at the top of the greenhouse cannot be closed quickly, and the crops inside the greenhouse can thus be damaged by a rainstorm. Many users stopped using the roll film ventilation mechanism and covered the roof with roll film to ensure the rainproof performance of the greenhouse, the ventilation instead being solved by setting ventilation channels between the arches; thus, a multi-arch split structure model was formed [17]. This structure was first used in Sanya, Dongfang, Ledong, and other places in Hainan for cantaloupe greenhouses, and it quickly became the mainstream cantaloupe greenhouse type (Figure 2a) due to its simple structure (no need to consider the typhoon load; the column can be directly inserted into the ground without setting the foundation) and low cost because it is only used in winter and spring (no typhoon and fewer rainstorms). Inspired by this, structural designers made some improvements (Figure 2b) to the multi-arch split structure and used it for summer and autumn vegetable cultivation in Hainan. After years of practice, the structure has achieved good results. As it is mainly used for off-season production in summer and autumn, it is necessary to consider the resistance against typhoons. An independent foundation needs to be set up at the column, larger and stronger materials should be used, and the cost should be at least twice that of cantaloupe greenhouses.

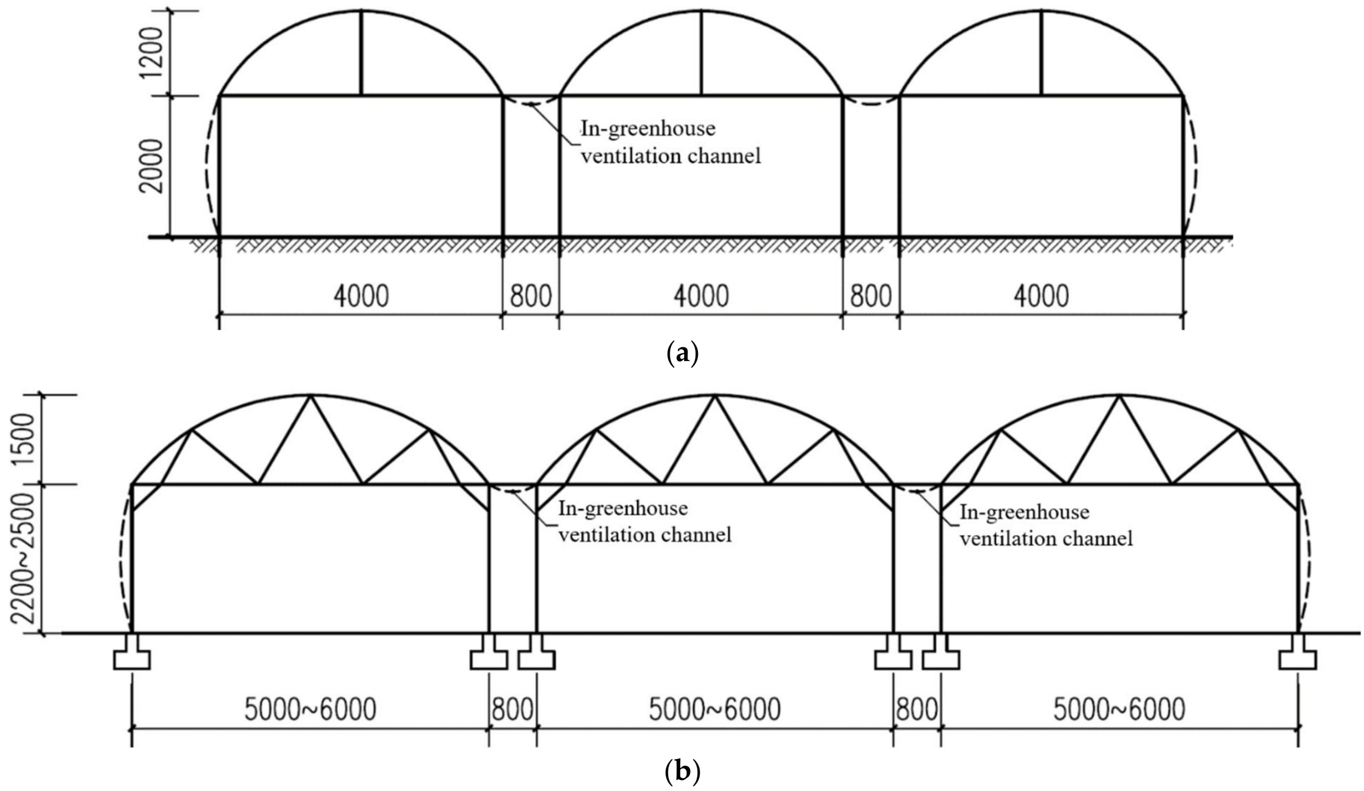



**Figure 2.** Multi-span round arch plastic greenhouse with an in-greenhouse ventilation channel (unit: mm). (**a**) Structure of the cantaloupe greenhouse; (**b**) Structure of the Hainan year-round vegetable production greenhouse.

*2.2. Structural Concept Design*

The arch bar of the floor-type round-arch greenhouse (Figure 3a) is directly connected to the foundation. The overall structure is a round arch that is evenly stressed with good stability. However, there is a large vacant space at the in-greenhouse ventilation channel and the inoperable area below the shoulder arc, which is a waste of land. A multi-span greenhouse structure (with a ventilation channel) (Figure 3b) has turned the arch bar below the shoulder into a vertical column and saved the in-greenhouse ventilation channel, which has a relatively good heat dissipation performance and a higher amount of available land to use. However, this structure has also changed its stress form and requires more column materials, which is not economical. Thus, is it possible to have a structure that retains the good stress resistance of a round arch as well as the function of the in-greenhouse ventilation channel whilst achieving a high amount of available land? After considerable analyses and calculations, and by combining the advantages of floor-type single-arch greenhouses and multi-span greenhouses (with a ventilation channel), this paper developed a crossed multi-arch greenhouse (Figure 3c; multi-arch greenhouse for short). The multi-arch greenhouse not only has the stress advantage of being a floor-type round-arch greenhouse but also retains the heat dissipation advantage of the in-greenhouse ventilation channel. Meanwhile, the stressed arches form a truss structure, which has better stress performance than a floor-type single greenhouse.

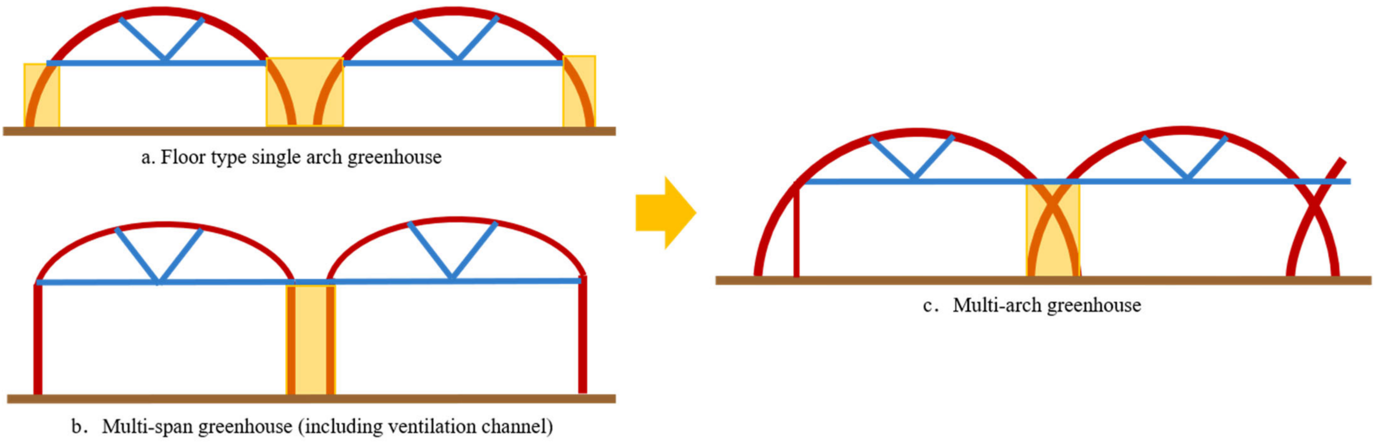



**Figure 3.** Development idea of a crossed multi-arch greenhouse.

### *2.3. Architectural and Structural Design*

The scale of the structure is mainly based on the convenience of farming management and construction. The minimum height of the internal space of the greenhouse is 2.2 m, the span is 6m, and the width of the in-greenhouse ventilation channel is 0.8 m. The crossed arch land part is located in the ventilation channel, so the farming operation is not affected. An open space of 6 m × 2.2 m is formed inside each span, which can meet the operation of small- and medium-sized machinery. The size of the opening direction can be 2~4 m according to the actual load, although 3 m is recommended for the machinery to pass through.

In terms of the arrangement of structural components, the arches are crossed to form a multi-arch structure in the span direction, and the tie beam and reinforcement bar are set between the greenhouses. Compared with an independent arch structure, the crossed arch structure is evenly stressed, and the horizontal wind load on either side can be evenly dispersed to each span of the arch bar, which is more conducive to improving the overall stability of the structure. At the same time, the crossed arches, together with the tie beams and supports, form a geometrically invariant system (as shown in Figure 4), greatly improving the wind resistance of the greenhouse structure.

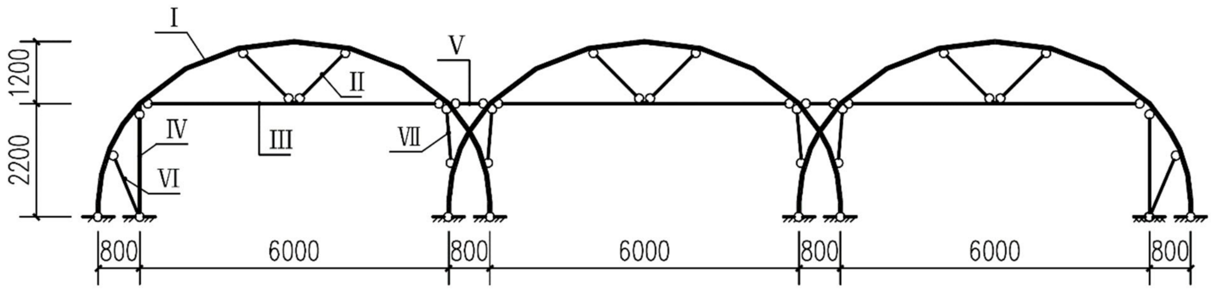



**Figure 4.** Systematic diagram of the multi-arch greenhouse structure (unit: mm). Notes: I—arch bar, II—web member, III—tie beam, IV—side wind-resisting column, V—in-greenhouse beam, VI—side reinforcement bar (adopted at a high wing load), VII—reinforcement bar; the icon of "o" is the hinged point or hinged support.

*2.4. Functional Design*

Summer and autumn vegetable greenhouse facilities in the tropical area of Hainan need to overcome some unfavorable meteorological factors such as high summer temperatures and frequent typhoons and rainstorms in order to meet the basic production conditions of ventilation, rain protection, pest control, and suitability for cultivation. Large-scale production applications should also achieve low building costs, less operating energy consumption, land saving, etc.

The top of the developed multi-arch greenhouse is covered with roof film (the thickness of the film is determined according to the actual loading conditions), and the vents between the arches and the surrounding vents are covered with an insect-proof screen. The inner curtain is installed at the internal shoulder-height beams. The entrance and exit are located at the hill wall, with a net width of no less than 2 m, which can meet the needs of small- and medium-sized farm machinery. The above basic dimensions and practices can achieve the basic functions of rain protection, ventilation, insect protection, internal shading, and suitability for cultivation (Figure 5). The multi-arch structure has combined the vacant area below the shoulder of the single-arch greenhouse (operating height restriction) and the ventilation and drainage space between the greenhouses to form a 0.8 m-wide ventilation belt. This belt also has the function of drainage, which improves the land use rate compared with a single-arch greenhouse. Only the top of the planting area of the greenhouse is covered with impermeable plastic film for rain protection; the surrounding and ventilation channels are covered with an insect-proof screen, allowing wind to blow from any direction. In addition, the height of the vent was increased from 1.6 m to 2.2 m, which has reduced the space for heat storage. During the growing stage, no extra energy is required for environmental control because the natural ventilation can remove excess heat from the greenhouse, thus realizing a low-energy-consumption operation.

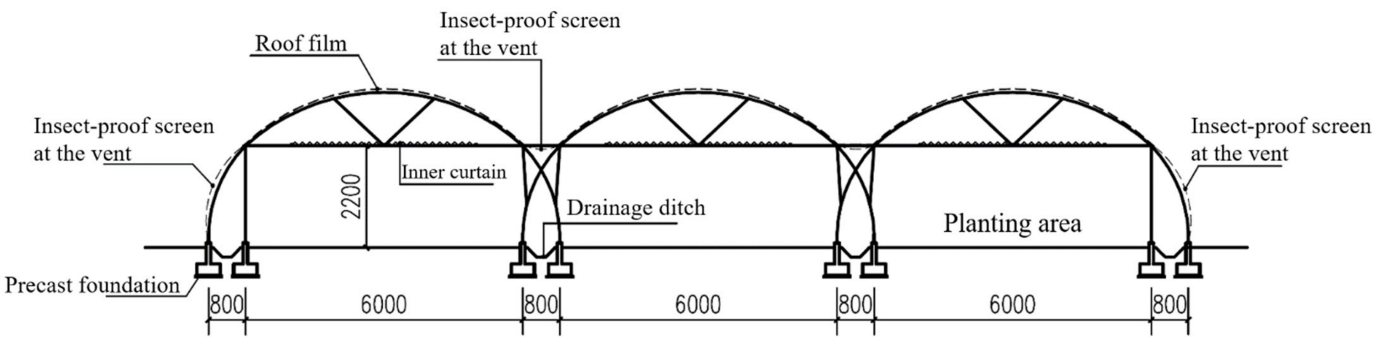



**Figure 5.** Diagrammatic cross-section of the multi-arch greenhouse structure (unit: mm).

Through continuous development and improvement, the structure of the crossed multi-arch greenhouse (Figure 6) has been improved, and relevant achievements have been made [18]. It is already used for vegetable cultivation in Hainan (Figure 7). This type of greenhouse is suitable for year-round vegetable cultivation in typhoon-resistant areas along the tropical coast, and by increasing the proportion of plastic film coverage and decreasing the proportion of insect-proof screen coverage or adding a film-rolling device, it can also be applied in winter production without heating in areas such as middle and low latitudes, especially in provinces with typhoons such as eastern China, where the advantages of their application are obvious.

**Figure 6.** Design sketch of a multi-arch greenhouse.

**Figure 7.** Production application example diagram of a multi-arch greenhouse.

## 3. Structural Calculation and Material Specifications

With the structural composition determined, different load parameters were selected for different regions and different design wind resistance classes to calculate the components that can meet the design load requirements [13]. This paper takes Haikou as an example. The structural calculation was conducted according to the parameters specified in GB/T 51183-2016 Structural Load Practice for Agricultural Greenhouses. The design life is 10 years.

### 3.1. Load Parameters

1. The permanent load, taking the self-weight of the frame, is 0.025 kN/m$^2$. For light steel greenhouses with wind resistance requirements, the self-weights of the structure and the equipment are both favorable loads, and only the self-weight of the frame structure is taken into account during the calculation;
2. The variable load, including the wind load and other variable loads. Multi-arch greenhouses are developed for year-round vegetable production in Hainan, which takes leafy vegetables as the production object, without considering the lifting weight of the crop.
   (1) Other variable loads: 0.15 kN/m$^2$;
   (2) Wind load: basic wind load (W0), 0.79 kN/m$^2$.

### 3.2. Calculation of the Load Standard Value and Design Value

The most unfavorable combination is constant load + wind load. Wind load is the dominant load, which can be calculated by the formula for the variable load control effect design value of $S_d$: $S_d = \gamma_G S_{Gk} + \gamma_{Q1} S_{Q1k} + \sum_{i=2}^{n} \gamma_{Qi} \psi_{ci} S_{Qik}$ [19], where $S_{Gk}$ is the constant load standard value, $S_{Q1k}$ is the wind load standard value, and $S_{Qik}$ is the live load standard value ($n$ = 2); take the constant load partial coefficient $\gamma_G$ as 1, the wind load partial coefficient $\gamma_{Q1}$ as 1, the live load partial coefficient $\gamma_{Qi}$ as 1.2, the combined value coefficient of live load $\psi_{ci}$ as 0.7, and the structural importance coefficient $\gamma_0$ as 0.9; the ground roughness is Category B, the height of the greenhouse is 3.4 m, and the wind pressure height variation coefficient $\mu_z$ is taken as 0.76 (the ground roughness is Category B); calculate with the open structure, and the wind load shape factor $\mu_s$ acting on the roof is taken as $-0.75$ [20]. The bay (opening) $L$ is 4.0 m.

Constant load standard value $S_{Gk}$ = 0.025 kN/m$^2$, wind load standard value $S_{Q1k} = W_0 \mu_Z \mu_S = 0.79 \times 0.76 \times (-0.75) = -0.4503$ kN/m$^2$, live load standard value $S_{Qik}$ = 0.15 kN/m$^2$.

The design values for each load acting on the arch are calculated as follows:

(1) Constant load design value: $\gamma_0 \gamma_G S_{Gk} L = 0.9 \times 1 \times 0.025 \times 4 = 0.09$ kN/m;
(2) Wind load design value: $\gamma_0 \gamma_{Q1} S_{Q1K} L = 0.9 \times 1 \times (-0.4503) \times 4 = -1.6211$ kN/m;
(3) Live load design value: $\gamma_0 \gamma_{Qi} \psi_{ci} S_{Qik} L = 0.9 \times 1.2 \times 0.7 \times 0.15 \times 4 = 0.4536$ kN/m.

The wind load at the insect-proof screen should also be multiplied by the wind resistance factor for the wind load. Take 0.75 for the wind resistance factor of a 32-mesh insect-proof screen and 0.81 for a 40-mesh insect-proof screen [21].

### 3.3. Structural Calculation

Arch frame part: Arch bar: φ42 × 1.5 mm; web member: φ25 × 1.5 mm; tie beam: φ42 × 1.5 mm; side wind-resisting column: φ42 × 1.5 mm; in-greenhouse beam: φ25 × 1.5 mm; reinforcement bar: φ25 × 1.5 mm. The bars are connected with U-bolts and clamps, bolts, and cross springs, and all steel pipes and connections are treated by hot dip galvanization.

Components other than the arch frame include the roof longitudinal tie bar, the tie bar on the internal horizontal pull bar, inter-column supports, greenhouse head (octagonal) horizontal supports, greenhouse head roof supports, the secondary arch bar, the gable auxiliary column, etc. The specifications of the components are: roof longitudinal tie bar: φ42 × 1.5 mm; tie bar on internal horizontal pull bar: φ32 × 1.5 mm; inter-column support: φ42 × 1.5 mm; greenhouse head (octagonal) horizontal support: φ32 × 1.5 mm; greenhouse head roof support: φ25 × 1.5 mm; secondary arch bar: φ32 × 1.5 mm; gable auxiliary column: φ32 × 1.5 mm.

PKPM (2010 edition) was used for the structural calculation. The stress ratios are shown in Figure 8, and the arch bars were hinged to the foundation. The calculation results show that the selected components were all qualified in specifications (the stress ratios were all below 0.8). It can be seen from the graphical results that the internal force is distributed evenly inside the components. The multi-arch form makes each component form a space system, and the whole arch presents a truss structure with an excellent stress performance. The connection between the column and the foundation is fixed at the hinge support, and in this paper, for example, the connection point is at a typical location (the second one on the left) for basic analysis and calculation. According to the calculation, the basic reaction force (standard combination) corresponding to the maximum foundation base area when the above connection point is under the effect of load is: M = 0 kN.m, N = −5.9 kN, V = 0.62 kN, and the calculated foundation base size required is 0.6 m × 0.6 m, with a burial depth of 0.7 m.

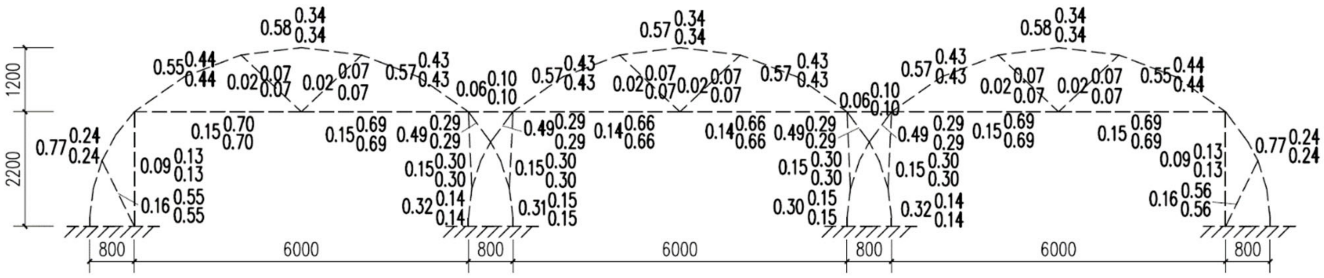



**Figure 8.** Stress ratios of structural calculation (unit: mm). Notes: The number on the left of each component is the strength stress ratio, that on the upper right is the in-plane stability stress ratio, and that on the lower right is the out-of-plane stability stress ratio.

## 3.4. Comparison of Structural Properties

In order to compare the structural properties between the multi-arch greenhouse and the multi-span round-arch greenhouse (with a ventilation channel), structural calculations of the multi-span round-arch greenhouse (with a ventilation channel) were conducted based on the load values of the previously mentioned multi-arch greenhouse. The column is rigidly connected to the foundation, and the stress ratios are shown in Figure 9. The results of the calculations show that the specifications of the selected components were all qualified (most of the stress ratios were under 0.8, and the stress ratio of the side column was under 0.9). The connection between the column and the foundation is fixed at the hinge support, and in this paper, for example, the connection point is at a typical location (the second one on the left) for basic analysis and calculation. According to the calculation, the basic reaction force (standard combination) corresponding to the maximum foundation base area when the above connection point is under the effect of load is: M = −2.35 kN.m, N = 1.52 kN, V = −2.34 kN, and the calculated foundation base size required is 0.8 m × 0.8 m, with a burial depth of 0.7 m.

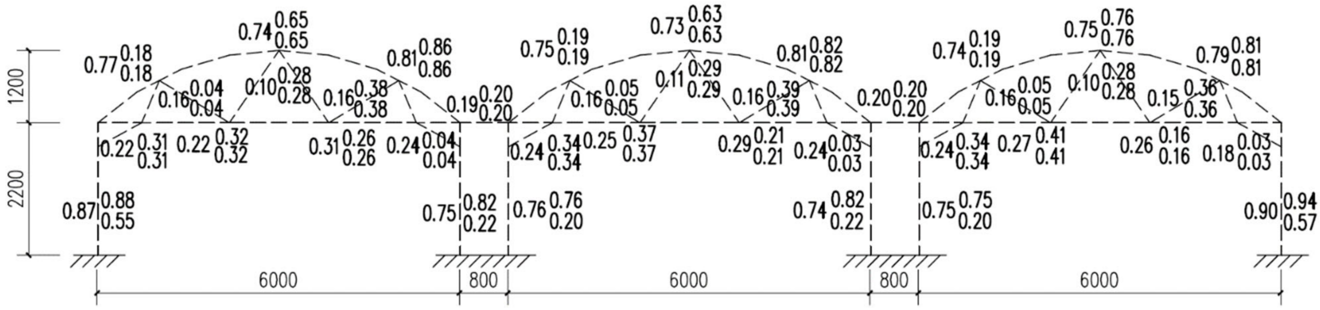



**Figure 9.** Stress ratios of structural calculation (unit: mm). Notes: the number on the left of each component is the strength stress ratio, that on the upper right is the in-plane stability stress ratio, and that on the lower right is the out-of-plane stability stress ratio.

Specifications of the main components: column: □80 × 60 × 2 mm; arc bar: φ50 × 1.5 mm; web member: φ25 × 1.5 mm; tie beam: φ42 × 1.5 mm; in-greenhouse beam: φ25 × 1.5 mm. The bars are connected with U-bolts and clamps, bolts, and cross springs, and all steel pipes and connections are treated by hot dip galvanization.

The materials of the multi-arch greenhouse and the multi-span round-arch greenhouse (with a ventilation channel) were calculated (Tables 1 and 2). The results show that the consumption of the steel pipe material for the main steel frame of the multi-arch greenhouse is 96.94 kg, while the steel pipe material consumption of the multi-span round-arch greenhouse (with a ventilation channel) is 143.45 kg, which is 46.51 kg higher than that of the multi-arch greenhouse; hence, the multi-arch greenhouse can save about 32.4% of the consumption of steel pipe materials. When calculated with a coverage area of 3 × 6 × 4 = 72 $m^2$, 0.646 kg of material per unit area is saved; when calculated using the greenhouse steel structure processing and the installation completed price of CNY 12.80/kg, CNY 8.27 per square meter is saved (CNY 5515/667 $m^2$).

**Table 1.** Components of the multi-arch greenhouse.

| No. | Item | Specification | Length (m) | Quantity | Unit Weight (kg) | Total Weights (kg) |
|---|---|---|---|---|---|---|
| 1 | Arch bar | φ42 × 1.5 mm | 11.2 | 3 | 16.78 | 50.33 |
| 2 | Web member | φ25 × 1.5 mm | 1.5 | 6 | 1.30 | 7.82 |
| 3 | Tie beam | φ42 × 1.5 mm | 6 | 3 | 8.99 | 26.96 |
| 4 | Side wind-resisting column | φ42 × 1.5 mm | 2.1 | 2 | 1.82 | 3.65 |
| 5 | In-greenhouse beam | φ25 × 1.5 mm | 0.8 | 2 | 0.70 | 1.39 |
| 6 | Side reinforcement bar | φ25 × 1.5 mm | 1.3 | 2 | 1.13 | 2.26 |
| 7 | Reinforcement bar | φ25 × 1.5 mm | 1.3 | 4 | 1.13 | 4.52 |
| 8 | | | Total | | | 96.94 |

**Table 2.** Components of the multi-span round-arch greenhouse (with a ventilation channel).

| No. | Item | Specification | Length (m) | Quantity | Unit Weight (kg) | Total Weights (kg) |
|---|---|---|---|---|---|---|
| 1 | Column | □80 × 60 × 2 mm | 2.2 | 6 | 9.39 | 56.36 |
| 2 | Arch bar | φ50 × 1.5 mm | 6.62 | 3 | 11.88 | 35.63 |
| 3 | Web member | φ25 × 1.5 mm | 7.2 | 3 | 6.26 | 18.77 |
| 4 | Tie beam | φ42 × 1.5 mm | 6 | 3 | 8.99 | 26.96 |
| 5 | In-greenhouse beam | φ25 × 1.5 mm | 0.8 | 2 | 0.70 | 1.39 |
| 6 | Reinforcement bar | φ25 × 1.5 mm | 0.83 | 6 | 0.72 | 4.33 |
| 7 | | | Total | | | 143.45 |

Note: The above material table only presents the steel structure materials of the previously mentioned calculation model of a three-span main arch structure. The load of the structural calculation is the same.

The foundation area of the multi-arch greenhouse is 0.6 m × 0.6 m, with a burial depth of 0.7 m, and the foundation area of the multi-span round-arch greenhouse (with a ventilation channel) is 0.8 m × 0.8 m, with a burial depth of 0.7 m. According to the estimation of similar projects, the overall unit price of the foundation of the greenhouse is about CNY 750/$m^3$ (with excavation, backfill, concrete, formwork, etc.), the cost of the foundation of the multi-arch greenhouse structure (eight independent bases) is 0.6 × 0.6 × 0.7 × 8 × 750 = CNY 1512, and the cost of the foundation of the multi-span round-arch greenhouse structure (six independent bases, with a ventilation channel) is 0.8 × 0.8 × 0.7 × 6 × 750 = CNY 2016. When calculated using a foundation bearing area of 3 × 6 × 4 = 72$m^2$, the average investment of the multi-arch greenhouse foundation is 1512 ÷ 72 = CNY 21/$m^2$, and the average investment of the multi-span round-arch greenhouse foundation is 2016.00 ÷ 72 = CNY 28/$m^2$. The multi-arch greenhouse can save CNY 7/$m^2$ or CNY 4669/667$m^2$.

Therefore, a total amount of CNY 10,184/667$m^2$ can be saved in the main steel frame and foundation of a multi-arch greenhouse compared with a multi-span round-arch greenhouse (with a ventilation channel).

## 4. Ventilation Simulation

### *4.1. Greenhouse Modeling*

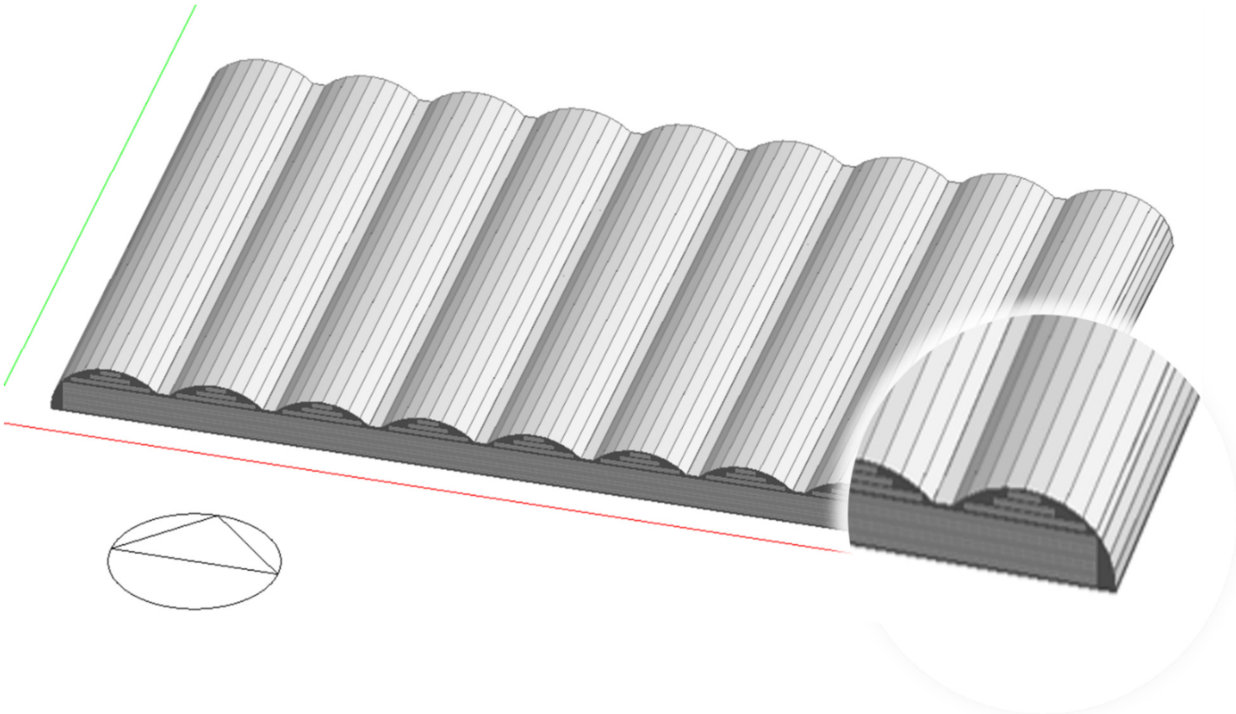
Natural ventilation is a simple and economical way of cooling. For open greenhouse structures in the tropics, the main purpose of ventilation is to remove excess heat and water vapor from the greenhouse to avoid high summer temperatures [22,23]. During the architectural and structural design phase of the greenhouse, the greenhouse vertical face is covered with an insect-proof screen to maximize the use of natural ventilation, but the roof is covered with plastic film for rain protection, which will inevitably cause heat accumulation, and the ventilation area of each greenhouse type and the distribution of ventilation areas have a direct effect on the cooling effect of natural ventilation. At the present stage, CFD simulations [24–30] were carried out using the software Design Builder to build a 3D model to test the spatial and temporal distribution of temperature in the greenhouse under given climatic conditions. The results were compared with the widely used multi-span round-arch greenhouses with and without ventilation channels in the industry.

Model parameter settings: the roofs of all three types of greenhouses were covered with 0.1 mm-thick transparent plastic film with 85% transmittance, and the heat transfer coefficient was 0.17 W/($m^2$.K); the vertical faces were all covered with a 0.2 mm-thick insect-proof screen, and the heat transfer coefficient was 203 W/($m^2$.K); the ground surface was covered with 13 cm-thick soil with a heat transfer coefficient of 3.188 W/($m^2$.K) (Handbook, 2007) which are shown in Figure 10.

Model a. Crossed multi-arch greenhouse: 6 m span, 0.8 m in-greenhouse ventilation channel (arch cross spacing), 4 m opening, single unit size 62 m × 36 m = 2232 $m^2$ (nine spans and nine openings), 3.4 m vector height, 2.2 m shoulder height.

Model b. Multi-span round-arch greenhouse with an in-greenhouse ventilation channel: the greenhouse models were all set to the same dimensions for the convenience of comparison, with a span of 6 m, an in-greenhouse ventilation channel of 0.8 m, an opening of 4 m, a single unit size of 60.4 × 36 m = 2174.4 $m^2$ (nine spans and nine openings), a vector height of 3.4 m, and a shoulder height of 2.2 m.

Model c. Multi-span round-arch greenhouse without an in-greenhouse ventilation channel: without the ventilation channel, the opening span height was the same as that of the above two models: span 6 m, opening 4 m, single unit size 54 × 36 m = 1944 $m^2$ (nine spans and nine openings), vector height 3.4 m, and shoulder height 2.2 m.



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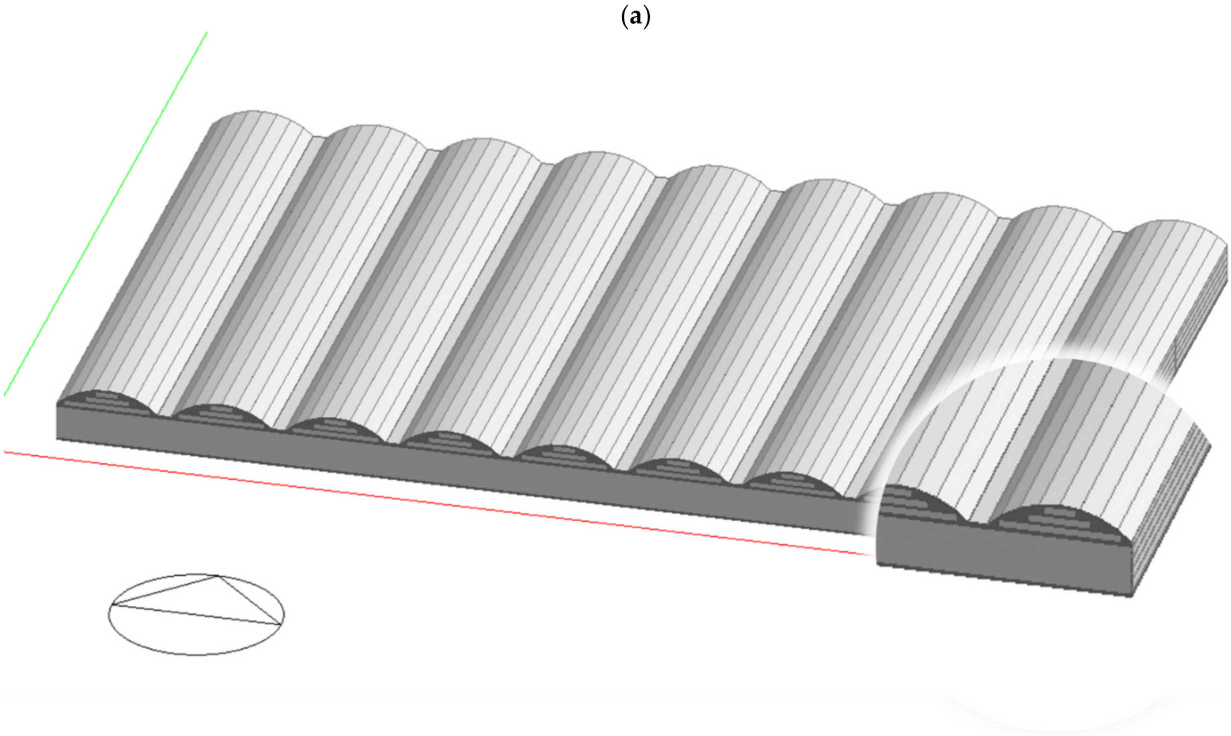
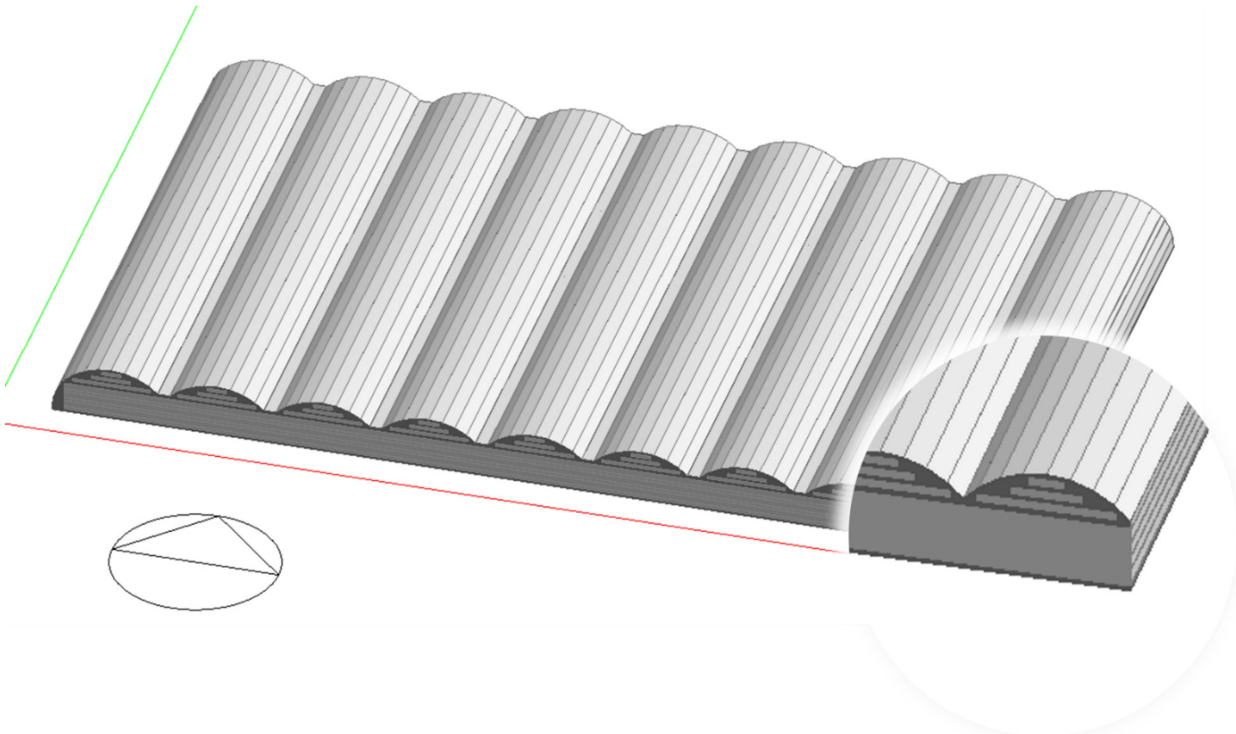


(**b**)

**Figure 10.** *Cont*.



(**c**)

**Figure 10.** Simulation models of three types of greenhouses. (**a**) Crossed multi-arch greenhouse; (**b**) Multi-span round-arch greenhouse with an in-greenhouse ventilation channel; (**c**) Multi-span round-arch greenhouse without an in-greenhouse ventilation channel.

*4.2. Simulation Environment Setting and Simulation Results Analysis*

This paper simulates the natural environment of a greenhouse in Haikou, Hainan (11°33′ E, 20°05′ N), and relevant environmental parameters were determined based on the natural environment. The greenhouse was oriented in a north–south direction (this type of open greenhouse can make full use of the wind coming from any direction, but there is no special requirement for the orientation of the greenhouse in practical production applications). The monsoon winds alternate in the Haikou area, with southeasterly winds prevailing in summer (May to October), which are formed by the northward expansion of warm tropical marine air masses, resulting in hot and humid summers, and northeasterly winds prevailing in winter (November to April), which are formed by the southward expansion of cold polar continental air masses, resulting in dry winters with little rain. The average wind speed in the Haikou area is 3.1 m/s throughout the year and 2.8 m/s in summer [31]. The purpose of the simulation is to analyze the cooling effect of the greenhouse model using thermal and wind pressure ventilation under the natural ventilation state. The wind speed, wind direction, solar radiation, outdoor air temperature, and surface temperature use the software's built-in time-by-time weather data, and the inlet air temperature is set as the outdoor air temperature. When judged by experience, the highest temperature in a day in the greenhouse often occurs around midday when solar radiation is at its maximum, and the earth is uniformly heated at midday, usually with no wind or low wind speed. For this reason, the simulation selected a wind speed of 0 m/s and 1 m/s (the wind direction is along the long axis of the greenhouse) on a certain day in summer as the most unfavorable conditions to compare the ventilation and cooling effect of each model, and the simulation environment parameters are set, as shown in Table 3.

**Table 3.** Parameter setting of the simulation environment.

| Location | Latitude and Longitude | Simulation Date | Outdoor Wind Speed (m/s) | Wind Direction (°) | Outdoor Temperature (°C) |
|---|---|---|---|---|---|
| Haikou, Hainan | East longitude 110°33′, Northern latitude 20°05′ | 8 July, 13:00 | 1 | 90 | 32.7 |
| | | 12 July, 15:00 | 0 | – | 35.0 |

Note: The 0° wind comes from due north, the 90° wind comes from due east, the 180° wind comes from due south, and the 270° wind comes from due west.

Figures 11–13 show the simulated temperature clouds inside the greenhouse at 15:00 on 12 July, when the wind speed was 0. The inlet temperature of the simulated environment was 35 °C. The cloud map takes the midline of each row of arch bars to make temperature slices. The slices are located 2 m away from the front and rear rows of the arch bars.

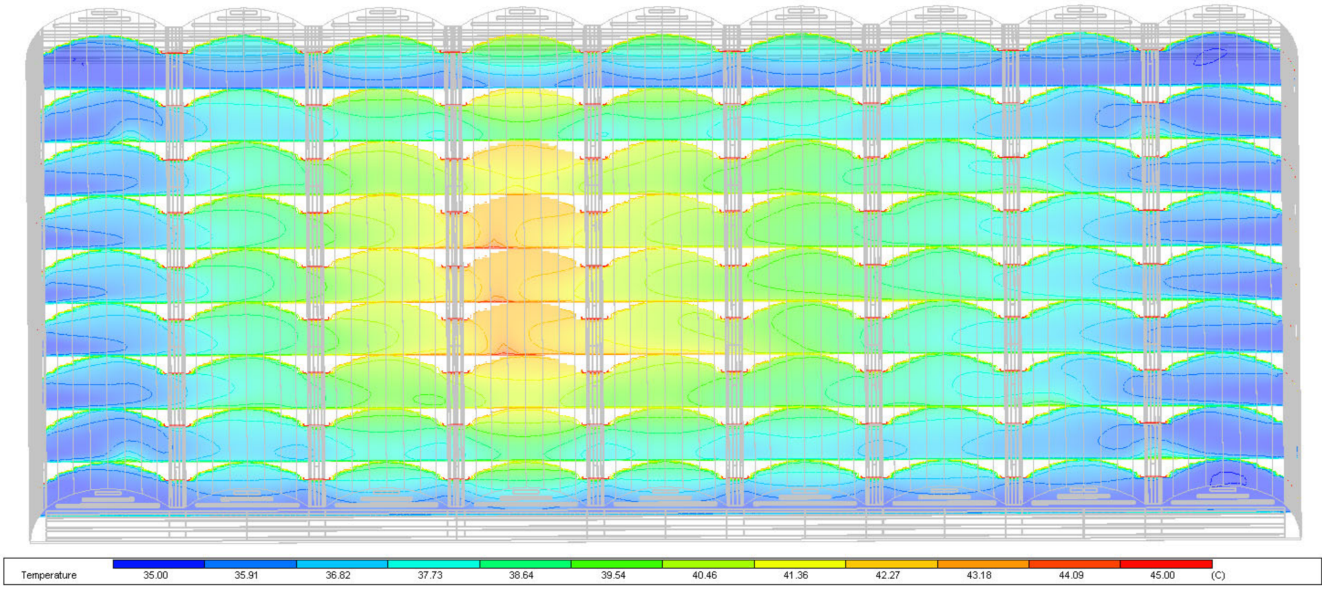



**Figure 11.** Temperature cloud map of the crossed multi-arch greenhouse (outdoor wind speed 0 m/s, outdoor temperature 35 °C).

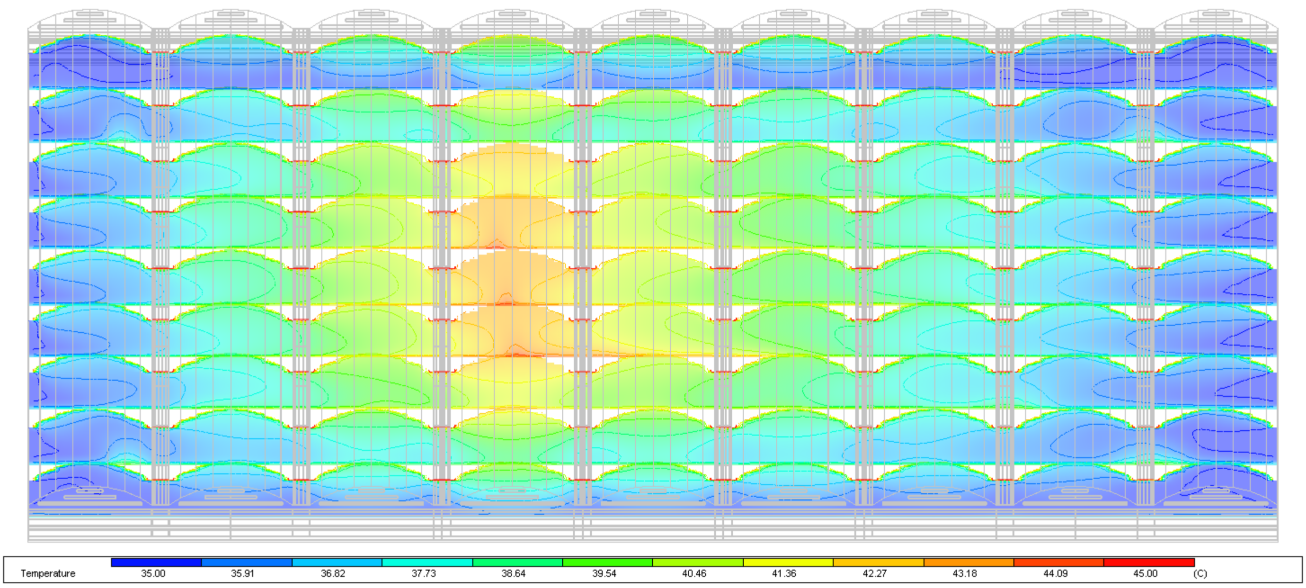



**Figure 12.** Temperature cloud map of the multi-span round-arch greenhouse (with an in-greenhouse ventilation channel) (outdoor wind speed 0 m/s, outdoor temperature 35 °C).

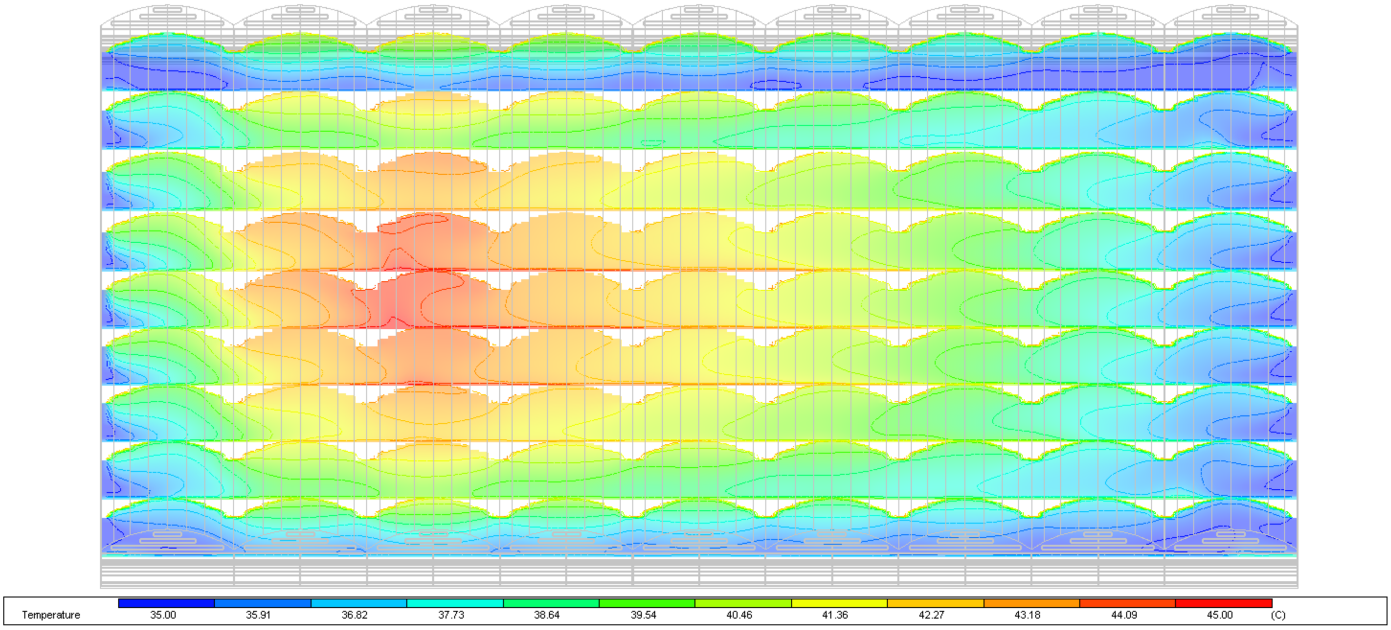



**Figure 13.** Temperature cloud map of the multi-span round-arch greenhouse (without an in-greenhouse ventilation channel) (outdoor wind speed 0 m/s, outdoor temperature 35 °C).

According to Figures 11–13, in the conditions of no wind (wind speed 0 m/s) and an external temperature of 35 °C, the internal ventilation of the greenhouse is only the heat pressure effect, and the heat is gathered in the middle of the greenhouse. The crossed multi-arch greenhouse and the multi-span round-arch greenhouse with a ventilation channel showed a good heat dissipation effect, with the edge temperature similar to the external temperature; the internal temperature at most points is around 36~39 °C, the highest temperature at the center is about 42 °C, and the average temperature difference is about 2~3 °C; as for the multi-span round-arch greenhouse without a ventilation channel, there is an obvious heat accumulation in the greenhouse, and the range of the high-temperature area is larger than that of the multi-span round-arch greenhouse with a ventilation channel, with most of the internal temperature being 37~41 °C, the highest temperature being about 44 °C, and the average temperature difference being about 4~5 °C. In the condition of no wind, the ventilation effect of the multi-span round-arch greenhouse with a ventilation channel is significantly higher than that of the greenhouse without a ventilation channel because the ventilation channel and surrounding vents can form good thermal pressure ventilation, and the air flows well inside and outside such that the heat collected inside can be exchanged with cooler air from outside more quickly. When there is no wind, the heat distributed asymmetrically, which is mainly affected by the monsoon and the solar orientation, especially the southeast monsoon that prevails in Hainan in summer. Although the outdoor wind speed is 0 m/s at the CFD simulation time, there may be southeast wind before and after the model time.

Figures 14–16 show the simulated temperature clouds inside the greenhouse at 13:00 on 8 July, when the outdoor wind speed was 1 m/s (windy hours around noon) and the inlet temperature of the simulated environment was 32.7 °C. The cloud map takes the midline of each row of arch bars to make temperature slices. The slices are located 2 m away from the front and rear rows of arch bars.

As can be seen in Figures 14–16, during windy hours (wind speed 1 m/s), the greenhouses simultaneously ventilated through the heat and wind pressure, with the wind coming from the east side along the greenhouse's long axis direction. The long axis direction has a long heat exchange path and inadequate heat exchange, causing heat accumulation in the greenhouse. The temperature at the edge of the two greenhouse types with ventilation channels is similar to that outside, and the internal temperature is roughly distributed between 34 and 37 °C, locally about 38 °C, with a maximum average temperature difference of about 2 to 3 °C. In contrast to Figure 14, the high-temperature areas of the multi-span round-arch greenhouse without a ventilation channel are more widely distributed than the two greenhouse types with ventilation channels, and the internal temperatures are mostly distributed between 34 and 38 °C, locally about 39 °C, with a maximum average temperature difference of about 4 to 5 °C.

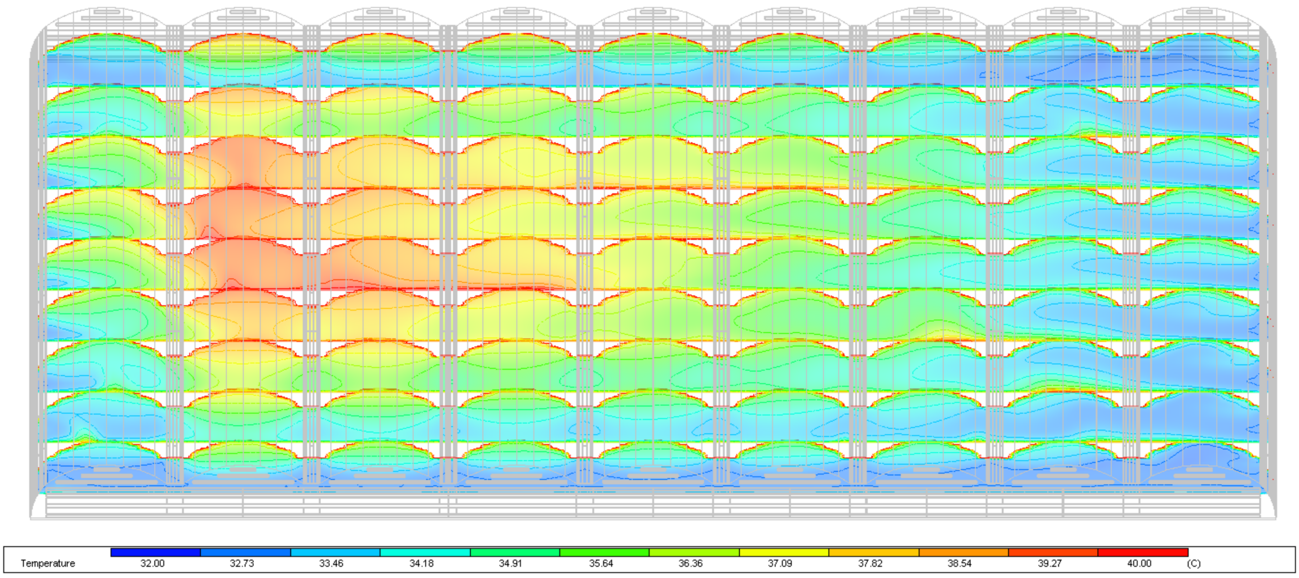



**Figure 14.** Temperature cloud map of the crossed multi-arch greenhouse (with an in-greenhouse ventilation channel) (outdoor wind speed 1 m/s, outdoor temperature 32.7 °C).

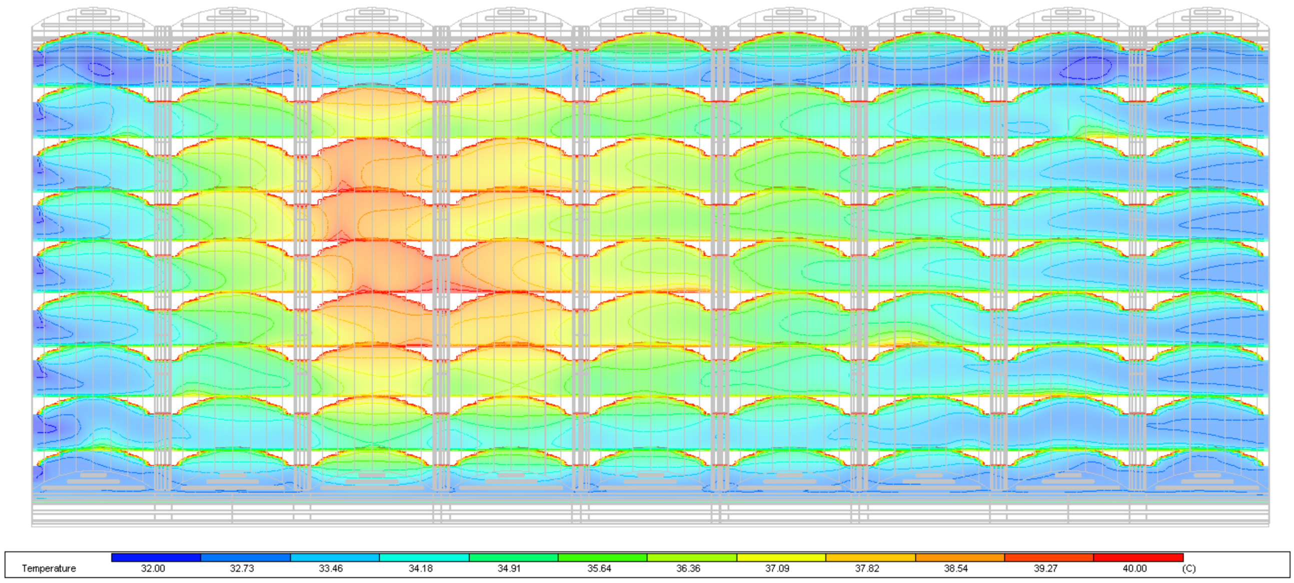



**Figure 15.** Temperature cloud map of the multi-span round-arch greenhouse (with an in-greenhouse ventilation channel) (outdoor wind speed 1 m/s, outdoor temperature 32.7 °C).

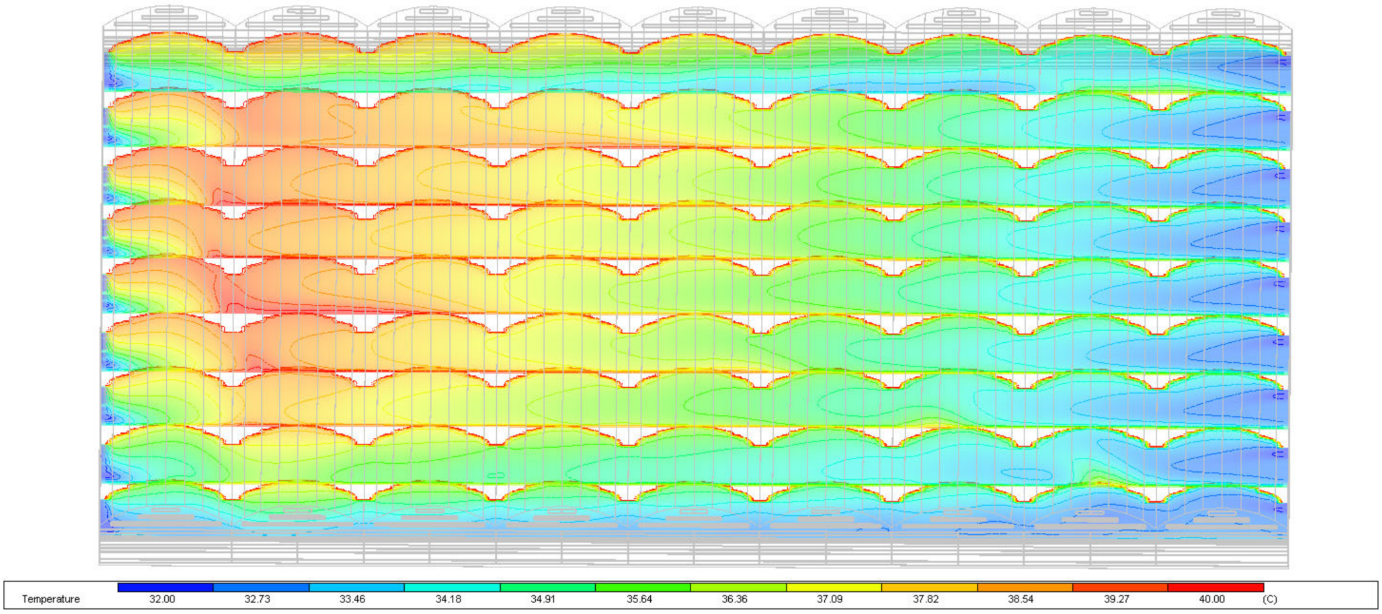



**Figure 16.** Temperature cloud map of the multi-span round-arch greenhouse (without an in-greenhouse ventilation channel) (outdoor wind speed 1m/s, outdoor temperature 32.7 °C).

Some studies [32] have shown that when the outdoor wind speed is higher than 2 m/s, the ventilation is mainly dominated by wind pressure, and the thermal pressure is negligible; when the outdoor wind speed is between 0.5 and 2 m/s, the ventilation process is dominated by wind pressure and supplemented by thermal pressure; when the outdoor wind speed is lower than 0.5 m/s, the role of thermal pressure ventilation cannot be neglected. From the temperature distribution in the greenhouse in the afternoon simulated in this study without wind and with a light breeze, it can be seen that the average temperature difference between the interior and exterior of the greenhouse is smaller when there is a ventilation channel, and the high-temperature area is significantly smaller than that of the greenhouse without a ventilation channel. It is concluded that a ventilation channel can effectively promote the flow of air inside and outside the greenhouse and lower the high temperature inside the greenhouse, and the ventilation and cooling capacity of the crossed multi-arch greenhouse and the multi-span round-arch greenhouse (with an in-greenhouse ventilation channel) are basically the same.

To further analyze the advantages and disadvantages of Model A and Model B, slice maps of the wind speed of the two types of greenhouses with a ventilation channel were formulated. Figures 17 and 18 show the wind speed cloud maps inside the greenhouse under the windless condition, and Figures 19 and 20 show the wind speed cloud maps inside the greenhouse under the windy condition (wind speed 1 m/s).

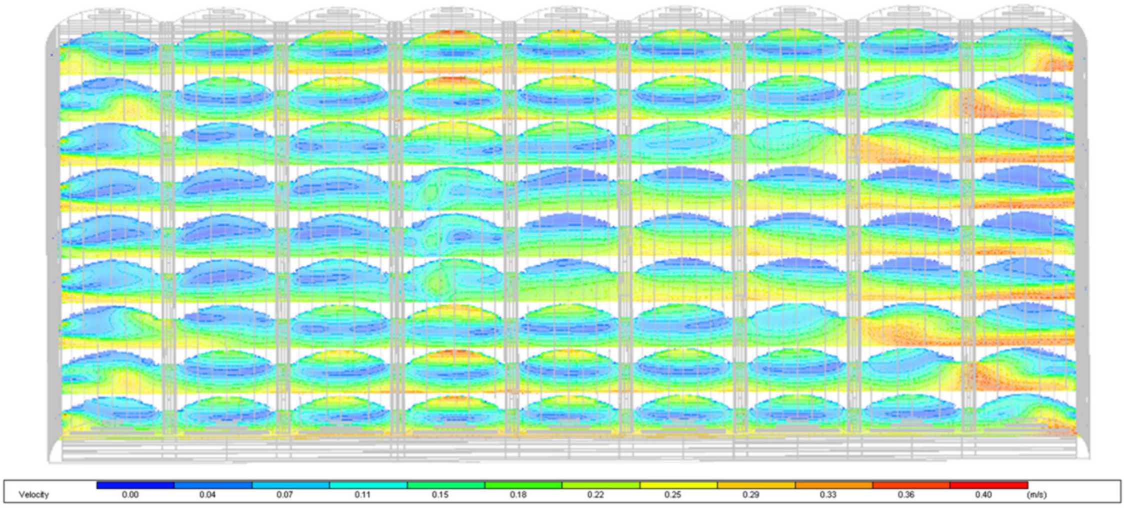



**Figure 17.** Wind speed cloud map of the crossed multi-arch greenhouse (outdoor wind speed 0 m/s).

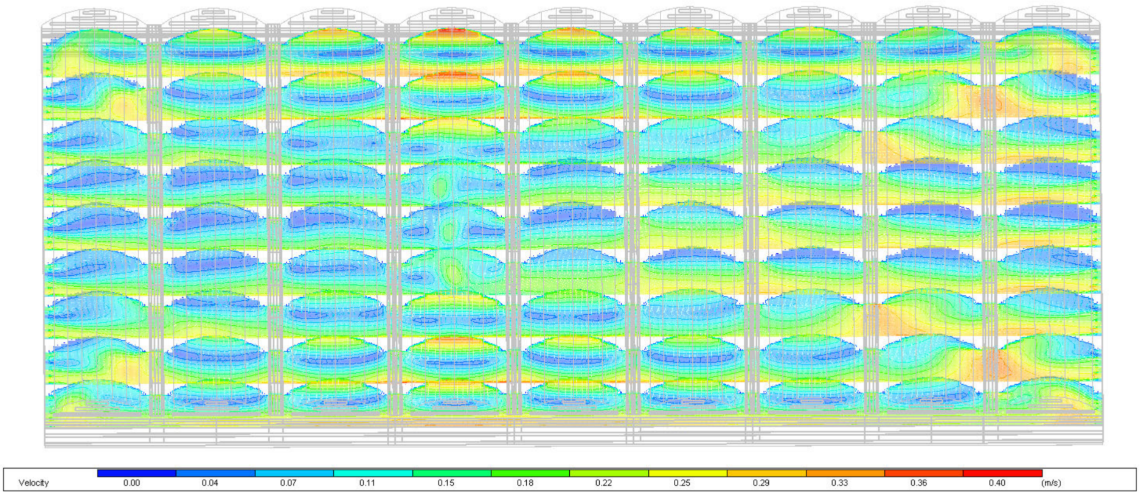



**Figure 18.** Wind speed cloud map of the multi-span round-arch greenhouse with an in-greenhouse ventilation channel (outdoor wind speed 0 m/s).

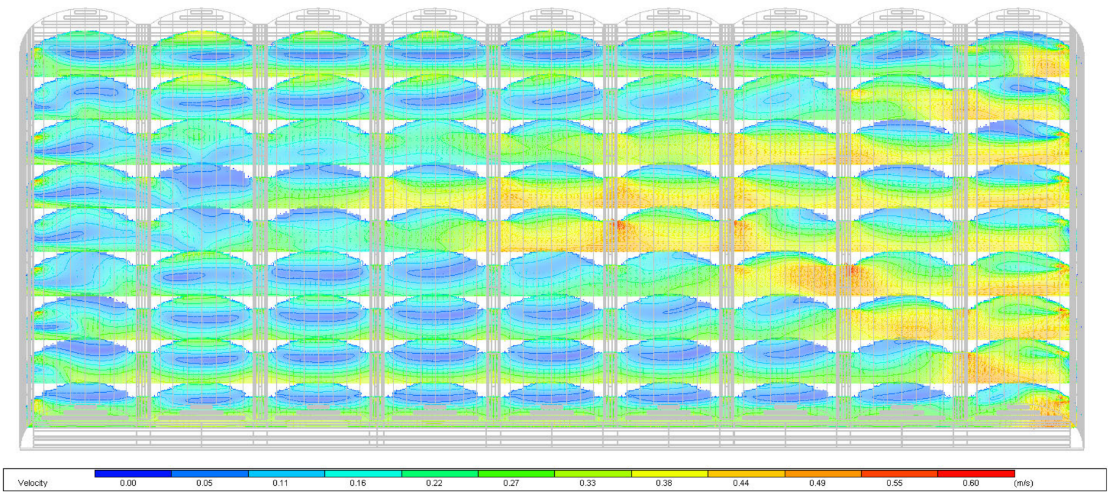



**Figure 19.** Wind speed cloud map of the crossed multi-arch greenhouse (outdoor wind speed 1 m/s).

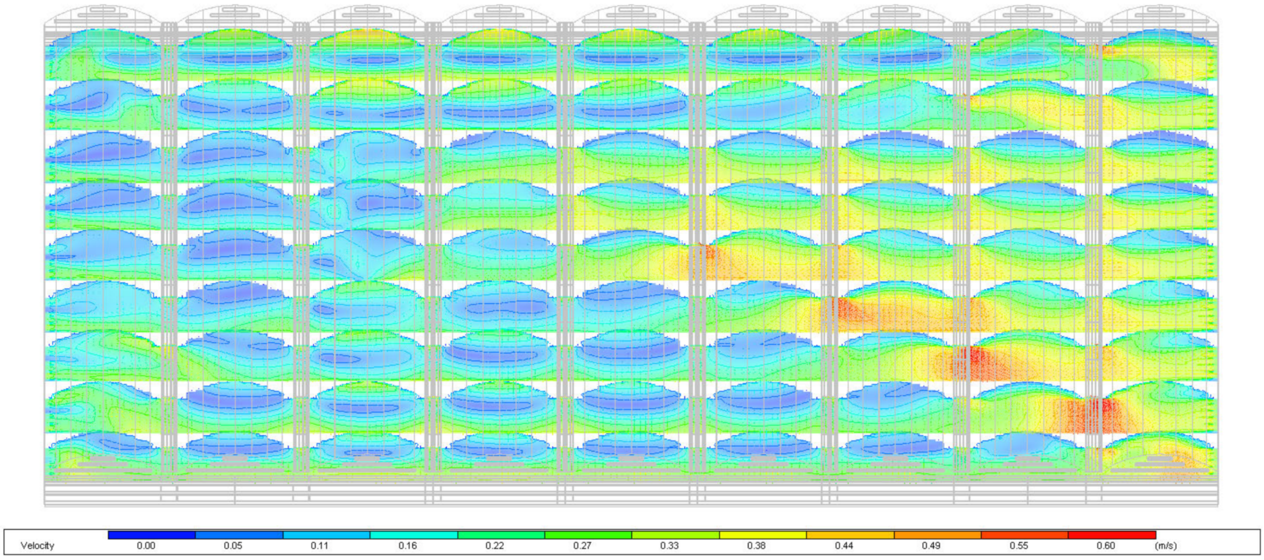



**Figure 20.** Wind speed cloud map of the multi-span round-arch greenhouse with an in-greenhouse ventilation channel (outdoor wind speed 1 m/s).

As shown, when the outdoor wind speed is 0 m/s, the maximum indoor wind speed of the two greenhouse types with a ventilation channel is 0.4 m/s; when the outdoor wind speed is 1 m/s, the maximum indoor wind speed of the two greenhouse types is 0.6 m/s. The speed of outside air entering the room decreased by about 40%, and there was no significant difference in the ventilation effect between the two types of sheds. The non-significant difference is because, in the same conditions, the wind speed near the ventilation opening of the round-arch greenhouse is larger than that of the multi-arch greenhouse, and the wind speed of the crossed multi-arch greenhouse is more evenly distributed. Some scholars [21,33–35] studied the ventilation of an insect-proof net from the perspective of the environment, obtained parameters such as the wind resistance coefficient, pressure drop coefficient, and flow coefficient of the screen net to describe the negative impact of insect-proof netting on natural ventilation, and fitted a series of formulas for quantifying the ventilation effect. However, due to the difference in the use environment, insect-control netting is used as the ventilation covering material in tropical China. In the same rainy and hot season in tropical China, the humid and hot environment speeds up the spread of diseases and pests. The selection of insect-control netting in production depends more on whether its pores can meet the plant-protection function [36]. Insect-proof netting and plastic film are the two most commonly used covering materials in tropical areas. Plastic film is used for rain protection, and insect-proof netting is used for insect control and ventilation. The ventilation effect of the greenhouse is affected by the size and distribution of the ventilation surface [37]. For greenhouses in tropical areas, the ventilation surface is the coverage of insect-control netting. On the premise of not affecting the internal rain protection function, increasing the proportion of insect protection net coverage can improve the ventilation and cooling effect in the shed.

## 5. Conclusions

Facility protection land cultivation can overcome summer and autumn rainstorms, high temperatures, frequent typhoons, and other unfavorable meteorological factors. A crossed multi-arch greenhouse is developed based on the existing production experience through extensive surveys, analogies, and analyses, which is a comprehensive application that combines various methods such as structural analyses and computations, environmental simulation analyses, and so on. As a new type of greenhouse structure suitable for planting in hot areas, a crossed multi-arch greenhouse is featured, with the following innovations and advantages:

(1) Structural innovation: the crossed multi-arch structure is similar to the integral truss structure, which can resist large wind loads with a smaller steel tube section. Under the same load condition, the structural force analysis and calculation of the crossed multi-arch greenhouse and the multi-span round-arch greenhouse (with a ventilation channel) show that the steel consumption of the main steel frame of the crossed multi-arch greenhouse is reduced by about 32.4%. At the same time, due to the uniform force inside the main steel frame, the connection between the steel frame and the foundation can be hinged in the form of column footings, so the bending moment generated by the wind load is not transferred to the foundation. Moreover, the size of the foundation is reduced compared to that of the solid jointed column footings, and the amount of material used for the foundation structure can be further reduced.

(2) Economic advantages: the crossed multi-arch greenhouse showed significant economic advantages, as it uses fewer materials. According to the statistics, a crossed multi-arch greenhouse can save 0.646 kg of materials per unit area compared with a multi-span round-arch greenhouse (with a ventilation channel). According to the material price and construction quota in the Hainan area, the cost of material processing and the installation of the greenhouse's steel structure is about CNY 12.8/kg, so it can save CNY 8.27 per square meter or CNY 5515/667 $m^2$ for steel investment; for the foundation part, the crossed multi-arch greenhouse can save CNY 7 per square meter or CNY 4669/667 $m^2$ compared with the multi-span round-arch greenhouse (with a ventilation channel). Thus, the crossed multi-arch greenhouse can save a total investment of CNY 10,184/667 $m^2$, which has obvious economic advantages.

(3) Ventilation and cooling: the temperature parameters inside different structural forms of greenhouses are simulated by simulation software under typical summer weather conditions. The results show that, under the conditions of no wind (wind speed 0 m/s) and breeze (wind speed 1 m/s), the crossed multi-arch greenhouse and the multi-span round-arch greenhouse with ventilation channels have a better heat-dissipation effect, and the average temperature difference between indoors and outdoors is about 2~3 °C. The greenhouse type without a ventilation channel has obvious heat accumulation, and the high-temperature area is larger than that of greenhouses with a ventilation channel. The average temperature difference between the indoor and outdoor space of this greenhouse type is about 4~5 °C.

In this paper, the research-and-development process of multi-arch greenhouses has been described from the perspectives of structure, the advantages of multi-arch greenhouses were compared from the perspective of cost, the ventilation simulation was used to prove that the multi-arch greenhouses have achieved the expected ventilation effect, and the ventilation performance was matched with the multi-span round arch plastic greenhouse with an in-greenhouse ventilation channel. At present, the multi-arch greenhouse structure has been built and applied to many planting bases in Hainan Province. It can meet the production function and has a good use effect.

## 6. Patents

One patent has been applied in China in this manuscript (Patent No. CN202021432481).

**Author Contributions:** Conceptualization, J.L.; methodology, B.W.; software, X.W.; validation, F.S.; formal analysis, B.W.; investigation, X.W.; resources, J.L.; data curation, J.L; writing—original draft preparation, F.S.; writing—review and editing, B.W.; visualization, F.S.; supervision, J.L.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

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