Transformable greenhouse for climatically optimized agriculture

Alexander Blazhnov, Maria Fetisova*, Lilia Glukhova, Sergey Volodin and Anastasia Kolomytseva
Oryol State Agrarian University named after N.V. Parakhina, Oryol, Russia

* E-mail: fetisovamaria@mail.ru

Abstract. Constructive solutions and advantages of a transformable greenhouse are considered. The greenhouse is provided with two welded frames - an external (stationary) one that can absorb atmospheric loads, and an internal (mobile) one made of less massive steel profiles with a translucent fence of each frame made of honeycomb polycarbonate panels. In order to reduce the cost of heating the greenhouse and eliminate the need to provide for a seedling department, a technical solution for a transformable energy-efficient greenhouse has been developed and patented, which can be used in small forms of farming. A technical solution for a transformable greenhouse has been proposed, which provides an opportunity to reduce energy costs when growing agricultural products in the cold season, eliminates the need to provide a seedling department and allows you to increase the planting area in the warm season. The economically feasible resistance to heat transfer of the greenhouse enclosing structure has been substantiated.

1. Introduction
The year-round cultivation of vegetables in cultivation facilities can significantly increase the yield compared to open ground. The disadvantage of year-round greenhouses is significant heat losses during the cold season. The aim of the work was to develop a greenhouse design for small farms, which would reduce heating costs in cold weather and increase the planting area in the warm season.

2. Materials and methods
The method of natural tests of a transformable greenhouse in the climate of the Central Russian zone. The tests were carried out during a calendar year, the test results were compared with similar structures, which made it possible to patent a structural solution [1].

3. Results and discussion
Year-round greenhouses are characterized by significant heat losses, which reduces the profitability of production and increases the payback period of structures. Several inventions have been patented [2-4]; in the authors' opinion, these are increasing the energy efficiency of the cultivation facilities, however, their practical application is beside the purpose.

The heat losses of the greenhouse during the cold season and the costs of its construction also increase when it contains a compartment for growing vegetable crops' seedlings. The structure of seedling greenhouses recommended by the Methodological Recommendations for the Technological Design of Greenhouses RD-APK 1.10.09.01-14 also increases non-recurrent and operating costs.

In order to reduce the greenhouse heating cost and eliminate the need to provide for a seedling compartment, a technical solution for a transformable energy-efficient greenhouse has been developed.
and patented, the use of which is possible in small forms of farming (Figure 1). The proposed greenhouse design also allows to increase the planting area for growing crops in the warm season [1].

![Figure 1. Structural scheme of the greenhouse.](image)

The greenhouse is provided with two welded frames - an external (stationary) one that can absorb atmospheric loads, and an internal (mobile) one made of less massive steel profiles with a translucent fence of each frame made of honeycomb polycarbonate panels (a less costly film fencing is possible for an internal frame).

The total thermal resistance of two fences made of polycarbonate panels and the air gap formed between them ensures a decrease in heat losses when growing agricultural products (vegetables, green crops, seedlings) in the cold season. In the warm season, the inner frame is moved along the guides (rails) laid at the floor level and end-docked with the stationary frame, which allows to increase the greenhouse planting area and yield.

The essence of the proposed structural solution for the greenhouse is illustrated by the drawing. Figure 1 shows two interlocked greenhouse frames: 1 - external stationary frame; 2 - internal mobile frame; 3 - steel arch made of rectangular pipe or formed section, welded by the profile end to the element 7; 4 - girders made of roll-formed channel welded to the arches; 5 - gate; 6 - fencing (roofing) made of honeycomb polycarbonate panels; 7 - a framing element made of roll-formed channel; 8 - wheel; 9 - guide element (rail) made of channel with bar sides up.

The frames' assembly of the transformable greenhouse can be carried out directly on the farm. First, the outer supporting frame is welded: the ends of the arch 3 are welded to the framing elements of the channel type 7, then the girders 4 are welded to the arches, along which the honeycomb polycarbonate panels 6 are laid. Hinged gates are installed on the end of the frame. Guides (rails) 9 made of channel with bar sides up are laid at ground level to move the inner frame. The production of the inner frame out of less massive steel sections is carried out outside the outer supporting frame. Framing elements 7 with attached wheels 8 are installed on rails 9. The ends of the arch 3 are welded to the elements 7, then the girders 4 are welded to the arches, along which the honeycomb polycarbonate panels 6 are laid. Hinged gates 5 are installed on the end of the inner frame. The finished frame is moved along the rails 9 to the inside of the outer frame. The necessary technological measures are carried out after installing the inner frame, such as soil preparation, planting, etc.

It is possible to grow green crops that require low light and temperature (onions, dill, parsley, etc.), as well as seedlings in the cold season in the greenhouse. In a warm period, the inner frame is moved along the guides (rails) and end-docked with the outer frame increasing the greenhouse planting area for the prepared seedlings.

It is possible to use honeycomb polycarbonate panels of various thicknesses in the enclosing structures of the greenhouse: 4, 6, 8, 10 and 16 mm, the necessary technical and economic indicators of which are given in Table 1. The greater the thickness, the higher the price of the panels (non-recurrent cost), yet the operational costs for cultivation facility heating will decrease. In this regard, it is possible to establish an economically feasible thickness of polycarbonate panels, at which the annual cost of the fence will be minimal.
So, for a single-layer enclosing structure

\[ A = C_P + C_T = \min \]  

where \( A \) is the annual cost of the fence, rubles/m\(^2\); \( C_P \) - the cost of 1m\(^2\) of a polycarbonate panel, rubles (an economic way of building a greenhouse is assumed); \( C_H \) - heat loss through the fence during the heated period, rubles/m\(^2\), taken equal to one year due to the uncertainty of future energy prices.

### Table 1. Key performance indicators of polycarbonate panels.

| Panel thickness, mm | Resistance to heat transfer in a single-layer enclosure \( R_O \), \( \mbox{m}^2\mbox{C}/\mbox{W} \) | Panel cost, rub/m\(^2\) ** |
|--------------------|---------------------------------|------------------|
| 4                  | 0.408                           | 198              |
| 6                  | 0.428                           | 332              |
| 8                  | 0.438                           | 388              |
| 10                 | 0.448                           | 431              |
| 16                 | 0.518                           | 841              |

* The resistance to heat transfer of polycarbonate panels \( R_O \) is taken based on the indicators of GOST R 56712-2015 "Multilayer polycarbonate panels" Table 3 considering the resistance to heat transfer of the inner and outer surfaces of the panel installed in the greenhouse fence.

** Prices for polycarbonate panels are given for Moscow [5].

The graph of the change in the specific cost of polycarbonate panels as a function of their resistance to heat transfer is shown in Figure 2 and can be expressed as a linear relation

\[ C_P = 5846.5 R_O - 2187 \text{ rub/m}^2 \]  

(2)

The deviations of the panels' cost indicators calculated from the dependence (2) from the actual ones vary in the range from 0.05 to 5%.

The cost of heat losses for the heating period in relation to the Moscow region can be approximately determined by the formula

\[ C_T = \frac{(t_i - t_a) Z}{R_O} \text{ rub/m}^2 \]  

(3)

Where \( t_i \) - the design temperature of the internal air in the greenhouse taken equal to -15°C (growing cold-resistant crops: lettuce, radishes, cabbage, dill, onions, tulips, etc.); \( t_a \) - the average outside air temperature for the heating period taken equal to -2.6°C according to SP 131.13330.2020 Construction climatology (for the period with an average daily outside air temperature \( \leq 10^\circ\mbox{C} \)); \( Z \) - the duration of the heating period equal to 228 days (5472 hours) for the period with an average daily outdoor temperature \( \leq 10^\circ\mbox{C} \); \( C_T \) - the cost of natural gas equal to 0.93 rubles/1000 kcal (0.8 rubles/1000 W•h); \( R_O \) - total resistance to heat transfer of the enclosing structure equal to

\[ R_O = \frac{1}{\alpha_i} + R + \frac{1}{\alpha_O} \]  

(4)

where \( \alpha_i, \alpha_O \) are the heat transfer coefficients of the inner and outer surfaces of the greenhouse enclosure equal to 8.0 (for windows) and 23 W/(m\(^2\)°C), respectively.
Figure 2. Change in the cost of polycarbonate panels depending on the resistance to heat transfer.

Summing up expressions (2) and (3), an expression for the annual costs of the fence is obtained, rubles/m²

\[ A = \frac{1}{T} (5846.5R_O - 2187) + \frac{(t_i - t_{a.o.})ZC}{R_O} \]  

(5)

where \( T \) is the estimated payback period of the greenhouse, taken equal to three years.

Differentiating (5) with respect to \( R_O \), we obtain

\[ \frac{dA}{dR_O} = \frac{5846.5}{T} - \frac{(t_i - t_{a.o.})ZC}{R_O^2} \]

With the accepted values of the quantities in relation (5), the first derivative is positive. That is, with an increase in the thermal resistance of the polycarbonate fence (panel thickness), the reduced costs \( A \) for the fence increase. The increase in costs is due to the outstripping growth in the cost of panels (more than 4 times) in relation to the cost of saved heat (Figure 3). Therefore, it is economically feasible to use 4mm thick polycarbonate panels in a single-layer enclosure of an all-season greenhouse.

A similar thickness of honeycomb panels is advisable in the stationary and mobile frames of the patented greenhouse [1], since with an increase in the thickness of the frames' translucent fencing non-recurrent costs will increase significantly without significant energy savings during the heating season.
Figure 3. Annual costs for fencing: 1 - the cost of the PC panel reduced to one year of the greenhouse payback period; 2 - heating costs; 3 - total costs.

A two-layer greenhouse fencing with an air gap will provide heat losses saving when growing agricultural products in the cold season compared to a single-layer outer roofing made of polycarbonate sheets. So, with a single-layer roof made of honeycomb polycarbonate with a thickness of 4 mm, the resistance to heat transfer of the fence will amount to 0.408 m²·°C/W. The air gap, the change in thermal resistance of which is shown in Figure 4 [6,7,8], and the double enclosure will increase it to 0.838 m²·°C/W and reduce heat losses by about a half.
Figure 4. Change in thermal resistance of a closed air gap depending on its thickness.

With a constant stationary part area of an arched greenhouse with a circular outline of the cover, a change in the span will affect the area of the translucent fence and the amount of heat loss in the cold season. A rational greenhouse span will correspond to the minimum value of the fencing coefficient (the ratio of the coverage area to the area of the stationary part of the greenhouse)

$$K_f = \frac{\pi}{2} \left( \frac{L^2}{2F_P} + 1 \right)$$

where $L$ is the span of the greenhouse equal to two radii of the covering outline; $F_P$ - the area of the stationary part of the greenhouse.

4. Conclusions

A technical solution for a transformable greenhouse has been proposed, which provides an opportunity to reduce energy costs when growing agricultural products in the cold season, eliminates the need to provide a seedling compartment and allows to increase the planting area in the warm season.

The economically feasible resistance to heat transfer of the greenhouse enclosing structure has been substantiated.

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