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Winter greenhouse combined heating system

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Abstract. Energy preservation and reduction in greenhouse gas emissions into the atmosphere can be partially gained through decentralization of heat supply. In the case of cultivation facilities, a solution is a combined heating system which includes soil infrared heating and air heating in the winter greenhouse up to the required values by means of autonomous convective heaters. Upon analysing domestic and foreign scientific publications, there has not been found any comprehensive calculation method of the combined heating system. The target of research is normally one of the space heating ways: either radiant or convective. The calculation method considered in the article is based on the solution of the coupled equations set of the greenhouse heat and material balances, its walling and soil surface. It takes into consideration both the features of radiant heat transfer between distant bodies, and convective air heating from heaters. The developed calculation method has been tested using the modern industrial greenhouse “Fermer 7.5” for year-round cultivation of crops. As shown by the results of software calculations, at low temperatures of the outside air, the heat power of winter greenhouse radiant heating should be twice as high as the heat consumption for convective heating of the cultivation facility. There have been obtained heat power change patterns of the winter greenhouse combined heating system depending on a number of important factors, such as: temperature of the outside air; walling thermal resistance; absorption coefficient of the soil surface. Due to the fact that according to the calculations results, the heat loss via the winter greenhouse ventilation proved to be significant, it makes sense to consider further the option of preheating outdoor air necessary for air exchange indoors.

1. Introduction

Heating of cultivation facilities during the cold period plays an important role in year-round cultivation of flowers, vegetables, seedlings, etc. The greenhouse heating costs make up about 30–50 % of the production costs, which is explained using glass and polycarbonate of low thermal properties for walling [1, 2]. The search for alternative materials, which can minimize energy needs in space heating and significantly improve conditions for growing plants, is underway, but at the moment there is no comprehensive solution to the problem [3, 4]. This applies to the search for optimal space planning designs of winter greenhouses as well: finding the correct shape and orientation of the facility by the cardinal directions for different climatic conditions [5]. In any case, the use of efficient heat supply of winter greenhouses is a priority in the greenhouse industry of the country. In the last century convective heating methods (heating internal air, but not soil) were actively used for greenhouses. They are not quite efficient, especially during the vegetative period, as the main part of heat is located in the upper zone of the facility, and not close to the soil surface where the plants grow [6]. Nowadays, there are some innovative technologies for cultivation facilities heat supply, based, for example, on the use of solar radiation [7–9], low grade heat of the environment and soil (heat pumps) [10–13] or geothermal energy sources [14–16]. It is often economically feasible to heat winter greenhouses using thermal energy from third-party production processes or from local heat sources [17]. Despite the fact that these heating systems have their distinctive advantages due to their nature, it is necessary, first of all, to focus on the greenhouses heating methods, which to a lesser extent depend on geographical conditions and environmental factors. These include radiant heating systems of winter greenhouses operating on fuel gas [18, 19]. However, as shown by the conducted research [20], the use of only infrared soil heating in the greenhouse does not allow to maintain the targeted indoor thermal conditions at low outdoor temperatures.

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It is commonly known that a heating system is designed to create the necessary indoor thermal conditions. This also applies to cultivation facilities as in case of winter greenhouses heated in the cold period. Table 1 presents, as an example, the required microclimate parameters in year-round vegetable greenhouses prior to fructification.

Table 1. Greenhouse temperature and humidity conditions (before fruitification).

Plant	Air temperature, ºC			Soil temperature, ºC	Relative humidity, %
	day		night		
	sunny	overcast			
Cucumber (winter-spring cycle)	22–24	20–22	17–18	20–24	70–75
Cucumber (autumn cycle)	25–26	22–23	19–20	22–24	70–75
Tomato (winter-spring cycle)	22–24	19–20	16–17	18–20	60–65
Tomato (autumn cycle)	24–26	18–20	16–18	18–19	60–70
Lettuce	20–23	16–18	10	15–16	70–80
Radish	20–22	7–9	5–6	15–16	60–70
Dill, spinach	17–18	8–12	5–6	15–16	65–80

According to Table 1, unlike conventional agricultural buildings and facilities, winter greenhouses need to maintain the required thermal conditions not only of the space itself, but also of the soil. A water (or air) heating system with additional soil heating, which is basically a system of pipelines laid in the soil, is an obsolete option. These include such disadvantages as: large quantity of metal per structure (10–12 kg/m^2) and slow response of the system; complexity of installation (underground piping, installation of a heating unit, etc.); need for a remote heat source; high energy consumption for circulation of the coolant; different coolant temperatures in the heating system circuits (above the surface and under it); possible leakage of water into the soil layer in case of pipelines damage, etc. In addition, most of the existing winter greenhouses with traditional heating systems were built before the implementation of modern energy-saving programs and, as a result, the amount of energy consumed in such cultivation facilities is much higher compared to the new agricultural sites [21]. The use of only radiant heating in the greenhouse also cannot be a solution, since most of the heat is spent on soil heating, and the inside air temperature, as a consequence, is relatively low (below the standard values given in Table 1).

In this case it is important to consider a combined heating system, which, in addition to convective space heating, also involves radiant heat flow generated by the overhead dark infrared emitters. Besides, the use of gas infrared emitters will allow, through decentralization of heat supply and relatively cheap fuel gas, to reduce the heat load of the convective heating system designed to heat the air, and reduce consumption of non-renewable fuel and energy resources. Gas-fired radiant heating will provide crops in the greenhouse with additional carbon dioxide (CO_2), which is necessary for photosynthesis reaction. This type of combined heating system will generate economic benefits due to the reduction in convective heat output (during less cold months of the heating period).

The research target is a combined heating system of the winter greenhouse with overhead gas infrared emitters for soil heating and convective heaters designed for maintaining the required temperature of the indoor air.

The research is focused on the patterns of heat power changes of the winter greenhouse combined heating system depending on environmental factors, walling design features and heat absorbing properties of the soil surface under conditions of ventilation and soil irrigation.

The purpose of the study is to develop a method of calculation of the winter greenhouse combined heating system, which includes overhead infrared radiators with convective heaters and is designed for maintaining the required heat and humidity conditions of the indoor space and the soil in the cultivation facility.

To achieve this purpose it is necessary to solve the following tasks:

1. Determine the main heat and mass transfer processes occurring in the winter greenhouse while using the combined heating system.

2. To compose a system of coupled equations of heat and mass transfer in the winter greenhouse with combined heating taking into account incoming and outgoing fluxes of heat and mass.

3. To test the developed calculation method of the combined heating system using a modern industrial greenhouse as an example.

4. To study the effect of various factors on the heat power of the winter greenhouse combined heating system with the help of the developed calculation method.

2. Methods

Fig. 1 shows the schematic diagram of the winter greenhouse combined heating system under steady-state heat and humidity conditions.

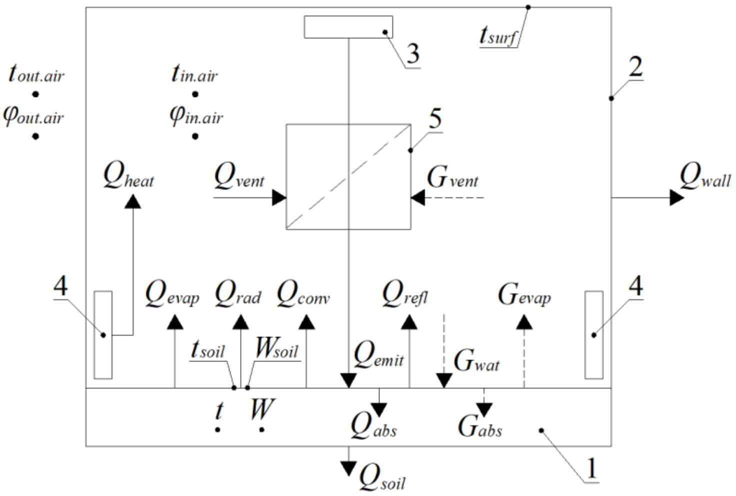

Figure 1. Calculation model of the winter greenhouse combined heating system: 1 – soil; 2 – walling; 3 – infrared radiation source (emitter); 4 – convective heaters; 5 – ventilation (supply, exhaust).

Under steady-state heat and humidity conditions in the winter greenhouse (Fig. 1), the heat balance equation can be written as follows, W:

$$Q_{emit} + Q_{heat} = Q_{wall} + Q_{vent} + Q_{soil}, \tag{1}$$

where Q_{emit} is the radiant heat flux coming from the emitter 3, W;

Q_{heat} is the convective heat flux coming from the heaters 4, W;

Q_{wall} is the heat loss by heat transfer through the greenhouse walling 2, W;

Q_{vent} is the heat loss with the ventilation air leaving the greenhouse through the exhaust ventilation aperture 5, W;

Q_{soil} is the heat loss into the deep soil horizons, W.

In the combined heating system, the thermal power Q_{heat}, W, of the convective heaters 4 is to maintain the required thermal conditions in the greenhouse and is used for heating the indoor air up to the target temperature (Table 1).

Heat loss Q_{wall} through the walling 2 of the winter greenhouse, W, can be found using the heat transfer equation:

$$Q_{wall} = \frac{t_{in.air} - t_{out.air}}{R_t} F_{wall} \left(1 + \beta_{inf}\right), \tag{2}$$

where $t_{in.air}$ is the indoor air temperature, ºC;

$t_{out.air}$ is the outside air temperature, ºC;

R_t is resistance to the greenhouse walling heat transfer 2, $m^2 \cdot K/W$;

F_{wall} is the total area of the greenhouse walling, m^2;

β_{inf} is a coefficient that factors in the additional heat energy consumption for heating the infiltrating air, usually taken to be 0.2.

Heat losses with the ventilation air leaving the greenhouse Q_{vent}, W, under balanced ventilation are numerically equal to the heat consumption for heating the supply air coming from outside into the winter greenhouse through the ventilation aperture 5:

$$Q_{vent} = G_{air}\left(h_{in.air} - h_{out.air}\right), \tag{3}$$

where G_{air} is the mass flow rate of the dry part of moist air participating in the greenhouse air exchange, kg/s;

$h_{in.air}$ and $h_{out.air}$ are specific enthalpy of indoor and outdoor humid air respectively, J/kg.

Heat losses into the soil Q_{soil}, W, due to their smallness are calculated in a simplified way by the equation:

$$Q_{soil} = \left(t_{in.air} - t_{out.air}\right)\sum_{i=1}^{n}\left(\frac{F_i}{R_i}\right), \tag{4}$$

where F_i is the projected area of the i-th soil zone in the greenhouse with their total number n, m^2;

R_i is resistance to heat transfer of the i-th soil zone in the greenhouse with their total number n, m^2·K/W.

The winter greenhouse material balance equation (Fig. 1) will be as follows, kg/s:

$$G_{evap} = G_{vent}, \tag{5}$$

where G_{evap} is the moisture evaporation from the soil surface 1, kg/s;

G_{vent} is the moisture loss with the exhaust air leaving the greenhouse through the exhaust ventilation aperture 5, kg/s.

The set of winter greenhouse walling thermal balance equations 2 (Fig. 1) includes the expression (2) and the formula, W:

$$Q_{wall} = \left(1 - \frac{A_1}{1 - k_{refl}}\right)Q_{emit} + Q_{rad} + Q_{conv2}, \tag{6}$$

where $k_{refl} = (1 - A_1)(1 - A_2)\varphi_{21}[1 - \varphi_{22}(1 - A_2)]^{-1}$ is a coefficient that factors in the repeated reflection of thermal radiation from the soil surface 1 and the internal surface of the greenhouse walling 2;

A_1 and A_2 are absorption coefficients of the soil surface 1 and the greenhouse walling internal surface 2 respectively;

φ_{21} is a radiation coefficient from the greenhouse walling internal surface 2 to the soil surface 1;

φ_{22} is a self-radiation coefficient of the greenhouse walling internal surface 2;

Q_{rad} is the resultant thermal radiation between the soil surface 1 and the greenhouse walling internal surface 2, W;

Q_{conv2} is a convective component of heat transfer between the indoor air and the greenhouse walling internal surface 2, W.

In formula (6) the resultant thermal radiation between the soil surface 1 and the greenhouse walling internal surface 2 provided that the angular radiation coefficient $\varphi_{12} = 1$, is calculated using the following equation, W:

$$Q_{rad} = c_0\varepsilon_{12}F_{surf}\left[\left(\frac{T_{surf}}{100}\right)^4 - \left(\frac{T_{wall}}{100}\right)^4\right], \tag{7}$$

where c_0 is a black body radiation coefficient, 5.67 W /(m^2·K^4);

ε_{12} is the reduced relative coefficient of the soil surface thermal radiation 1 and the greenhouse walling internal surface 2;

F_{surf} is the soil surface area 1 in the greenhouse, m^2;

$T_{surf} = t_{surf}$ + 273.15 and $T_{wall} = t_{wall}$ + 273.15 are the absolute temperatures of the soil surface 1 and of the greenhouse walling internal surface 2 respectively, K.

The heat balance equation of the soil surface 1 in the winter greenhouse (Fig. 1) will be as follows, W:

$$\frac{A_1 Q_{emit}}{1-k_{refl}} = Q_{rad} + Q_{conv1} + Q_{evap} + Q_{soil}, \qquad (8)$$

where Q_{conv1} is the heat flux caused by convective heat transfer between the soil surface 1 and the surface air in the greenhouse (in Fig. 1 is marked as Q_{conv}), W;

Q_{evap} is the heat flux spent on moisture evaporation from the soil surface 1, W.

The material balance equation of the soil surface 1 in the winter greenhouse (Fig. 1) is as follows, kg/s:

$$G_{wat} = G_{evap}, \qquad (9)$$

where G_{wat} is the water flow for watering the soil 1, kg/s.

On the right side of equation (9) there must also be water flow G_{abs}, kg/s, absorbed by plants. At this stage, we assume that plants are temporarily absent in the greenhouse (fetal period, until fruitification), so the value $G_{abs} \approx 0$.

3. Results and Discussion

Let us consider the solution of the coupled equations set of the greenhouse thermal and material balances, its walling and soil when utilizing the combined heating system for space heating using the industrial greenhouse “Fermer 7.5” (Fig. 2) as an example.

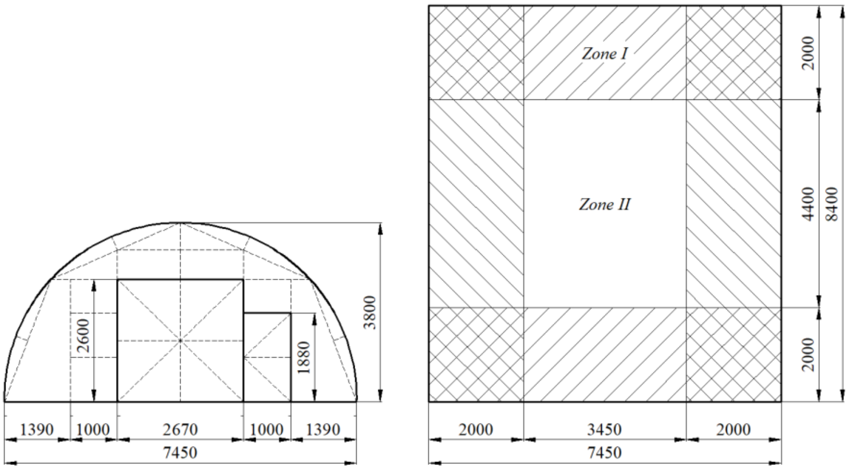

Figure 2. Industrial greenhouse “Fermer 7.5” and the soil zone layout chart.

Initial data to perform the calculation:

1. Greenhouse dimensions: width a = 7.45 m; length b = 8.40 m; height h = 3.80 m.
2. Ventilation apertures dimensions:
   - for air inflow: width a_{in} = 1.0 m; height h_{in} = 1.88 m; opening rate χ_{in} = 0.25; quantity N_{in} = 1;
   - for air exhaust: width a_{ex} = 0.75 m; height h_{ex} = 1.0 m; opening rate χ_{ex} = 1; quantity N_{ex} = 2.

3. The soil surface parameters (tomatoes before fruitification in winter-spring cycle, according to Table 1): temperature t_{surf} = 20 ºC; absorption coefficient A_1 = 0.65 (reflection coefficient R_1 = 0.35); thermal radiation coefficient (emissivity factor) $\varepsilon_1 = A_1$ = 0.65.

4. Walling parameters: material – cellular polycarbonate with walling heat transfer resistance R_{wall} = 0.45 m²·K/W; absorption coefficient A_2 = 0.94 (reflection coefficient R_2 = 0.06); thermal radiation coefficient (emissivity factor) $\varepsilon_2 = A_2$ = 0.94.

5. Design parameters of the internal air (Table 1): temperature $t_{in.air}$ = 22 ºC; relative humidity $\varphi_{in.air}$ = 60 %.

6. Design parameters of the outdoor air for the climatic conditions of the city of Vologda (Russia): temperature $t_{out.air}$= –32 ºC; relative humidity $\varphi_{out.air}$ = 85 %.

7. Ventilation parameters: natural ventilation; design height of the ventilation system Δh = 0.45 m.

8. Irrigation parameters: soil irrigation coefficient k_{irr} = 1(the whole soil surface in the greenhouse is irrigated).

The calculation of the combined heating system of the industrial greenhouse “Fermer 7.5” (Fig. 2) has been performed in the mathematical editor “Mathcad”.

Further to the program calculation of the combined heating system of the industrial greenhouse “Fermer 7.5” the following results were obtained:

1. Temperature of the greenhouse walling internal surface t_{wall} ≈ 22 ºC.

2. The required power of infrared radiation Q_{emit} ≈ 44.2 kW (thermal density q_{emit} ≈ 705.8 W/m^2) and convective space heating Q_{heat} ≈ 22.2 kW (specific convective heat q_{heat} ≈ 121.1 W/m^3).If we compare the thermal density found q_{emit} ≈ 705.8 W/m^2 with the results of other researchers, it is comparable to the specific installed heat power of infrared emitters 706 W/m^2, intended for heating plants in greenhouses [22].The total heat power of the winter greenhouse combined heating system is Q_{tot} ≈ 66.4 kW.

3. Heat loss: through the greenhouse walling Q_{wall} ≈ 14.7 kW; with the ventilation air going from the greenhouse into the environment, Q_{vent} ≈ 49.8 kW (with the flow of dry air equal to G_{air} ≈ 2264 kg/h); into the soil Q_{soil} ≈ 1.82 kW.

4. Heat loss from heat exchange by radiation between the greenhouse walling internal surface and the soil surface Q_{rad} ≈ 0.46 kW (in this case $t_{wall} > t_{surf}$, ºC).

5. Heat loss from convective heat transfer between the indoor air and the soil surface in the greenhouse Q_{conv1} ≈ 0.30 kW (provided that $t_{in.air} > t_{surf}$, ºC); between the indoor air and the greenhouse walling internal surface is almost absent, i.e. Q_{conv2} ≈ 0.

6. Heat loss caused by the moisture evaporation process from the soil surface in the greenhouse amounted to Q_{evap} ≈ 27.9 kW.

7. The required water flow rate for watering the soil G_{wat} ≈ 41.0 kg/h.

Fig. 3 shows the dependence of the design heat power of the winter greenhouse combined heating system (Fig. 2) on the outside air temperature $t_{out.air}$, ºC, during the heating period.

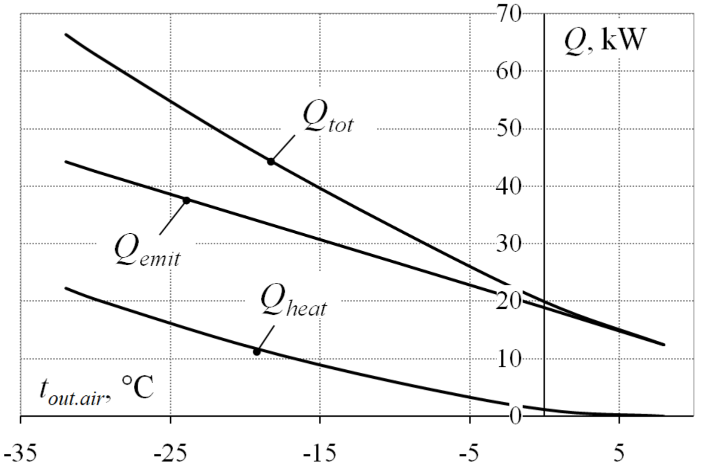

Figure 3. Heating system capacity $Q = Q(t_{out.air})$.

As is clear from Fig. 3, the increase in the outside air temperature $t_{out.air}$, ºC, leads to the decrease in the total heat power of the combined heating system Q_{tot}, kW. This is due to the fact that the increase in temperature $t_{out.air}$ naturally results in heat loss reduction through the greenhouse walling Q_{wall}, for air exchange Q_{vent} and into the soil Q_{soil}. According to the greenhouse heat balance equation (1), the design heat power of the heating system should be reduced.

The relationship between the design heat power of the winter greenhouse combined heating system and the walling thermal resistance R_t, m^2·K/W, is shown in Fig. 4.

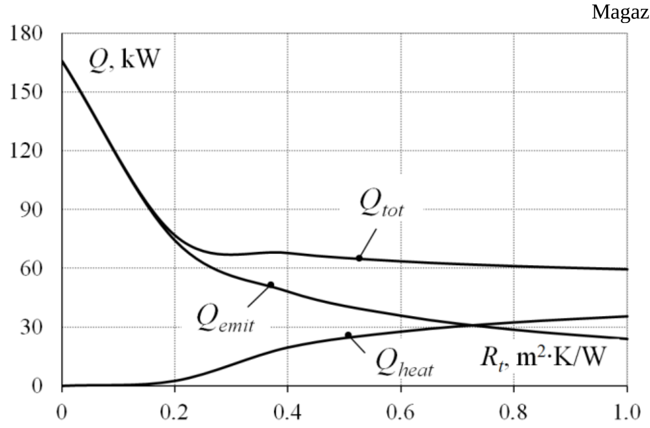

Figure 4. Heating system capacity of $Q = Q(R_t)$ type.

The walling thermal resistance R_t, m²·K/W, plays an important role in creating the required microclimate in the winter greenhouse. The use of ultra-thin translucent covering materials in the cold season, especially in the northern regions of the country with severe climate, is impractical. The greenhouse walling is one of the main problems in the cultivation facilities construction from the point of view of energy saving, as it should simultaneously effectively transmit sunlight (have a high light transmittance coefficient) and perform heat shielding functions. Even modern materials, such as cellular polycarbonate with closed cellular structure (honeycomb), have relatively low thermal insulation qualities (for example, at a significant thickness of the cellular polycarbonate sheet δ_{wall} = 32 mm the R_t value does not exceed 0.83 m²·K/W). In accordance with Fig. 4, the increase in the thermal resistance R_t will naturally lead to a decrease in the design heat power of the heating system. It is worth noting that the total heat flux Q_{tot}, kW, decreases less intensively at R_t > 0 values, which are usually found in practical work. This is due to the fact that at the design temperature of the outside air $t_{out.air}$ = –32 °C, the main part of the heat is used for ventilation in order to provide the necessary air exchange indoors. In addition, there is a gradual redistribution of the heat load for heating needs: in order to obtain the total heat power Q_{tot} while reducing the radiant component Q_{emit}, there is a natural increase in convective heat flux Q_{heat}.

The heat and mass balances of the soil, and therefore the greenhouse as a whole while heated are affected by the ability of the soil surface to absorb (or reflect) thermal energy. Fig. 5 shows the relationship between the heat power of the winter greenhouse combined heating system and the absorption coefficient of the soil surface A, %.

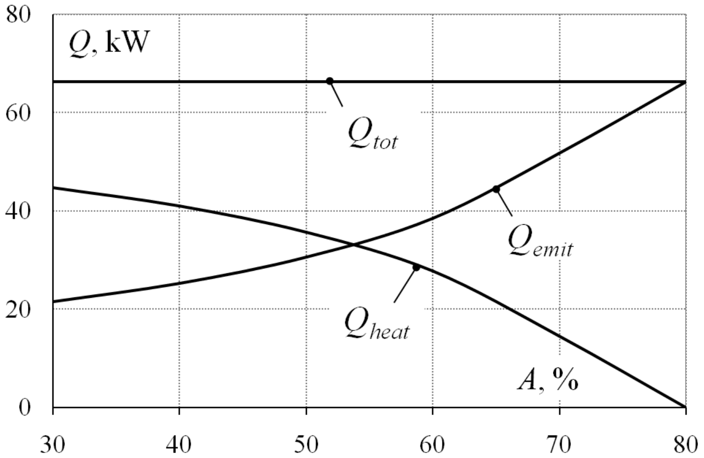

Figure 5. Heating system capacity of $Q = Q(A)$ type.

The total heat power of the winter greenhouse combined heating system Q_{tot}, kW, does not depend on the absorption capacity of the soil surface A, %. As it is known, heating is intended to compensate for heat losses into the environment in order to maintain a given microclimate indoors (Table 1). Heat fluxes Q_{wall}, kW, Q_{vent} and Q_{soil} do not depend on the absorption coefficient A and their values remain constant in this case. Then according to the equation (1), the design heat power Q_{tot} must also be a constant value. In order to maintain the required temperature of the indoor air and soil, the heat power Q_{emit}, according to the formula (6), should increase together with the absorption coefficient A rise. At the constant total heat power of the heating system Q_{tot}, the increase of radiant component Q_{emit} will naturally lead to a decrease in the heat power of convective heating Q_{heat}.

4. Conclusions

1. There has been developed a calculation method of the winter greenhouse combined heating system which includes both overhead infrared radiators for heating the soil surface, and convective heaters for heating the indoor air.

2. When using radiant heating of the winter greenhouse, the following effects on the indoor thermal conditions have been factored in: the effect of infrared radiation repeated reflections and the walling self-radiation.

3. The equations set of heat and mass fluxes reflects the relation between evaporative processes on the soil surface and their influence on the indoor thermal processes.

4. The calculation method has been tested using a modern industrial greenhouse “Fermer 7.5” taking into account the initial data for a given region of construction.

5. It has been established that at low outdoor temperatures in case of indoor air ventilation heat consumption for heating needs is rather significant (≈ 66.4 kW). The heat load ratio of radiant heating to convective heating stands approximately at two to one.

6. The obtained change patterns of the heat power of the winter greenhouse combined heating system depending on a number of key factors allow to estimate the feasibility of using this heating method for specified climatic conditions. In addition, based on the constructed patterns it is possible to create an engineering calculation method of the combined heating system, as the program calculation requires a certain amount of time and the appropriate skill level of a technician. This method may include a graph for finding the base value of the heating system capacity, as well as a number of auxiliary patterns to determine the adjusting coefficients that take into account various factors.

7. Considering that the heat losses by ventilation turned out to be significant (75 % of the total heat losses), the authors of the work are planning to further research a possibility of preliminary heating the outside air up to the design temperature for the indoor air exchange needs.

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