Enhancing Energy Efficiency in Greenhouses: Gas-Radiant Heating with Preheated Ventilation

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Abstract. This paper presents an engineering methodology for calculating the heating system of a cultivation facility, employing ceiling-mounted infrared radiators as the primary heat source. The methodology addresses the challenge of maintaining consistent soil surface temperature amidst fluctuating weather conditions. Gas-fired air heaters supplement the system, preheating incoming air to achieve the desired thermal regime within the space. This approach enables designers to swiftly estimate the required heating equipment capacity and water consumption for soil irrigation under specified conditions. However, for more precise calculations encompassing the full spectrum of microclimate parameters and heat fluxes within the facility, advanced computational tools are necessary. The article details the essential input data for the engineering calculations (including approximate values where applicable) and analyzes the key findings. A case study of the "Farmer 7.5" industrial greenhouse in Moscow, Russia, demonstrates the application. The calculated results for the gas-radiant heating system capacity (34.0 kW), preheating energy consumption (38.9 kW), and irrigation water requirement (32.0 kg/h) were validated through computational analysis.
Keywords: gas-radiant heating; cultivation facility; gas-fired infrared radiator; gas-fired air heater; room microclimate.

1 Introduction

Energy efficiency is a pressing issue not only for residential and public buildings but also for agricultural facilities [1]–[7]. Focusing specifically on cultivation structures (greenhouses, orangeries, winter gardens, etc.), energy efficiency can be improved through three key approaches: space planning and construction solutions, and the selection of an optimal heating method.

The shape and orientation of a cultivation structure relative to the cardinal directions are particularly important when designing solar greenhouses (heliotеплицы). The building envelope of a cultivation structure must simultaneously provide thermal protection and allow for the transmission of sunlight. Achieving both conditions simultaneously is challenging, as increasing the thickness of the structure will inevitably reduce its light transmittance. Nevertheless, low-emissivity energy-saving glass and thermal curtains, used at night, have become widely used in greenhouse farming in recent years [7]–[12].

Let us focus specifically on heating cultivation structures. This is a particularly important factor, as maintaining the required microclimate parameters is essential for successful generative plant development in closed ground conditions [3], [5], [9], [13]–[15]. Due to the specific features and purpose of the building, effective operation of a cultivation structure requires heating not only the air but also the soil (ground), which necessitates additional energy consumption.

Gas radiant heating can be a solution to this problem. In this system, the soil surface receives heat from a gas infrared emitter. The heating system compensates for the heat energy deficit required to heat the indoor air by using a gas air heater. The use of gaseous fuel is a promising option, as obtaining heat energy will be cheaper than using electrical energy in any case. Additionally, it is potentially possible to utilize carbon dioxide from the combustion products of gaseous fuel for the photosynthesis reaction, which is vital for plants. The gas radiant heating system is autonomous, so there is no need to connect the cultivation structure to external heat sources [16]–[23].

Any heating method for a building object requires a corresponding engineering calculation methodology [1], [3]–[5], [7]–[11], [14], [15], [18], [22], [24]. The complexity of creating such a calculation lies primarily in radiant heating. The gas infrared emitter heats the soil surface to the required temperature, passively heating the cultivation structure. As previous studies have shown [5]–[15], [17]–[26], this "passive heat" is clearly insufficient to maintain the required thermal regime of the room during the winter period. Therefore, an additional heat supply is necessary. In this case, a gas air heater (calorifier unit) can perform this function, which is intended for heating the supply (outdoor) air.

This heating method, in contrast to other innovative energy supply technologies for cultivation structures: solar heating, heat pumps, geothermal energy sources or pyrolysis plants, is less dependent on climatic conditions and other local factors (solar radiation intensity, temperature in deep soil horizons, availability of local organic waste, etc.).

2 *Methodology*

Let us enumerate the input data required for calculating gas-radiant heating in a cultivation facility with preheating of supply air:

1. Indoor air parameters: The calculation requires the indoor air temperature $t_{int.air}$, in degrees Celsius (°C) and the relative humidity $\varphi_{int.air}$, in percentage (%). For year-round cultivation of vegetables (e.g., tomatoes, cucumbers, or greens), these parameters can be assumed as $t_{int.air} = 15$ °C and $\varphi_{int.air} = 60$ %, respectively. The microclimate within the cultivation facility is also influenced by the soil surface temperature $t_{soil\,surface}$, °C.

2. Outdoor air temperature: The outdoor air temperature $t_{ext.air}$, °C, is determined based on the relevant regulations applicable to the locality.

3. Air exchange rate: The air exchange rate n_{air}, m^3/min per $1\ m^2$ of calculated area is crucial for ventilation system design with mechanical stimulation. For instance, the normative air exchange rate for mechanical ventilation can be adopted as follows (minimum

values): $1.0\,m^3/min$ per 1 m^2 for individual winter greenhouses, $1.5\,m^3/min$ per 1 m^2 for industrial standard block-type greenhouses, and $2.0\,m^3/min$ per 1 m^2 for hangar-type greenhouses.

4. Thermal resistance of enclosing structure: The thermal resistance R_{enc} of the enclosing structure $m^2 \cdot K/W$, is determined based on thermal technical calculations. Table 1 presents approximate values of $R_{\text{огр}}$, $m^2 \cdot K/W$, for polycarbonate and organic glass (PMMA) depending on their thickness.

These input parameters are fundamental for conducting accurate calculations pertaining to gas-radiant heating systems in cultivation facilities with preheating of supply air.

Table 1 Thermal Insulation Characteristics of Enclosing Structures $R_{\text{огр}}$, $m^2 \cdot K/W$

Thickness of the wall δ, mm	4	6	8	10	16	20	25	32
Monolithic polycarbonate	0.017	0.026	0.034	0.043	0.068	0.085	0.11	0.14
Cellular polycarbonate	0.08÷0.10	0.11÷0.15	0.12÷0.26	0.13÷0.24	0.20÷0.35	0.21÷0.40	0.49÷0.52	0.47÷0.67
Organic glass (PMMA)	0.014	0.017	0.023	0.023	–	–	–	–

5. The coefficient of soil surface absorption, denoted as A, %, is dependent on factors such as color, roughness, slope of the surface, soil moisture, and vegetation cover. Table 2 presents the values of the coefficient A, %, for common soil types without vegetation cover.

Table 2 Absorptive Capacities of Various Soil Covers A, %

Soil Type	*A*, %	Soil Type	*A*, %
Dry Chernozem	86	Plowed Field (Moist)	86
Moist Chernozem	92	Surface of Clay Desert	69÷71
Dry Serozem	70÷75	Yellow Sand	65
Moist Serozem	88÷90	White Sand	60÷66
Dry Blue Clay	77	Gray Sand	77÷82
Moist Blue Clay	84	River Sand	57
Dry Vapor Field Surface	88÷92	Light, Fine Sand	63
Moist Vapor Field Surface	93÷95	Peat Dark Brown Fields	91

6. Additionally, geometric parameters of the cultivation facility include the soil surface area F_{soil}, m^2, and the volume of the space V, m^3.

The following parameters can be attributed to the results of calculating the gas-radiant heating system of the cultivation facility with preheating of supply air:

1. The total thermal power of the gas-fired infrared radiators $Q_{radiators}$, W, installed in the cultivation facility.
2. The total quantity $N_{radiators}$, arrangement scheme, and hanging height of the gas-fired infrared radiators above the soil surface.
3. The total thermal power of the gas-fired air heaters $Q_{heaters}$, W.
4. The total quantity $N_{heaters}$ of gas-fired air heaters.
5. The calculated water consumption for soil irrigation $G_{\text{пол}}$, kg/h.
6. The total quantity $N_{irrigation}$ and arrangement scheme of irrigation devices.

The total thermal power of the gas-fired infrared radiators and gas-fired air heaters for heating the cultivation facility, as well as the required water consumption for soil irrigation, should be determined according to the following equations:

$$Q_{radiators} = C_R C_A q_{radiators} F_{\text{пов}}, W, \tag{1}$$

$$Q_{heaters} = C_R' q_{heaters} V, W, \tag{2}$$

$$G_{irrigation} = g_{irrigation} F_{soil}, kg/h, \tag{3}$$

where C_R and C_R' are correction coefficients accounting for the influence of thermal resistance of the enclosing structure; C_A is a correction coefficient considering the absorptive capacity of the soil surface; $q_{radiators}$ is the radiant heat flux density, W/m^2, determined based on the outside air temperature $t_{ext.air}$, °C, and the air exchange rate n_{air}, m^3/min per 1 m^2, as shown in Figure 1; $q_{heaters}$ is the specific thermal power of the gas-fired air heater (Figure 2), W/m^3; $g_{irrigation}$ is the surface water consumption for soil irrigation (Figure 3), $kg/(m^2 \cdot h)$.

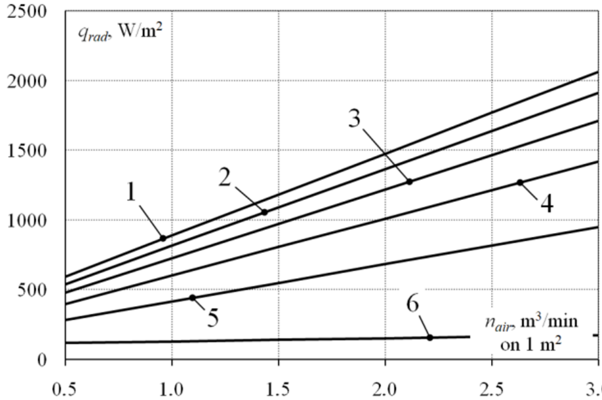

Fig 1 Graph for Determining the Surface Thermal Power of the Gas Infrared Radiator $q_{radiators}$, W/m^2, at Outside Air Temperature:
1 – $t_{ext\ air} = -40$ °C; 2 – $t_{ext\ air} = -30$ °C; 3 – $t_{ext\ air} = -20$ °C; 4 – $t_{ext\ air} = -10$ °C; 5 – $t_{ext\ air} = 0$ °C; 6 – $t_{ext\ air} = 10$ °C

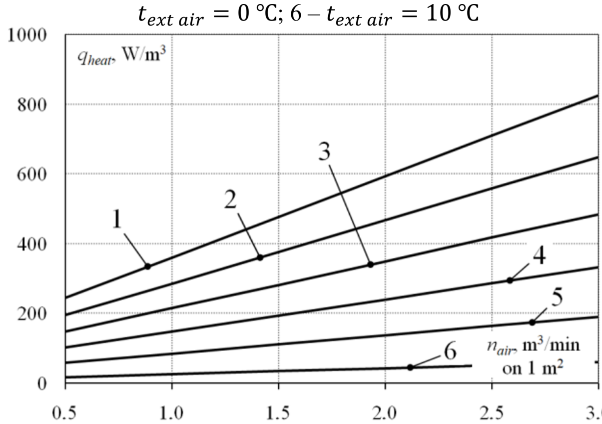

Fig 2 Graph for Determining the Specific Thermal Power of the Gas-Fired Air Heater $q_{heaters}$, W/m^3, at Outside Air Temperature:
1 – $t_{ext\ air} = -40$ °C; 2 – $t_{ext\ air} = -30$ °C; 3 – $t_{ext\ air} = -20$ °C; 4 – $t_{ext\ air} = -10$ °C; 5 – $t_{ext\ air} = 0$ °C; 6 – $t_{ext\ air} = 10$ °C

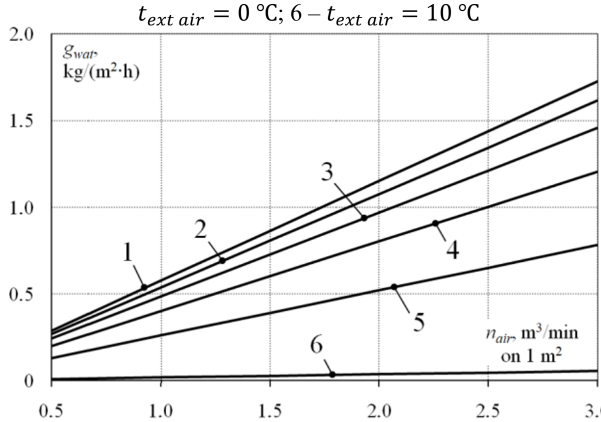

Fig 3 Graph for Determining the Surface Water Consumption for Soil Irrigation $g_{irrigation}$, $kg/(m^2 \cdot h)$, at Outside Air Temperature:

1 – $t_{ext\ air} = -40$ °C; 2 – $t_{ext\ air} = -30$ °C; 3 – $t_{ext\ air} = -20$ °C; 4 – $t_{ext\ air} = -10$ °C; 5 – $t_{ext\ air} = 0$ °C; 6 – $t_{ext\ air} = 10$ °C

Figure 4 illustrates a graph for determining the correction coefficients C_R and C_R'.

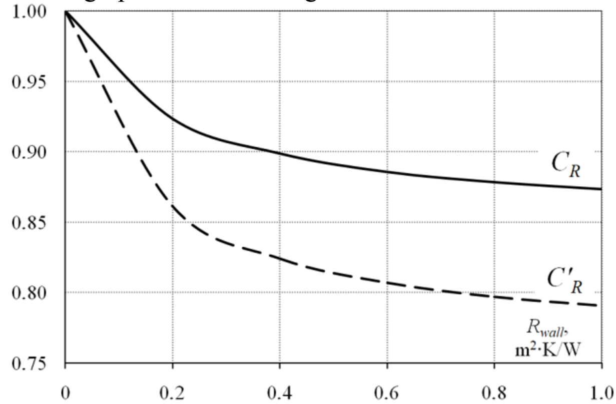

Fig 4 Graph for Determining Correction Coefficients C_R and C_R'

Figure 5 presents a graph for determining the correction coefficient C_A.

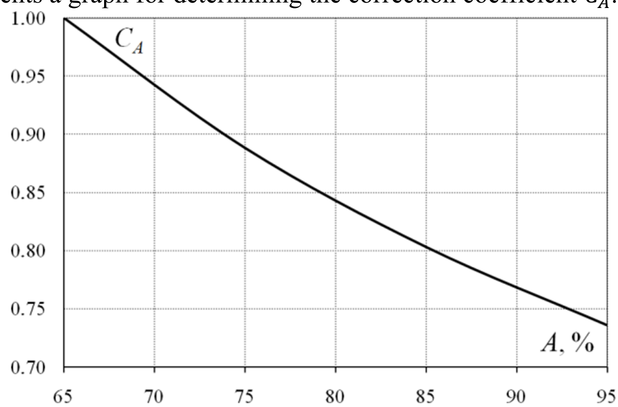

Fig 5 Graph for Determining the Correction Coefficient C_A

The required quantity of gas-fired infrared radiators, gas-fired air heaters, and irrigation devices to be installed in the cultivation facility is determined respectively by the following formulas:

$$N_{radiators} = \frac{Q_{radiators}}{Q_{nom}\eta_{radiators}}, \tag{4}$$

$$N_{heaters} = \frac{Q_{heaters}}{Q'_{nom}\eta_{heaters}}, \tag{5}$$

$$N_{irrigation} = \frac{G_{irrigation}}{G_{nom}}, \tag{6}$$

where Q_{nom} is the nominal thermal power of the gas-fired infrared radiator, W; $\eta_{irrigation}$ is the efficiency coefficient of energy conversion of the gas-fired infrared radiator, expressing the proportion of energy generated during the combustion of gaseous fuel and converted into infrared radiation; Q'_{nom} is the nominal thermal power of the gas-fired air heater, W; $\eta_{irrigation}$ is the efficiency of the gas-fired air heater; G_{nom} is the water consumption of one irrigation device, kg/h.

3 Results and Discussion

Consideration of the engineering methodology for calculating the gas-fired heating system of a cultivation facility with preheating of supply air will be illustrated using the example of the industrial greenhouse "Farmer 7.5" located in Moscow, Russian Federation.

The initial data for the calculation are as follows:

1. The calculated temperature and relative humidity of the indoor air are respectively $t_{in} = 15$ °C and $\varphi_{in} = 60$ %.
2. The calculated outdoor temperature for Moscow's conditions is $t_{out} = -25$ °C.
3. The air exchange rate $n_{air} = 1.0\, m^3/min$ per $1\, m^2$ of the calculated area of the industrial greenhouse.
4. The thermal resistance of the enclosing structure $R_{enc} = 0.25\, m^2 \cdot K/W$.
5. The surface absorption coefficient of the soil $A = 90$ %.
6. The surface area of the soil $F_{soil} = 62.58\, m$; the volume of the space $V = 183.085\, m^3$.

According to Figures 1-3, the density of radiant heat flux, the specific thermal power of the gas-fired air heater, and the surface water consumption for soil irrigation are respectively $q_{rad} = 770\, W/m^2$, $q_{heater} = 250\, W/m^3$ и $g_{irrigation} = 0.512\, kg/(m^2 \cdot h)$.

In accordance with Figures 4 and 5, the correction coefficients in Equations (1) and (2) will have the values: $C_R = 0.915$; $C_R' = 0.85$; $C_A = 0.77$.

Thus, according to Equations (1)-(3), we have the following results:

$$Q_{rad} = 0.915 \cdot 0.77 \cdot 770 \cdot 62.58 \cdot 10^{-3} = 34.0\, kW,$$
$$Q_{heater} = 0.85 \cdot 250 \cdot 183.085 \cdot 10^{-3} = 38.9\, kW,$$
$$G_{irrigation} = 0.512 \cdot 62.58 = 32.0\, kg/h.$$

Based on the results of computational analysis in the "Mathcad" mathematical editor using the developed method for calculating the gas-fired heating system of the cultivation facility with preheating of supply air, the following values were obtained: $Q_{rad} = 31.9\, kW$, $Q_{heater} = 35.0\, kW$ and $G_{irrigation} = 32.1\, kg/h$. As evident, the discrepancies between the corresponding values of Q_{rad}, Q_{heater} and $G_{irrigation}$ are within acceptable limits.

For the heating source in the industrial greenhouse "Farmer 7.5", a ceiling-mounted infrared radiator of the "SPACE-RAY SRU 35" model (North Carolina, USA) with a nominal thermal power of 34.5 kW can be installed. The weight of the unit is 66 kg. The infrared radiator can operate on natural gas (17÷25 mbar), propane (25÷45 mbar), or butane (20÷35 mbar). The height of suspension of the gas-fired infrared radiator above the soil surface is 3.8 m. In accordance with the device's technical specifications, the thermal radiation flux emanating from the gas-fired infrared radiator "SPACE-RAY SRU 35" will completely cover the soil surface area in the industrial greenhouse, as the necessary geometric conditions are met:

$$a_{rad} = 2.2h = 2.2 \cdot 3.8 = 8.36\, m > 7.45\, m \text{ (greenhouse width)},$$
$$b_{rad} = 2.5h + l_{rad} = 2.5 \cdot 3.8 + 5.51 = 15.01\, m > 8.4\, m \text{ (greenhouse length)}.$$

As a heat source for preheating supply air from the surrounding environment, the installation of a gas-fired air heater of the "Pakole GTV-40 A" model (Hungary) with a nominal thermal power of 40.0 kW is possible.

4 Conclusion

It should be noted that the developed engineering methodology is intended solely for approximate calculations and yields quite acceptable results when the ratio of areas $F_{soil}/F_{enc} = 0.4 \div 0.5$, where F_{enc} represents the area of enclosure of the cultivation facility, m^2. However, it can be applied to other values of F_{soil}/F_{enc}, since the quantities q_{rad}, q_{heater} and $g_{irrigation}$ are specific indicators (although deviations from computational results will increase in this case). For more precise calculations and determination of such important parameters as the temperature of the inner surface of the enclosure of the cultivation facility t_{enc}, °C, the temperature of the supply air t_{sup}, as well as for determining heat losses and gains in the space, it is necessary to perform computational calculations using the developed method for calculating the gas-fired heating system of the cultivation facility with preheating of supply air [27].

5 References

1. Xi, Xiuzhi and Duan, Dingli and Xu, Xiang and Liu, Feng and Zhang, Bo. *Performance assessment of a novel combined heating mode integrated greenhouse and closed drying system with a dual-temperature steam jet heat pump*. Sustainable Energy Technologies and Assessments. 53. 102470. **2022**. https://doi.org/10.1016/j.seta.2022.102470.
2. C. Maraveas, C.-S. Karavas, D. Loukatos, T. Bartzanas, K. G. Arvanitis and E. Symeonaki. *Agricultural Greenhouses: Resource Management Technologies and Perspectives for Zero Greenhouse Gas Emissions*. Agriculture. Vol. 13. No. 7. Pp. 1464. **2023**. https://doi.org/10.3390/agriculture13071464.
3. XiaoLong Wang, GuoChen Sun, LinHua Zhang, WenJun Lei, WenKe Zhang, HaoYi Li, ChunYue Zhang, JingChenxi Guo. *Application of green energy in smart rural passive heating: A case study of indoor temperature self-regulating greenhouse of winter in Jinan, China*. Energy. Volume 278. **2023**. 127770. ISSN 0360-5442. https://doi.org/10.1016/j.energy.2023.127770.
4. Bazgaou, A.; Fatnassi, H.; Bouharroud, R.; Tiskatine, R.; Wifaya, A.; Demrati, H.; Bammou, L.; Aharoune, A.; Bouirden, L. *CFD Modeling of the Microclimate in aGreenhouse Using a Rock Bed Thermal Storage Heating System*. Horticulturae. **2023**, 9, 183. https://doi.org/10.3390/horticulturae9020183.
5. Tianyang Xia, Yiming Li, Zhouping Sun, Xiuchao Wan, Dapeng Sun, Lu Wang, Xingan Liu, Tianlai L. *Performance study of an active solar water curtain heating system for Chinese solar greenhouse heating in high latitudes regions*. Applied Energy. Volume 332. **2023**. 120548. ISSN 0306-2619. https://doi.org/10.1016/j.apenergy.2022.120548.
6. A. J. Mendoza-Ferní¡ndez, A. Peña-Ferní¡ndez, L. Molina, and P. A. Aguilera. *The role of technology in greenhouse agriculture: Towards a sustainable intensification in campo de dalías (Almería, Spain)*. Agronomy. Vol. 11. No. 1. Pp. 1-14. **2021**. https://doi.org/10.3390/agronomy11010101.
7. Zhang C, Zou D, Huang X and Wu Y. *Study on hot air heating characteristics of greenhouse in cold region*. Front. Energy Res. 11:1038182. **2023**. https://doi.org/10.3389/fenrg.2023.1038182.
8. Brækken, August and Sannan, Sigurd and Ionut-Ovidiu, Jerca and Badulescu, Liliana. *Assessment of heating and cooling demands of a glass greenhouse in Bucharest, Romania*. Thermal Science and Engineering Progress. 41. 101830. **2023**. https://doi.org/10.1016/j.tsep.2023.101830.
9. Joudi, Khalid and Hasan, Mustafa. *Cooling and Heating a Greenhouse in Baghdad by a Solar Assisted Desiccant System*. Journal of Engineering. 19. 933-951. **2023**. https://doi.org/10.31026/j.eng.2013.08.01.
10. Ihoume, Ilham and Tadili, Rachid and Arbaoui, Nora and Krabch, Hind. *Design of a low-cost active and sustainable autonomous system for heating agricultural greenhouses: A case study on strawberry (fragaria vulgaris) growth*. Heliyon. 9. e14582. **2023**. https://doi.org/10.1016/j.heliyon.2023.e14582.
11. Hao, Wang and Jintao, Wei and Ruifeng, Zhang and Zhenjun, Xu. *Study of Solar Combined Air Energy Greenhouse Heating System Model*. Frontiers in Energy Research. **2022**. https://doi.org/10.3389/fenrg.2022.927048.
12. Sun, Weituo and Wei, Xiaoming and Zhou, Baochang and Lu, Chungui and Guo, Wenzhong. *Greenhouse heating by energy transfer between greenhouses: System design and implementation*. Applied Energy. 325. 119815. **2022**. https://doi.org/10.1016/j.apenergy.2022.119815.
13. Bista, P., Hartman, M.D., DelGrosso, S.J. et al. *Simulating long-term soil carbon storage, greenhouse gas balance, and crop yields in semi-arid cropping systems using DayCent model*. Nutr Cycl Agroecosyst. **2024**. https://doi.org/10.1007/s10705-023-10335-4.

14. Hegazy, Anwar and Subiantoro, Alison and Norris, Stuart. *Closed Greenhouse Heating in an Arid Egyptian Winter Using Earth-Air Heat Exchangers*. Conference: ASME 2021 International Mechanical Engineering Congress and Exposition (IMECE2021-69509, V011T11A077). **2021**. https://doi.org/10.1115/IMECE2021-69509.
15. Persson, Tomas and Chaillou, Amélie and Huang, Pei. *Low temperature heating system for greenhouses based on enclosed water curtain and liquid foam insulation*. Sustainable Energy Technologies and Assessments. 53. 102472. **2022**. https://doi.org/10.1016/j.seta.2022.102472.
16. Reinoso Moreno, José Vicente and Pinna Hernández, María Guadalupe and Sánchez-Molina, Jorge and Fernández, M.D. and Hernández, Juna Carlos and Fernández, F.G. *Carbon capture from biomass flue gases for CO2 enrichment in greenhouses*. Heliyon. 10. e23274. **2023**. https://doi.org/10.1016/j.heliyon.2023.e23274.
17. Molina-Aiz, F.D. and Honore, M. and Fatnassi, Hicham and Valera, Diego and López, A. and Moreno-Teruel, M.A. *Experimental and numerical assessment of carbon sequestration in horticultural crops inside Mediterranean naturally ventilated greenhouses*. Acta Horticulturae. 117-126. **2023**. https://doi.org/10.17660/ActaHortic.2023.1377.14.
18. Zarei, Ghasem and Khaledi, Mohammad. *Zoning the heating and cooling requirements of several major greenhouse plants in Iran*. 11. 27-35. **2023**. https://doi.org/10.22125/AGMJ.2023.367371.1141.
19. Felek, T., and Kürklü, A. *Climate Control and Irrigation Automation Systems in Turkish Greenhouses: A Comparative Study*. Asian Journal of Agricultural and Horticultural Research, 10(4), 394-417. **2023**. https://doi.org/10.9734/ajahr/2023/v10i4281.
20. Léveillée-Dallaire, Xavier and Raymond, Jasmin and Snæbjörnsson, Jónas and Fujii, Hikari and Langevin, Hubert. *Performance Assessment of Horizontal Ground Heat Exchangers under a Greenhouse in Quebec, Canada*. Energies. 16. 5596. **2023**. https://doi.org/10.3390/en16155596.
21. Boyaci, Sedat and Atilgan, Atilgan and Kocięcka, Joanna and Liberacki, Daniel and Rolbiecki, Roman and Jagosz, Barbara. *Determination of the Effect of a Thermal Curtain Used in a Greenhouse on the Indoor Climate and Energy Savings*. Energies. 16. **2023**. https://doi.org/10.3390/en16237744.
22. Ghaderi, Mohsen and Reddick, Christopher and Sorin, Mikhail. *A Systematic Heat Recovery Approach for Designing Integrated Heating, Cooling, and Ventilation Systems for Greenhouses*. Energies. 16. 5493. **2023**. https://doi.org/10.3390/en16145493.
23. Dimitropoulou, Anna-Maria and Maroulis, Vasileios and Giannini, Eugenia. *A Simple and Effective Model for Predicting the Thermal Energy Requirements of Greenhouses in Europe*. Energies. 16. 6788. **2023**. https://doi.org/10.3390/en16196788.
24. Bodaghi, Morteza and Esmailpour, Kazem and Refahati, Nima. *Feasibility study and thermoeconomic analysis of cooling and heating systems using soil for a residential and greenhouse building*. **2023**. https://doi.org/10.48550/arXiv.2304.05507.
25. Asibeluo, Uzuazokaro and Ekruyota, Ovuakporaye. *Design and Development of Smart Agricultural Greenhouse*. Turkish Journal of Agricultural Engineering Research. 4. 191-202. **2023**. https://doi.org/10.46592/turkager.1362000.
26. Maranghi, Florian and Raymond, Jasmin. *Numerical Evaluation of the Benefits Provided by the Ground Thermal Inertia to Urban Greenhouses*. Thermo. 3. 452-482. **2023**. https://doi.org/10.3390/thermo3030028.
27. Mikhail Pavlov and Denis Karpov. Scientific and technical journal "Energy saving and water treatment". *Calculation method of winter greenhouse combined heating system*, 5 (127), 26-32. **2020**.