MICROCLIMATE CONDITIONS AND THE DESIGN OF OPTIMAL HEAT TRANSFER IN GREENHOUSES

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Abstract

In this paper, we present the contributions of a microclimate enclosure for cultivating plants and a mathematical model of heat transfer for greenhouses without cultivation, from which it will be possible to define the heat balance of different months, taking into account day and night effects on the microclimate of greenhouses.

Key words: *greenhouses, heating, heat balance, radiation, microclimate*

1. INTRODUCTION

New events in the field of garden crop and flower cultivation in greenhouses display the need for a more precise examination of energy sources necessary for these processes. As greenhouses represent one of the oldest methods of industrial use of solar energy, their efficient use demands a precise study of the heat interchange of the greenhouse and the climate conditions of the area where the greenhouse is located. For a calculation of the needs and demands of the greenhouse, computer programmes as well as simpler graphic methods may be used. In order to limit the number of variable parameters, it is necessary to precisely study certain simplified presuppositions. The below described methods are used mainly for the calculation of heat balance in extreme conditions and may be used in any climate area.

2. MICROCLIMATE IN THE GREENHOUSE (Osvald, 1994)

In the greenhouse, we must create an adequate microclimate in order to create optimal conditions for cultivated plants, as well as adequate heat and light, which are adjusted manually or by computer.

The main factors that efficiently influence microclimate are:

- illumination,
- air temperature,
- ground temperature,
- carbon dioxide concentration,
- humidity of ground and air and
- ventilation,

taking into account limits, such as:

- maximum permissible lighting based on temperature of leaves,
- minimum permissible temperature of interior surface of transparent barrier and
- maximum permissible speed of air.

2.1 Light and illumination (Giacomelli, 1993; Mettawee, 2002)

Light is one of the main factors that enable successful growth and a large crop. This is why it is often necessary to execute measures that enable adequate illumination, such as:

- regular cleaning of roofing,
- supplementary lighting when cultivating light-demanding plants; namely, when cultivating in an area where there is less light and during light-poor periods;
- shading – veiling when cultivating demanding garden crops in periods where illumination and heat are too strong. We achieve this by fitting various shades – energy curtains or by painting the glass of the greenhouse with lime milk and renewing it after each large rainfall.

The intensity of light in the greenhouse is dependent on the roofing and the angle of incidence of solar rays. For the majority of cultivated plants, there must be a minimal illumination of 5,000 to 6,000 lux, which must span 8 to 10 hours daily. Based on the process of photosynthesis, the level of illumination is determined by an equation.

$$A = \frac{E \cdot A_{\max}}{E + EE} \qquad [\text{mg } CO_2/(m^2 s)] \tag{2.1}$$

where: A intensity of photosynthesis

A_{max} maximum intensity of photosynthesis for a specific plant

EE intensity of illumination (lux)

E current level of illumination (lux)

For each plant, it is possible to create diagrams that enable the determination of the intensity of photosynthesis in actual lighting conditions and the growth control of the plant (Fig. 1). Photosynthesis of the leaves of the plant is expressed in units of carbon dioxide, which is absorbed per unit of leaf in a unit of time, that is, mg $CO_2/(m^2s)$. Besides intensity, illumination is also important for a plant. Of the entire spectrum of incident light, only the spectrum above 0.7 μm directly affects the plant's life processes.

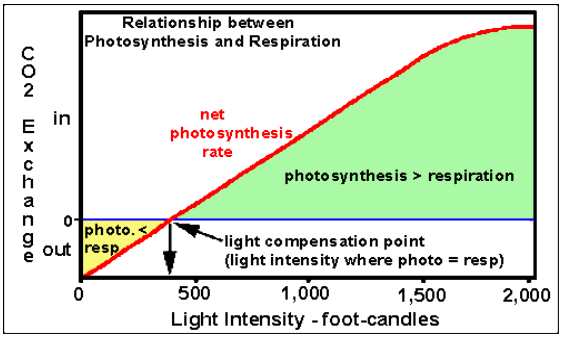


Fig. 1 Intensity of photosynthesis in relation to illumination (Generalhorticulture)

2.2 Air temperature

Special attention must be given to the maintenance of optimal temperature of the space due to growth and avoidance of unfavourable temperature changes. In special circumstances, it is permissible for the

temperature to fall below the biological minimum for 24 hours and the temperature to rise above the biological maximum for 4 to 6 hours. Temperature for good growth is dependent upon the temperature of the soil and the walls, emissivity of the wall surface and infrared radiation.

Increasing the intensity of the lighting and the air temperature leads to an increase in photosynthetic activity, but only to a certain border temperature, at which photosynthetic activity begins to decrease and the process of respiration begins.

The day temperature is regulated in relation to solar radiation and is regularly 5 to 7°C higher than the night temperature. The day temperature regulates the photosynthetic activity of the plant, the night temperature, the plants' breathing (use of assimilated materials). The relationship between the day and night temperatures affects the speed of growth and the development and quantity of yield. The most critical time is during the night, which is why it is necessary to carry out an analysis of the relative heat balance on the basis of which the average temperature of the plant may be determined. The temperature of the soil, which has often not been taken into account in analyses, is one of the most significant parameters, as it affects plant growth and must urgently be studied more in depth, in order to correctly direct energy.

Fig. 2 displays the temperature change in a greenhouse in the spring at a nominal temperature of 20°C, which is suitable for the cultivation of pelargonium.

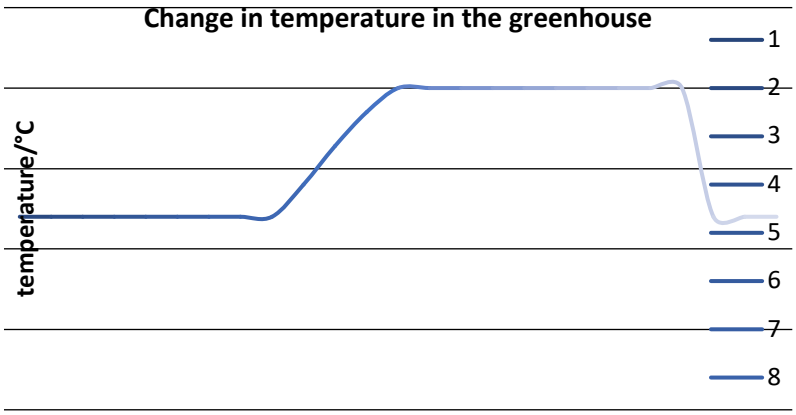


Fig. 2 Change in temperature in the greenhouse at a nominal temperature of 20°C (Aaslyng, 2003)

During the time of photosynthesis and at the end of the day, a period of maximum heating is necessary in order to enable plants to absorb and hold in the substances necessary for growth.

The amount of energy needed is highly dependent on the climate area in which the greenhouse is located, the needs of the cultivated plants, the method of use of the greenhouse, the type of covering and the external temperature.

In favourable conditions, the following amounts arrive to the surface of the greenhouse floor:

- 70 to 80% of solar rays - summer,
- up to 50% of solar rays - winter.

Due to dirt, the permeability of the covering is decreased from 20% to as much as 70% in the case of very dirty roofing.

The amount of heat that remains in the greenhouse as a result of solar radiation, in relation to the type of covering, is displayed in Table 1.

Table 1: Heat balance of greenhouse in relation to type of covering (J/cm^2), according to Vesneus (Mettawee, 2002)

	PE	PVC	Polyester and PVC sheets	Glass
Amount of solar energy outside structure	1,700	1,700	1,700	1,700
Amount of energy arrived into greenhouse interior	1,340	1,340	1,170	1,430
Heat loss – day	230	130	0	0
Heat loss – night	950	730	118	0
Remainder of energy in greenhouse (morning)	170	486	1,060	1,430

2.3 Ground temperature

The necessary temperature of the greenhouse ground depends on the phase of plant development, intensity of photosynthesis and the temperature equilibrium of the plant. Table 2 displays the values for the example of tomato cultivation.

Table 2 Optimal temperature range for the root system of a tomato (Mettawee, 2002)

Development phase	**Optimal temperature range of soil/K**	
	Weak illumination	Strong illumination
Development prior to blossoming	286 ÷ 287	290 ÷ 293
Blossoming	288 ÷ 289	292 ÷ 295
Developed plant	293 ÷ 295	296 ÷ 298

2.4 Humidity of ground and air

The system for providing the plant with water depends on the type of plant (transpiration coefficient is 350 to 700 l/kg of dry weight of garden crop), areas of development of the root system, cultivar, period of cultivation, and technical possibilities of the irrigation system. The most adequate provision of plants with water when cultivating in a secure area with regular soil cultivation is the drip system in combination with the fogging and sprinkler irrigation system. This system enables an optimal humidity of the soil substrate in the root area; at the same time the air is adequately humid and the overheating of the leaf surface is decreased.

Air humidity in the greenhouse is one of the main conditions for intense photosynthetic activity. Deviance from the relatively narrow ranges of optimal air humidity directly affects plant development, with the phase of plant blossoming most affected.

The necessary humidity of the ground for a specific culture depends on the collective needs of the plants and the amount of humidity that evaporates into the air of the greenhouse. Ground composition, method of water inflow, the branching of the root system, ground temperature, ground treatment and method of water distribution in the ground are factors that commonly determine the need of the plant for water. If the inflow of water is not adequate, the self-regulated temperature of the leaf mass of the plant may fail and lead to overheating, causing the plant to wither and die. The recommended speed of air movement in the plant area is between 0,2 and 0,7 m/s, except for certain plants with special growth needs.

3. HEAT BALANCE (Kurevija, 2004; Naterer, 2003; Duffie, 1991)

The following factors affect the heat balance of a greenhouse:

- the Sun, with shortwave radiation;
- the area of the greenhouse, with transfer of long wave radiation into thermal radiation;
- external environment, transfer of thermal radiation;
- air currents flowing into the greehouse;
- air in the greenhouse;
- ground and plants in the greenhouse; (a heat interchange is created with the radiation of the internal walls of the greenhouse, transmitting of heat to internal air and evaporation and transpiration).

3.1 Thermal balance – method of analysis

The calculation is based on the following presumptions:

- temperature of the soil in the greenhouse and the environment is uniform horizontally (T_{in} and T_{out}),
- temperature of the air in the greenhouse and the environment is uniform vertically and horizontally (T_{ain} and T_{aout});
- temperature of the transparent wall (T_{st}) is uniform;
- the wall is without thermal inertia;
- the soil and wall are gray bodies;
- the greenhouse is without vegetation.

The heat requirements of the greenhouse, according to the below equation (3.1), determine the:

- heat flow rate necessary for the heating of refreshed air (Φ_{as});
- heat flow rate necessary for the maintenance of humidity of refreshed air (Φ_{al});
- heat flow rate necessary for recovering of heat loss created in heat interchange with soil (Q_{cs});
- heat flow rate necessary to recover losses through transparent roofing (Φ_{cp}).

$$\Phi = \Phi_{as} + \Phi_{al} + \Phi_{cs} + \Phi_{cp} \tag{3.1}$$

3.2 Heat balance of fresh air

The quantity of fresh air depends on the greenhouse type, its permeability for external air and the ventilation conditions.

Within the infiltration of fresh air, we distinguish:

- uncontrolled entry of external air into the greenhouse,
- controlled entry of external air into the greenhouse.

In regular greenhouses, uncontrolled entry of air is expressed by the value of the total greenhouse volume per unit of time (vol. green./h) – equation (3.2):

$$R = a \cdot v^2 + b \cdot (T_{ain} - T_{aout}) \quad [\text{vol. green./h}] \tag{3.2}$$

where:

a, b empirical constants dependant on the achieved airtightness of the greenhouse, wind direction and height of greenhouse;

v speed of wind.

The empirical relation of changes in uncontrolled entry of air (R), dependant on change of speed and wind direction, is given by equation (3.3.),

$$R = (0.19 + 4.5 \cdot 10^{-3} \cdot v + 10^{-4} \cdot v^2) \cdot c \cdot v \tag{3.3}$$

where:

c correction factor of angle of incidence of air currents,

v speed of wind.

The thermal influence of the infiltrated air is calculated by equation (3.4.),

$$\Phi_a = \Phi_{as} + \Phi_{al} = R \cdot V \cdot (H_u \cdot \rho_u - H_s \cdot \rho_s) \quad [\text{W}] \tag{3.4}$$

where:

Φ_a total heat load of infiltrated air (W),

Φ_{as} considerable heat load (W),

Φ_{al} latent heat load (W),

V volume of greenhouse (m^3),

H_u enthalpy of internal air (kJ/kg),

H_s enthalpy of external air (kJ/kg),

R quantity of infiltrated air (vol.green./h),

ρ_u density of internal air (kg/m^3),

ρ_s density of external air (kg/m^3).

In the calculation, we do not take into account the effect of condensation on the walls of the greenhouse.

3.3 Heat requirements due to convection

For simpler calculation, let us assume that the coefficient of heat transmittance due to convection between internal air, soil and walls of the greenhouse, is constant. The heat load due to convection is calculated with equation (3.5):

$$\Phi_b = \Phi_{cs} + \Phi_{cp} = A_t \cdot U \cdot (T_{ain} - T_{in}) + A \cdot U \cdot (T_{ain} - T_{st}) \quad (3.5)$$

where:

Φ_b entire heat flow rate due to convection (W),

Φ_{cs} heat loss due to convection with soil (W),

Φ_{cp} heat flow rate due to convection with transparent roofing (W),

U coefficient of heat transmittance from walls and soil to internal air (W/m^2),

A_t surface area of ground in greenhouse (m^2),

A surface area of external walls (m^2),

T_{in} temperature of ground in greenhouse (K),

T_{ain} temperature of air in greenhouse (K),

T_{st} temperature of walls (K).

For the calculation of Φ_b , we must know:

- T_{st} – the temperature of the transparent walls,
- T_{stin} – the temperature of the interior surface of the transparent wall (K),
- T_{stiout} – the temperature of the exterior surface of the transparent wall (K),

For greenhouses with a double-wall, the equation (3.6) applies.

$$\Phi_b = A_t \cdot U \cdot (T_{ain} - T_{in}) + A \cdot U \cdot (T_{ain} - T_{stin}) \quad (3.6)$$

The equation (3.6) must be corrected by taking into account the effect of wind, for which we use equation (3.7).

$$\alpha_{aoutv} = 2 + 10 v_v \quad [W/m^2K] \quad (3.7)$$

where:

α_{aoutv} coefficient of heat transfer between the transparent wall and the exterior air due to effect of wind (W/m^{2}K),

v_v speed of wind (m/s).

In the case of heat transfer via conduction from the interior to the exterior surface of the wall, we calculate the heat flow rate with equation (3.8).

$$\Phi_{cc} = \frac{\lambda_p}{d_p} A (T_{stin} - T_{stout}) \quad (3.8)$$

where:

λ_p heat conductivity of wall (W/mK),

d_p thickness of wall (m).

4 EFFECT OF RADIATION OF TRANSPARENT WALL ON HEAT BALANCE (Lilic, 2000; Planning, 2005)

4.1 Night cycle

In general, if the wall accepts radiation from the interior of the greenhouse, we calculate heat loss due to radiation with equation (4.1).

$$\Phi_{rn} = \varepsilon_i \cdot \varepsilon_p \cdot \sigma \cdot A_t \cdot (T_{in}^{\ 4} - T_{stin}^{\ 4}) \tag{4.1}$$

where:

ε_p emissivity factor of transparent wall;

ε_i emissivity factor of soil without plants;

σ Stefan-Boltzmann constant.

Equation (4.1) is valid in the event that the wall absorbs infrared radiation emitted by the soil. If the absorption of the wall (α_p) is lesser than or equal to one, equation (4.2) applies.

$$\Phi_{rn} = \varepsilon_i \cdot \varepsilon_p \cdot \alpha_p \cdot \sigma \cdot A_t \cdot (T_{in}^{\ 4} - T_{stin}^{\ 4}) \tag{4.2}$$

The heat flow rate of the radiation of the walls to the external air of the environment is calculated by equation (4.3).

$$\Phi_{re} = \varepsilon_i \cdot \varepsilon_p \cdot \alpha_p \cdot \sigma \cdot F_a \cdot A \cdot (T_{stout}^{\ 4} - T_e^{\ 4}) + \cdot \varepsilon_p \cdot \alpha_p \cdot \sigma \cdot F_v \cdot A \cdot (T_{stout}^{\ 4} - T_c^{\ 4}) \tag{4.3}$$

where:

F_a non-dimensional corner factor, dependent on the soil and the walls of the greenhouse. In the case of greenhouses with convex walls, it is calculated with equation (4.4).

$$F_a = \frac{x-1}{2x} \tag{4.4}$$

where:

x ratio between the surface of the roofing walls and covered surfaces ($x = A/A_t$).

F_v non-dimensional corner factor between the greenhouse wall and the external atmosphere;

In the event of convex walls, it is calculated with equation (4.5).

$$F_v = \frac{x+1}{2x} \tag{4.5}$$

T_e temperature of soil outside greenhouse (K)

T_c temperature of sky (K), which is treated as a black body, with an emissivity factor of one

The temperature of the sky is dependent on the temperature of the air at the surface of the soil and its relative humidity and can be calculated using the Brant equation (4.6).

$$T_c^4 = T_{cout}^4 \left(0{,}55 + 0{,}0567\sqrt{P_{ae}}\right) \tag{4.6}$$

where:

(mbar) partial pressure of water in external air, at a temperature of T_{aout}.

Taking into account all the previous statements, we can note the following equations:

a) The wall receives heat flow from the interior through convection and radiation - equation (4.7).

$$\Phi_1 = A \cdot U \cdot (T_{ain} - T_{stin}) + \varepsilon_i \cdot \varepsilon_p \cdot \alpha_p \cdot \sigma \cdot A_t \cdot (T_{in}^4 - T_{stin}^4) \quad (4.7)$$

b) The wall transfers heat flow with conduction from internal to external surface - equation (4.8).

$$\Phi_2 = \frac{\lambda_p}{d_p} A (T_{stin} - T_{stout}) \quad (4.8)$$

c) The external surface of the transparent wall emits heat flow with convection and radiation to the firmament - equation (4.9).

$$\Phi_3 = \varepsilon_i \varepsilon_p \alpha_p \sigma F_\alpha A (T_{stout}^4 - T_s^4) + \varepsilon_p \alpha_p \sigma F_v A (T_{stout}^4 - T_c^4) + A \alpha_{aout} (T_{stout} - T_a) \quad (4.9)$$

Because the walls have a negligible amount of inertia, equality (4.10) applies:

$$\Phi_1 = \Phi_2 = \Phi_3 = \Phi \quad (4.10)$$

4.1.1 Temperature of ground in greenhouse - simplifications

Due to a large thermal inertia, the heat balance of the soil can be expressed by Fourier's differential equation (4.11):

$$\frac{\partial t}{\partial \tau} = \frac{\partial^2 t}{\partial x^2} \quad (4.11)$$

The equation can be solved numerically only if all the characteristics of the ground are known, which is very difficult in practice. This is why it is necessary to take into account certain simplifications:

- In the case of very long greenhouses, where the ratio between the length and the width is greater than or equal to five, we assume that the ground has infinite conductivity and that the temperatures of the external and internal ground and the temperature of the external air are equal.
- When the soil does not function as an infinite conductor, we may note the heat balance of the ground surface.

The heat flow that the ground receives is equal to the amount of heat flow that is accumulated in the ground and the heat flow towards the greenhouse walls. Equation (4.12) applies:

$$A_t U_{ain} (T_{ain} - T_{in}) = \Phi_s A_t + \varepsilon_i \varepsilon_p \alpha_p \sigma A_t (T_{in}^4 - T_{st}^4) + \varepsilon_i \tau_{ic} \sigma A_t (T_{in}^4 - T_c^4) \quad (4.12)$$

where:

τ_{ic} permeability of the transparent wall

Φ_s heat flow rate of the Sun.

Equation (4.12) can also be written in the form of (4.13):

$$A_1 T_{in}^4 + B_1 T_{in} + C_1 = 0 \quad (4.13)$$

where coefficients A_1, B_1 in C_1 are determined by equations (4.14), (4.15) and (4.16).

$$A_1 = \sigma \alpha_p \varepsilon_p \varepsilon_i + \varepsilon_i \tau_{ic} \sigma \quad (4.14)$$

$$B_1 = U_{ain} \quad (4.15)$$

$$C_1 = -(\varepsilon_i e_p \alpha_p \sigma T_{stin}^4 + U_{ain} T_{ain} - \Phi_s + \varepsilon_i \tau_{ic} \sigma T_c^4) \quad (4.16)$$

The heat flow rate of the Sun depends on the thermal inertia of the soil, watering, type of culture being cultivated, etc. In the case of cultivation of traditional cultures, the values for density of solar heat flow vary between 25 and 35 W/m^2. The given equations enable iterative calculation of the temperature of the walls and temperature of the ground in the greenhouse.

4.2 Day cycle

When noting the heat balance, as a result of radiation throughout the day, we assume an equal temperature of the ground inside and outside the greenhouse.

The sky is treated as a black body with an imaginary temperature of T_c, which is dependent on the temperature in the lower atmosphere, T_{aout}. The interdependence of both temperatures is given by equation (4.17).

$$T_c^4 = 0{,}72\, T_{aout}^4 \quad (4.17)$$

For a simplification of the calculation, we may use Lambert's Law, which states that the sky radiates uniformly, that visible radiation becomes infrared radiation, and that we must take into account corner factors between the wall and the sky. Simplification is also achieved by the presumption that transparent walls enable a complete and uniform casting of light.

For a calculation of the heat flow accepted by the wall (Φ_d), we must take into account the albedo (reflectance) of the Earth for visible radiation as well as the internal effect of the walls on the system as described by equation (4.18).

$$\Phi_d = A\alpha q_c \left(\frac{x+1}{2x}\right) + \alpha(1-\alpha) A q_c \left(\frac{x-1}{x}\right) + \alpha(1-\alpha) A_t \rho_{ok} q_c + A_t \alpha (\quad (4.18)$$

where:

Φ_d heat flow, received by the transparent wall,

ρ_{ok} albedo (for ground without plants from 0.10 to 0.25, with plants from 0.15 to 0.30);

α coefficient of absorption of transparent wall for visible radiation,

q_c intensity of solar radiation measured on the horizontal surface of the greenhouse (W/m^2),

F non-dimensional corner factors

The surface of the greenhouse receives direct radiation $q_c A_t F_v$, as a certain percentage (n) of the radiation is absorbed, the rest is transmitted; thus, it is not necessary to take into account the reflexivity factor. The transmitted part of the radiation amounts to $q_c A_t F_v(1-\alpha)$.

Part of the transferred energy returns to the wall from the interior, with the help of the corner factors of the interior walls ($F_{st.}$). In the stated conditions, the corner factor on the interior wall can be calculated with equation (4.19).

$$F_{st} = 1 - \frac{A_t}{A} = \frac{x-1}{x} \tag{4.19}$$

The walls receive energy from the soil in the greenhouse, which is dependent on the albedo. The chain of events is as follows: the interior ground receives a certain amount of energy from the external surface of the wall; because there is no inertia, equation (4.20) applies.

$$q_c A_t F_i(1-\alpha) = q_c A F_{ii}(1-\alpha) \tag{4.20}$$

Because the value of the factor F_{ii} equals 1, this parameter will receive $q_c A$ (1-α), absorb $q_c A F_{ii}$(1-ρ_{ok})(1-α), and return to the wall $q_c A F_{ii}\rho_{ok}$(1-α) energy. At the end, the wall absorbs $q_c A \rho_{ok}$ α(1-α) energy. Of course, the influence of the soil outside the greenhouse also exists, which we acknowledge with the expression $q_c A_t \rho_{ok}$ αF_t.

4.2.1 Temperature of ground in greenhouse - simplification

The hypothesis regarding the ground as an infinite conductor, which can allow maximum heat losses during the night, does not apply to the day cycle. In this case, it is better if we presume that the soil is a partial or complete insulator.

Suitable to the heat balance of the ground, which was expressed in equation (4.12), can in this case be expressed in equation (4.21).

$$A' T_{in}^4 + B' T_{in} + C' = 0 \tag{4.21}$$

From the expression C´, we subtract the heat flow absorbed by the soil: $G_c A_t$(1- ρ_{ok})(1-α).

4.2.2 Energy received by the greenhouse from the walls

Equation (4.22) applies.

$$H_{stout} + H_{stin} = \frac{\alpha q_c A}{x}\left(x\left(\frac{3}{2} + \frac{\rho_{ok}}{2} - 2\right) + \alpha + \frac{\rho_{ok}}{2}\right) \tag{4.22}$$

where:

H_{stout} solar radiation absorbed by the exterior surface of the transparent wall,

H_{stin} solar radiation absorbed by the interior surface of the transparent wall

In determining the heat balance of the wall, we must add to the heat flow received by the interior surface of the wall, the solar radiation absorbed by the interior surface of the wall, and the solar radiation absorbed by the exterior surface of the wall, in order to balance it with the heat flow coming through the exterior surface of the wall. The equations (4.23), (4.24), (4.25) and (4.26) apply.

$$\Phi_{inst} = H_{stin} + A U_{ain}(T_{ain} - T_{stin}) + \varepsilon_i \varepsilon_p \alpha_p \sigma A_t (T_{in}^4 - T_{stin}^4) \tag{4.33}$$

$$\Phi_{stp} = U_{st} A (T_{stin} - T_{stout}) \tag{4.34}$$

$$\Phi_{outst} = -H_{stout} + AU_{aout}(T_{stout} - T_{aout}) + \varepsilon_i \varepsilon_p \alpha_p \sigma A F_a \left(T^4_{stout} - T^4_{aout}\right) + \varepsilon_p \alpha_p \sigma A F_v (T^4_{stout} - T^4_{cs}) \quad (4.35)$$

$$\Phi_{inst} = \Phi_{stp} = \Phi_{outst} = \Phi_{st} \quad (4.36)$$

where:

Φ_{inst} heat flow rate, which is transferred from the greenhouse interior to the transparent roofing;

Φ_{stp} heat flow rate through the walls,

Φ_{outst} heat flow rate received by the environment from the greenhouse walls.

A solution to the equations of daily heat balance is enabled by the calculation of the temperature of the walls, internal temperature, heat loss due to convection with the soil, heat loss through the walls (Φ_b), as well as the quantity of heat necessary for the provision of suitable conditions in the greenhouse.

5. DECREASING HEAT LOSSES (Krope, 1997; Lilic, 2000, Oletic, 2001)

A decrease in heat losses and savings in thermal energy in greenhouses can be achieved in various ways. In the case of classic heating, energy can be saved by supplying energy only to the area where plants are cultivated and so preventing the rising of warm air to the higher layers of the greenhouse. In order to decrease heat losses, it is necessary to increase the effect of solar radiation with active or passive use.

5.1 Passive use of solar energy

We can use solar energy in a passive manner:

- for heating concrete floors in the greenhouse or
- for heating water in wide polythene pipes.

The effect of passive energy is greater if we use an energy curtain or many-layered covering to decrease the loss of energy through the roofing.

5.2 Active use of solar energy

In active systems for use of solar energy, special collectors filled with energy obtained from solar cells or heat pumps are used. From the heat collector, heated water is transported with the help of a regulatory system along the cable management system into areas dedicated to plant cultivation.

Filling of the collector takes place with the removal of heat from the air of the greenhouse with the help of the ground heat transferrer. For stationary status, equality/equation (5.1) applies:

$$m_z \cdot c_z \cdot (-dT) = k\,(T_u - T_{ac})dA \quad (5.1)$$

On the basis of equation (5.1), it is possible, through integration along the entire surface of the heat transferrer, to calculate the return air temperature, T_A. Thermal energy, which flows from the air to the heat collector can be calculated with equation (5.2):

$$d\Phi = \rho_u \cdot V_z \cdot C_z \cdot (T_u - T_A)dt \quad (5.2)$$

In the growth season, when the air temperature of the greenhouse (T_A) becomes lower than the temperature of the first layer in the heat collector, the process of heat removal from the collector begins.

6. CASE STUDY OF GREENHOUSE HEATING

6.1 Basic information

The subject of this study, namely of these calculations, is the greenhouse in Fig. 3, dedicated to cultivating pelargonium and located on a fairly open location in the orientation SW – NE. It is built of four naves, of which one is meant as a sales centre. There are no tall buildings in the vicinity, nor are there tall trees, which would cast shade and thus prevent the passage of light to the plants. The foundations of the greenhouse are post and beam bands, the means of support are entirely of metal and are anti-corrosively tinned; the entire structure is covered with glass; the roof is safety glazed.

The façades, up to a height of 50cm, are protected with AB preparations, first to the whorls, and the roof is entirely covered with glass; the load-bearing construction is tinned and decoratively painted green.

The panels of the roofs above the four naves of the greenhouse are at an angle of 20°; the ridges are in the SW – NE orientation; the gutters between the neighbouring panels have internal drains along the load-bearing columns; the roofing is comprised of toughened, safety glazed glass in metal mountings.



Fig. 3: Construction of the greenhouse

Average, maximum and minimum temperatures throughout the year in the referential period from 1981 to 2006 are displayed in Fig. 4.

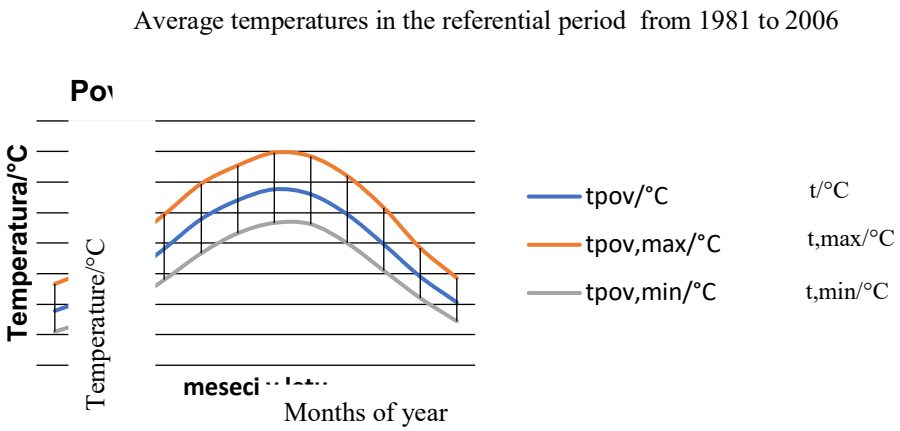


Fig. 4: Average temperatures in the referential period from 1981 to 2006 in the city of Velenje.

In choosing the material for the roofing, the following factors were taken into account:

- geographic positioning,
- needs of plants being cultivated in the greenhouse,
- experience of producers and, as a key factor,
- needs for heat and cooling.

Taking into account the first three points, a comparison of heat losses of the greenhouse for the existing 4mm toughened glass, double glass and 16mm polycarbonate sheets, follows. The physical properties of the materials are listed in Table 3.

Table 3: Comparison of physical properties of roofing materials

Physical Properties	**Materials**				
Type of Material	Toughened Single Glass	Toughened Single Glass	Double Insulating Glass		Polycarbonate Sheets
Thickness of material /mm	4	6	Walls 4/16/4	Roof 8K/16/4+4L	16
Emissivity	0,89	0,89	/	/	/
Weight (g/m^2)	/	/	/	/	2700
Heat passability / U (W/m^{2}K)	5,8	5,7	1,1	1,1	3,1
Transmissivity of light, τ_s	0,9	0,89	0,76	0,76	0,85
Reflection of light, ρ_s	0,08	0,08	0,12	0,12	/
g – value*/%	/	/	58	58	/
*part of the energy of solar radiation, expressed in percentages, which comes through the glass into the interior of the structure and is an amount of direct and diffuse energy					

6.2 Project data and heat requirements

The project data of the heating of the greenhouse is the following:

- external project temperature t_z= -20°C
- lowest permissible temperature of the space t_p=10°C
- permeability of the glass 87%
- heat transfer coefficient on the internal side of the wall α_1 = 8 W/m^{2}K
- heat transfer coefficient on the external side of the wall α_2 = 20 W/m^{2}K
- total area of the greenhouse roofing A = 3157m^2

The heat balance of the transparent walls, namely, the greenhouse, is formed by various factors that are greatly supplemented by each other. These factors are:

- The Sun,
- The atmosphere,
- The environment,
- Air in the greenhouse,
- The ground and plant base in the greenhouse.

The notation of the heat balance includes all the sources of heat in the greenhouse. The roofing and plants have a negligible amount of thermal inertia; only the soil has the property of accumulating heat. When noting the thermal balance, it is necessary to take into account the following presumptions:

- The temperatures of the soil inside and outside the greenhouse are linearly dependent, as are the temperatures of the air inside and outside the greenhouse,
- The temperature of the glass wall is equal everywhere,
- The soil and walls are gray bodies,
- The greenhouse is a space without vegetation.

Heat requirements of the greenhouse are determined in a fairly simple way; the following must be taken into account:

- Heat flow rate necessary for the air in the greenhouse to warm up to a certain temperature,
- Heat flow rate necessary for the humidity of the air to be maintained,
- Heat flow rate that replaces losses due to exchange of heat with the soil and
- Heat flow rate that replaces losses through the transparent surface.

Alongside the heat requirements due to the transmitting of heat, it is also necessary to add a portion of heat that must be replaced due to ventilation losses. Because the location of the greenhouse is not explicitly windy and lies in a fairly open position, we can take on a 24% addition. Total heat requirements are displayed in Figure 5.

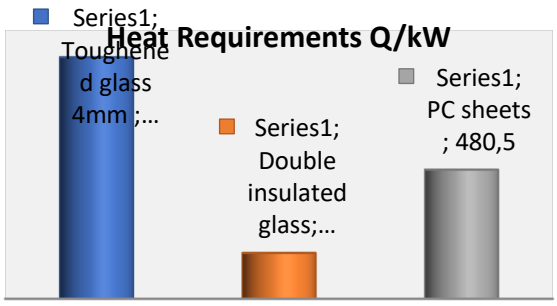


Fig. 5: Total heat requirements for different roofing materials.

The annual use of energy for heating is primarily dependent on the number of heating days. Heating days are comprised of the days when the external temperature throughout the day has been less than 16°C, as, in this way, all the requirements for minimal temperature in the greenhouse are met. In order to determine the need for heat that is necessary to heat the greenhouse, we must take into account:

- Average median temperatures according to month,
- Level of average daily global radiation,
- Available energy for heating and
- Heat requirements of greenhouse.

We assume that due to the large surface of the roof to the walls, there is an average 85% radiation of the entire surface of the greenhouse. The largest energy losses are created by the convection of heat through material into the environment. Annual heat requirements for the greenhouse covered with double insulated glass amount to 1,594,435.82 kWh.

Figure 6 graphically represents the heat requirements and the amount of incident solar energy throughout the year for a greenhouse with 4mm toughened glass.

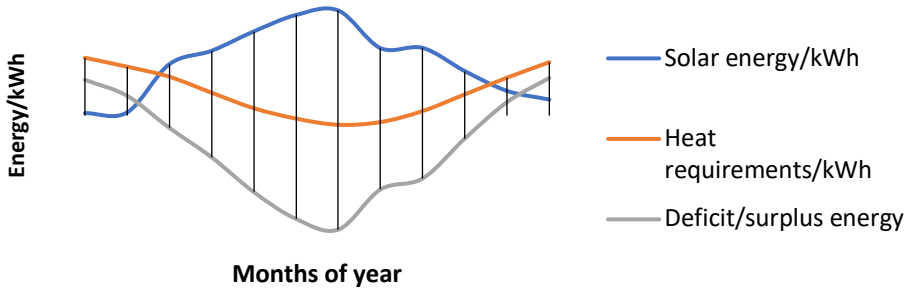


Fig. 6: Heat gains and requirements according to month for a greenhouse with 4mm toughened glass

A comparison of materials is displayed in Table 4. Annual gains and heat requirements for a greenhouse of various materials are displayed in Table 4 and Fig. 7.

Table 4: Comparison of energy deficits and surpluses in various greenhouse materials

Roofing material	Heat gained by solar radiation/kWh	Heat requirements of greenhouse/kWh	Energy deficit when using thermal energy from solar radiation/kWh	Unused surplus of thermal energy from solar radiation/kWh
Single, toughened, 4mm glass	2,096,411.30	1,594,435.82	850,400.20	1,495,259.77
Double insulated glass	1,765,288.30	302,449.03	16,052.18	1,499,216.89
Polycarbonate sheets	1,979,932.29	852,352.49	309,866.12	1,495,313.37

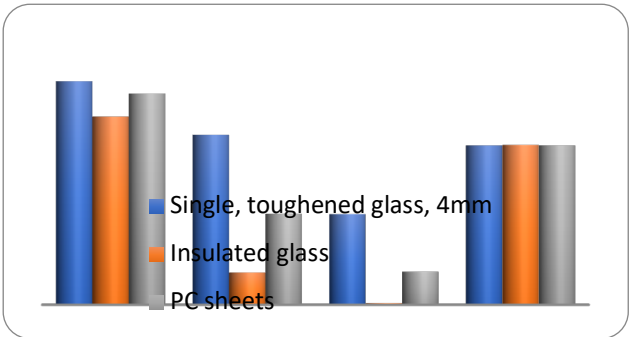


Fig. 7: Annual heat gains and heat requirements of the greenhouse in kWh

6.3 Expenses of greenhouse heating

With a good choice of roofing and an optimal combination of all listed heating options and in accordance with natural conditions and energy sources that are available, it is possible to:

- Decrease energy use,
- Improve production conditions and enable a larger yield,
- Have cheaper and simpler maintenance of installations and
- Replace imported energy.

The costs invested in the construction of heating devices are, depending on the surface area, type of processing and type of heating device, returned in anywhere from three months to five years. The success of efficiency is very much linked to the use of new techniques of fertilisation and is dependent on choosing a suitable variety range.

Comparative prices of chosen materials are presented for the case at hand. For 4mm glass, prices range from EUR 14.40 to EUR 30 per square meter of glass. An even larger price range exists for double insulated glass. Prices vary from EUR 47.99 to EUR 100.87 per square metre. Polycarbonate sheets are valued at EUR 39.5 per square metre. For comparative uses, the average price of the material per square metre is used. The surface area of the roofing is calculated in Chapter 6 and amounts to 3,157m^2. Table 5 gathers average prices and costs for the greenhouse roofing that has been examined.

Table 5: Comparison of prices for various greenhouse roofing

Material	Price/(EUR/ m^2)	Price of used roofing/EUR
Single toughened glass; 4mm thickness	22.20	70,081.85
Double insulated glass (4/16/4 and 8/16/4+4)	75.00	236,763.00
Polycarbonate sheets; 16mm thickness	39.50	124,695.18

From the results, we can gather that the double insulated glass, which was shown in the previous analysis as the most affordable, is much more expensive than the currently used single glass; the price is 3.37 times higher.

The energy-generating product currently used is warm water. The price per MWh is EUR 17.4035. In the case of using landfill gas, the price per kilowatt-hour is EUR 0.05.

In the continuation, we compare the cost of heating without the use of solar energy and with the complete use of solar energy, for 4mm toughened glass and double insulated glass.

The cost of accounted power is calculated monthly or in accordance with the stipulations in the contract for provision of heat.

There are many recognised methods for determining the economic return of projects. The methods for such assessments are divided into static and dynamic methods, based on whether they take into account the component of time.

In the continuation, the method used for assessing the return on investment of heating the greenhouse with various roofing methods and use of various energy-generating products is the net present value method, which gives the results presented in Table 6 and Fig. 7.

Table 6: Heating costs of various roofing methods

Material	Annual energy requirements of greenhouse/MWh	Price of hot-water heating/EUR	Price of landfill gas/EUR	Annual requirement of energy, when using thermal energy from solar radiation/MWh	Price/EUR	Price for landfill gas/EUR
Single glass, 4mm thickness	1,599.43	27,748.66	79,721.15	850.40	14,799.93	42,520.00
Double insulated glass	302.45	5,263.68	15,122.50	16.05	279.32	802.50

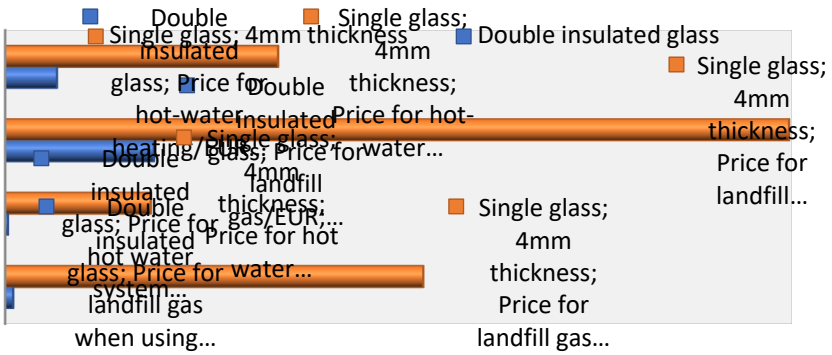


Fig. 7: Heating costs of various roofing methods in EUR

The energy savings with insulated glass and the existing method of hot-water heating amounts to EUR 22,484.98 per year. With such savings, the cost of the roofing is returned in 7.5 years, when using solar energy, in 6 years. In the latter case, the costs necessary for the installation of an active solar system are not taken into account.

6. CONCLUSION

In this article, facts on the microclimate of a closed space (greenhouse) for plant cultivation have been presented. Optimal conditions that are dependent on the phase of plant development, along with the effect of external climate parameters on growth, have been especially defined.

This article presents a mathematical model of the heat transfer in a greenhouse without cultivation, on the basis of which it is possible to note the heat balance of various months, taking into account the day and night influences on the microclimate of the greenhouse.

Of course, there are many other possible adjustments to the mathematical model, as well as adjustments of the technical conditions to the economy of production and market demands, which itself, demands much more work and research. On the basis of approximate calculations of the greenhouse taken as an example, we see that the most heat from solar radiation is procured from single glass, while the least is obtained from double insulated glass. Annual requirements for thermal energy significantly decrease with double insulated glass, and halve with the use of PC sheets. The requirements for additional energy for heating are less with double insulated glass, while surpluses of solar energy are almost identical for all compared materials.

Given the properties of the various materials and the potential energy savings, the best is most definitely the double insulated glass, which, due to a heightened greenhouse effect, increases the quantity of unutilised solar energy.

A price comparison of the various materials also shows a different side of the materials compared, as the average price of the double insulated glass is relatively high in comparison to single glass. PC sheets also reach quite a high price. An investment in double insulated glass for new greenhouses would be returned in 7.4 years, if we take into account only energy savings without solar energy surpluses. If we take into account surpluses of solar energy, the investment would be returned in 6 years.

In any case, double insulated glass is a good choice, but as there are many versions of this glass on the market, a more thorough comparison between them and a precise calculation of NPV are necessary.

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