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EFFECT OF PLASTIC TUNNEL EQUIPMENT ON ITS THERMAL BALANCE COMPONENTS

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Key words: plastic tunnel, thermal screen, thermal transmittance coefficient, convert rate of solar radiation.

Abstract

The paper presents results of research conducted in a standard plastic tunnel equipped with thermal screens measuring 144 m^2. During the experiment the thermal screens in the tunnel were either in a folded or unfolded position (both during the radiation weather and at night), whereas vents were closed. Parameters of the ambient climate (the temperature, wind velocity, air humidity and solar radiation intensity) were measured during the experiment, as well as the parameters of the microclimate inside the objects (the temperature and air humidity).Thermal balance including: the change of heat accumulated inside the object, heat gains from the substratum (through radiation and penetration), heat gains from solar radiation and the heat flux loss were formulated for the discussed cases. In result of the analysis the differences of internal temperature were stated for the object with and without thermal screens. It was found that for the identical values of the ambient climate parameters the temperature inside the object without the thermal screen was c.a. 4.0% higher than in the object equipped with the thermal screen. The thermal transmittance value through the object casing was determined and the convert rate of solar radiation to heat causing increase in the internal temperature in the objects both with and without thermal screens.

Introduction

The necessity to reduce fossil fuels consumption, care for the natural environment and striving for minimization of production costs stimulate the users, including also crop producers under plastic to apply the technical

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solutions which would lead to decrease in heat consumption. One of the solutions conditioning effective heat consumption is installing thermal screens in horticultural facilities (e.g. in plastic tunnels). The screens are standard equipment of the objects under cover. The issues of modification of such objects construction or the effect of screen installation were addressed by studies conducted in many research centers. For instance, ZHANG et al. (1996) found that installing thermal screens in a greenhouse led to a decrease in total heat consumption on the level of 24÷26%. The Authors' own investigations (KURPASKA 2003) demonstrated that in result of installing in a greenhouse thermal screens and radiator reflector (1 m wide and 4 mm thick polyurethane covered with aluminum foil) the maximum heat saving (at the minimal ambient temperature) was almost 50%. On the other hand, studies by GRABARCZYK (2010) revealed the heat saving between 30 and 42% at the difference between the indoor and outdoor temperature in the range 5÷20 K. SETHI and SHARMA (2008) presented thermal effects obtained in the investigations conducted in greenhouses in various centres, where thermal screens were installed. Depending on the localization and screen type, obtained savings ranged from 20% (Madrid) to 60% (Pennsylvania). KITTAS et al. (2003) analyzed microclimate parameters of the objects with and without thermal screens. They established that the use of thermal screens led to a better levelling of the air temperature around the cultivated plants. Installing the screen caused almost a 15% decrease in heat demand. SILVIA et al. (1991) developed and verified a mathematical model of the sunbeams reaching the interior of a greenhouse quipped with thermal screens. Various radiation fluxes were considered, whereas detailed analysis was conducted on net radiation reaching the substrate surface in the greenhouse. Usability of the model for internal microclimate parameters control was stated. CANAKCI and AKINCI analyzed the costs of various vegetables production in a greenhouses with diverse equipment, including these with and without thermal screens. They established, that under the investigated conditions (the Mediterranean area) heat costs constituted between 19 and 32% of all operational costs for the discussed vegetable species. CELIK and MUNEER (2013) tested the effects of solar radiation conversion (measured by two independent pyranometers: horizontal and parallel with the roof surface) in photovoltaic panels integrated with the greenhouse construction. Generated energy was accumulated in batteries. The forecast was based on SSN in which input variables were reduced to the radiation intensity and incidence angle of the sunbeams. It was found that the final result of the conversion, as compared with the standard models, was characterized by a lower value of estimated intensity reaching the sunlit surface. NAYAK and TIWARI (2008) analyzed the system composed of a laboratory tunnel and photovoltaic panels. The panels were installed on the roof. Beside the energy issues (annual and daily gain of electrical energy, effectiveness of solar radiation conversion) the authors developed a mathematical model of heat and mass transfer inside the facility. The model included real geometry of the studied object. TEITEL et al. (2009) analyzed the change in the air temperature in a greenhouse with and without thermal screens. They determined also leaves temperature, whereas they made the energy consumption dependent on the difference in temperature between the leaf and the indoor air. They also determined the value of effective thermal transmittance through the object casing and made it dependent on wind velocity. HASSANIEN et al. (2016) made a synthetic review (combined with an economic analysis) of the implemented technical solutions using solar radiation energy in the context of ensuring the required environment conditions in a greenhouse. LAMNATOU and CHEMISANA (2013), ABDEL-GHANY and AL-HELAL (2011) analyzed the effect of diversified greenhouse cover materials on light conditions and light emission (within IR range) inside the facility. ABDEL-GHANY (2011) considered the effect of greenhouse longitudinal axis situation towards geographical directions in order to obtain the maximum insolation during the light deficiency period, recommending the east-west direction for the winter months. VADIEE and MARTIN (2014) found a considerable influence of the cover on heat transfer from inside the object to the environment, concluding that application of double glazing and thermal screens led to diminishing the light accessibility, yet the advantage of this type of cover is obtaining almost 60% savings in heat demand. In result of conducted analysis the authors stated that additional savings in heat consumption may be obtained using a semi-closed greenhouse with a dehumidifier. SANAYE and SARRAFI (2015) conducted the procedure of temperature optimization inside the object (including also controlling the position of shade screens) for the system using solar radiation. SETHI et al. (2013) made a review of technical solutions stimulating a change of the parameters of microclimate inside heated greenhouse facilities. They also discussed the application of foils preventing water vapour condensation and determined the influence of this foil on light accessibility in the range of PAR length. YANO et al. (2014) analyzed in detail a prototype greenhouse where PV cells were applied on a part of the roof. Beside determining the amount of generated energy, they also investigated a change in light accessibility inside the facility.

The review of research works presented above shows unanimously that the problems of environmental conditions inside a greenhouse facility, analysis of thermal issues under the influence of the construction or technical equipment modification are still relevant research problems. Therefore the aim of the paper was an analysis of thermal balance components describing a horticultural facility together with an analysis of the intensity of the change of solar radiation conversion to heat in the objects where thermal screens were installed.

Material and Methods

The investigations were conducted in a tunnel measuring 9 × 16 m, covered with double skinned PE foil; white foil was placed inside the tunnel on a substratum. During the experiment the thermal screens in the object were either folded or unfolded (both during the radiation weather and at night), whereas the vents were closed.

The temperature was measured during the experiment using PT 1000 meters, relative air humidity by means of HD 4917 meters, wind velocity using a cup anemometer and the intensity of solar radiation by means of LP PYRA 02AV pyranometer. The scheme of the measurement station with marked thermal balance components and measured values were presented in Figure 1.

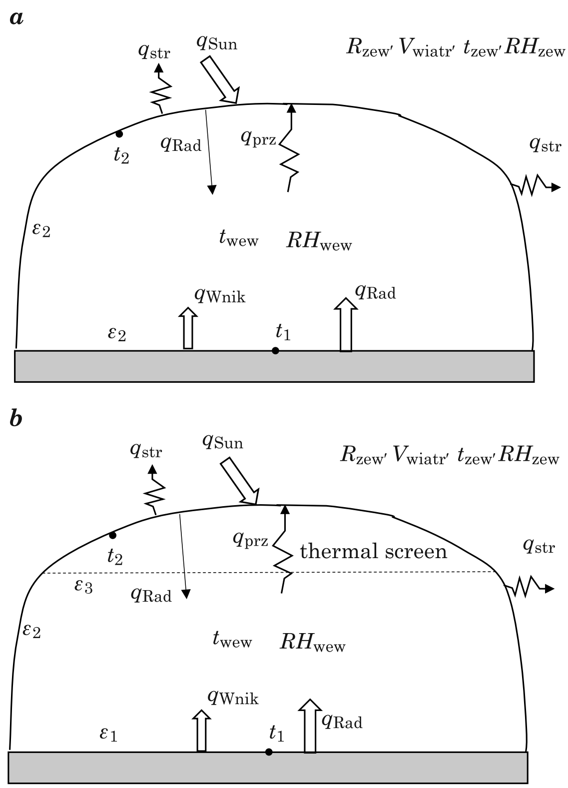

Fig. 1. Scheme of test bench without (*a*) and with (*b*) thermal screens installed inside the tunnel

In the differential time ($d\tau$) the energy balance of analyzed tunnel volume under the conditions of radiation weather may be described as follows:

$$V_p \cdot \rho \cdot c_w \frac{dt_{\text{wew}}}{d\tau} = q_{\text{Sun}} + q_{\text{Rad}} + q_{\text{Wnik}} - q_{\text{str}} \tag{1}$$

whereas after taking into consideration the elementary dependence as:

$$\begin{gathered} V_p \cdot \rho \cdot c_w \frac{dt_{\text{wew}}}{d\tau} = f \cdot F_{\text{tun}} + R_{\text{zew}} + \varepsilon_{\text{ef}} \cdot \sigma \cdot F_{\text{tun}} \left(\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right) + \\ + \alpha_{\text{wnik}} \cdot F_{\text{tun}} \cdot (t_1 - t_{\text{wew}}) - U_{\text{osł}} \cdot F_{\text{osł}} \cdot (t_{\text{wew}} - t_{\text{ot}}) \end{gathered} \tag{2}$$

Alternative emission (ε_{ef}) of the substratum top layer was computed from the following dependence:

$$\varepsilon_{\text{ef}} = \frac{1}{\dfrac{1}{\varepsilon_1} + \dfrac{F_{\text{tun}}}{F_{\text{osł}}} \left(\dfrac{1}{\varepsilon_2} - 1 \right)} \tag{3}$$

where:
V_p – volume of air [m^3],
ρ – air density [kg $\cdot$ m^{-3}],
c_w – sensible heat of the air [J $\cdot$ kg^{-1} $\cdot$ K^{-1}],
T_{wew} – temperature inside [K],
q_{Sun} – heat flux transmitted to the interior of the solar radiation [W],
q_{Rad} – heat flux transferred from the substrate surface to the interior [W],
f – conversion of radiation into heat [–],
R_{zew} – the intensity of solar radiation [W $\cdot$ m^{-2}]
ε_{ef} – effective emission coefficient [–],
σ – Stefan-Boltzmann constant $\sigma = 5.67$ [W $\cdot$ m^{-2} $\cdot$ K^{-4}],
T_1, T_2 – emperature of the surface layer of the substrate (T_1) and shields (T_2) [K],
α_{wnik} – heat transfer coefficient between the air and the top layer of the substrate [W $\cdot$ m^{-2} $\cdot$ K^{-1}],
T_{ot} – ambient temperature [K],
$U_{\text{osł}}$ – heat transfer coefficient of the cover [W $\cdot$ m^{-2} $\cdot$ K^{-1}],
$F_{\text{osł}}$ – surface shields tunnel [m^2],
F_{tun} – usable area tunnel [m^2],
ε_1, ε_2, ε_3 – emissivity surface tunnel (ε_1), shields (ε_2) and screen heat (ε_3) [–].

When the alternative emission factor for the object with the thermal screen was determined, the final value of the (ε_2) parameter was computed as a weighted average considering the casing and thermal screen area. Heat penetration coefficient (α_{wnik}) was calculated using standard dependencies between criteria of similarity.

The methods presented above show that determining the convert rate of solar radiation (f) is possible when the thermal transmittance value through the casing (U_{ost}) has been established at the first stage of research. Therefore, after finding the relationship of this coefficient (U_{ost}) as a function of measured ambient climate parameters, the obtained value was applied for the analysis of the period with radiation weather. The necessary parameters (ambient climate and inside the object) were monitored and saved by a computer system with sampling time equaling 30 s. The temperature of the object casing was computed in accordance with generally used dependencies as 40% of the ambient temperature value and 60% of the temperature inside, whereas the temperature of the substratum top layer was measured by resistance sensor.

Computations of the air parameters (c_w, ρ) were conducted using standard psychrometric dependencies. Quantitative measures of approximation accuracy (compliance) of the parameter computed from the conducted measurements with the values approximated by the model were determined from mean square error (σ) known from the elemental error calculation.

Results and Discussion

The investigations conducted when no plants were cultivated for the following range of variable values (the data refer to both radiation weather and solar radiation decay):

a) tunnel without thermal screen: $-3 \leq T_{wew} \leq 35.1$ [°C]; $17.1 \leq RH_{wew} \leq 92$ [%]; $-4.5 \leq T_{zew} \leq 14.9$ [°C]; $0 \leq V_{wiatr} \leq 2.0$ [m · s^{-1}]; $0 \leq R_{zew} \leq 380$ [W · s^{-2}]; $35.9 \leq RH_{zew} \leq 100$ [%];

b) tunnel with thermal screen: $-3 \leq T_{wew} \leq 33.8$ [°C]; $22.1 \leq RH_{wew} \leq 89.6$ [%]; $-2.3 \leq T_{zew} \leq 15.9$ [°C]; $0 \leq V_{wiatr} \leq 1.9$ [m · s^{-1}]; $0 \leq R_{zew} \leq 395$ [W · s^{-2}]; $35.2 \leq RH_{zew} \leq 100$ [%].

Figure 2 presents the dependence of the temperature inside the objects (with and without thermal screens) as a function of ambient temperature and solar radiation intensity.

The equation found for measured values (t_{wew}), comprising the relationship between this value and independent variables (the form of power model was selected on the basis of the highest value of determination coefficient; the dependency was determined by non-linear estimation using quasi-Newton

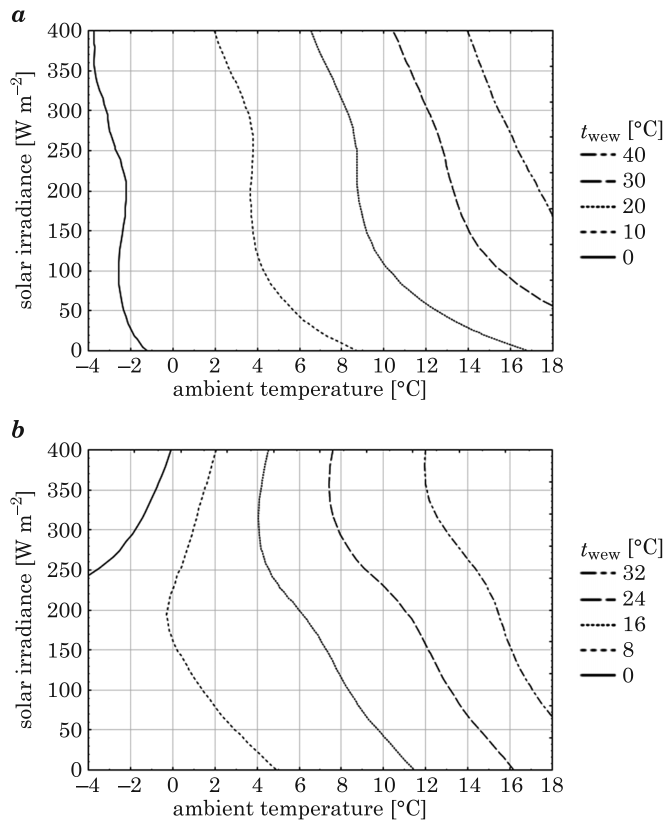

Fig. 2. Course of internal temperature as a function of ambient climate parameters for the object (*a*) without and (*b*) with thermal screen

method at maintained convergence coefficient 0.001), assumes the following form:

a) tunnel without thermal screen; $R^2 = 0.96$

b) tunnel with thermal screen; $R^2 = 0.95$

The dependencies given above may be applied within the stated range of experimental variables. Comparison between the values measured and computed from the suggested models were presented in Figure 3.

Detailed analysis revealed that for the same values of the ambient climate parameters, the temperature inside the object without a thermal screen was by c.a.4% higher in comparison with the temperature in the object equipped with thermal screen.

Using the derived dependencies, thermal transmittance value through the object casing ($U_{osł}$)was calculated. The course of its value as a function of the experimental variables: the difference in temperature (between the tunnel interior and ambient air) and wind velocity was presented in Figure 4.

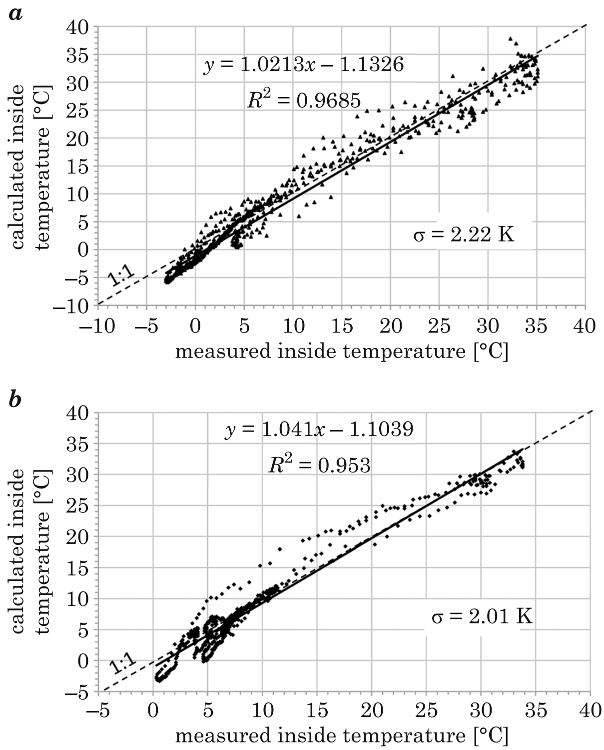

Fig. 3. Comparison of the temperature computed from the models and the values measured for the object (*a*) without and (*b*) with thermal screen

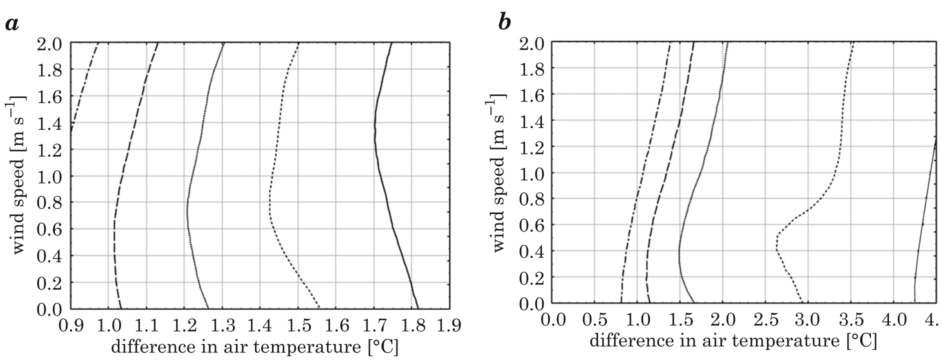

Fig. 4. Thermal transmittance value as a function of variable parameters during experiments for the object (*a*) without and (*b*) with thermal screen

It may be seen that in both cases thermal transmittance value ($U_{\text{osł}}$) is an increasing function of the difference of temperature and wind velocity. Mean thermal transmittance value in the analyzed range of the experimental parameters is 5.32 for the object without thermal screen and 4.61 $W \cdot m^{-2} \cdot K^{-1}$ for the object with a thermal screen.

Using the value of $U_{osł}$ computed for the period without solar radiation, the values of individual heat fluxes were calculated for both objects; additionally a change was marked in the amount of heat accumulated in their interior. The results were shown in Figure 5.

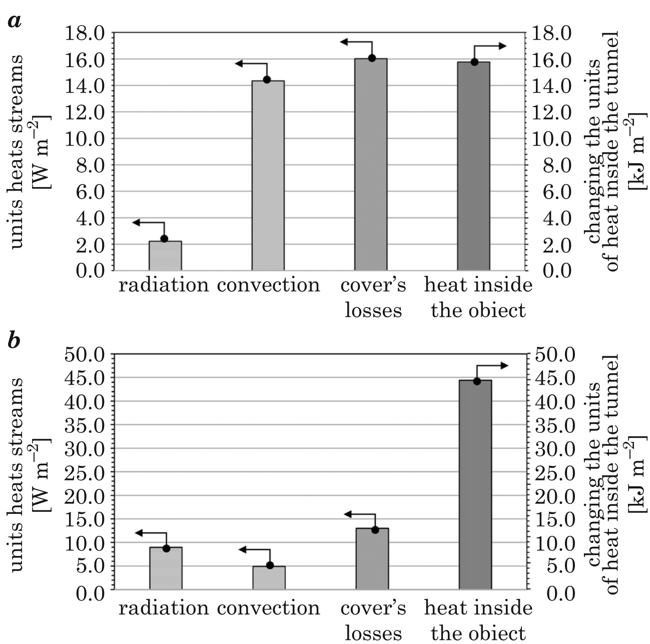

Fig. 5. Values of individual components of thermal balance in the objects for a selected cycle without solar radiation for the object (*a*) with and (*b*) without thermal screen

Conducted detailed analysis for the performed experimental cycles revealed that heat transfer through radiation was c.a. 18% of the total heat flux loss in the object without thermal screen, whereas for the object with thermal screen, mean values are about 68%. The final conclusion of the conducted analysis is determining the convert rate of solar radiation to heat (*f*) whose course as a function of solar radiation intensity was presented in Figure 6.

As may be seen, the value of this rate is growing with increasing solar radiation intensity. Mean values of this rate in the studied range of the ambient climate parameter values are 0.36 for the object without a thermal screen and 0.26 for the object with a thermal screen. It denotes that depending on the equipment, between 26% and 36% of solar radiation energy measured outside the tunnel is converted into heat.

Analyzing the obtained values and their dependencies on the ambient climate parameters it may be stated clearly, that apart from cognitive advan-

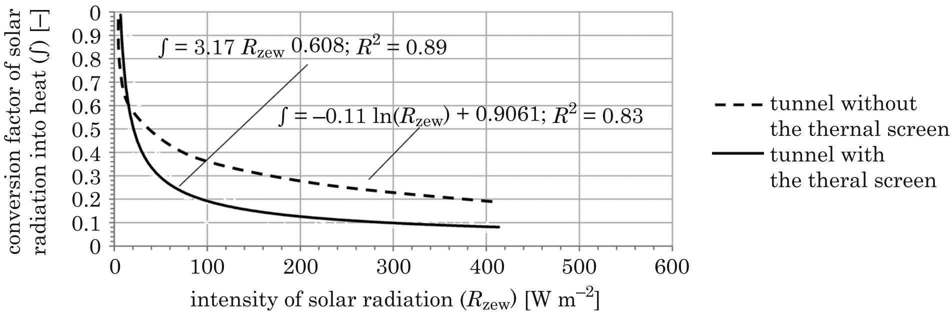

Fig. 6. Changeability of conversion rate of solar radiation to heat (f) inside the tunnel for the tested equipment

tages, they may find applications also for control of the microclimate parameters inside the object.

The values may prove debatable in the tunnel where plants are grown, because of additionally occurring heat flux used for plant transpiration, however it would not impact their tendencies and trends of changes.

Conclusions

1. For identical parameters of the ambient climate, the temperature inside the object without a thermal screen is about 4% higher compared to the temperature in the object equipped with thermal screen.

2. Mean thermal transmittance value in the analyzed range of climate parameters is 5.32 for the object without a thermal screen and 4.61 $W \cdot m^{-2} \cdot K^{-1}$ for the object with a thermal screen.

3. Heat transfer through radiation in the object without thermal screen is c.a. 18% of the total heat flux loss, whereas for the object with the screen mean value is around 68%.

4. Mean value of convert rate of solar radiation to heat in the investigated range of ambient climate is 0.36 for the tunnel without a thermal screen and 0.26 for the object with thermal screen.

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