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HEAT AND MASS EXCHANGE MODEL IN THE AIR INSIDE A GREENHOUSE

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ABSTRACT

The objective of the paper was to draw up a mathematical model of heat and mass exchange in the air inside a big-size greenhouse, where commodity cultivation of plants is carried out. During formulation of the model, inter alia, models described in literature and results of experimental research were used. A developed mathematical model was implemented in MATLAB/Simulink software and simulations carried out with a computer model were used for carrying out graphical and statistical validation of a model. Analysis of simulation results allows making statement of logical correctness of the developed model and makes it possible to determine critical points of failure to adjust the model. A simplification degree of the developed heat exchange model influences its precision. In order to use the developed model e.g. for the control purposes, it requires to be more detailed.

Introduction

The interest in the greenhouse climate modeling dates back to the commodity crops under cover. Greenhouse climate models are the main tool helping to control thermal and humidity parameters inside the greenhouse. Knowledge of them supports decision-making related to cultivation, and also allows the use of modern, complex microclimate control algorithms. In the literature we can find many greenhouse climate models, they are both static and dynamic mathematical models, as well as „black box" models based on artificial intelligence methods. A review of these models can be found in the works (Boaventura Cunha, 2003; Raczek, 2012). Among the most important in this respect are the works of Bot (1983) and Jong (1990). Most greenhouse climate models are formulated for the experimental facilities, equipped with many additional sensors. Often these models are deliberately simplified. Some processes are omitted in the description in order to investigate a phenomenon which is interesting for the researchers (e.g. studies on ventilation are carried out in the facility without plants). The greenhouse climate models are formulated and validated taking into account: the crop type and development phase of crops, region and weather conditions; the structure and type of a greenhouse, and the operation of ventilation equipment as well. Therefore, it is not easy to directly extrapolate these models to differently built greenhouses located elsewhere.

The object of the research in this paper was modern Venlo type greenhouse located in Różanki in Lubuskie Voivodeshop, where on 5.9 hectares tomato cultivation was carried out. For the greenhouse a mathematical model of heat and mass transfer processes in the indoor air was developed which is presented below. In March and April 2011 temperature and relative humidity of air inside the greenhouse was recorded by a climate computer every 15 minutes, which in the model constitute the output signals, and control signals (input in the model): in the form of the heating pipe temperature and the degree of opening vents. Environmental parameters of the greenhouse constituted interference: temperature and humidity of the outside air, radiation and wind speed. The weather data were recorded by a weather station.

The objective of the paper was to draw up a dynamic, mathematical model of heat and mass exchange in air inside a big-size greenhouse, where a commodity cultivation of plants is carried out when we are provided with data on the climate parameters normally collected by a climate computer and a weather station.

The scope of work related to the greenhouse climate modeling included:

– adaptation of literature models to the test object, by taking into account characteristic dimensions of the tested greenhouse and its technical equipment,
– draw up a computer model and perform simulations,
– graphical and statistical validation of the resulting model of the process of heat exchange and mass transfer in the air inside the greenhouse using the results of experimental studies.

Mathematical model of greenhouse microclimate

Microclimate in the greenhouse is the result of combination of complex mechanisms involving processes of heat and mass transfer occurring in the greenhouse, and the processes between the interior of the greenhouse and the surroundings. Processes occurring in the greenhouse are highly non-linear, related to each other. During the formulation of a mathematical model of these processes, equations of heat and mass balances for the air inside the greenhouse should be formulated. (Wachowicz, 2006).

To develop a model the following simplifying assumptions were made:

– a greenhouse is treated as a perfectly mixed tank, i.e. the analyzed air parameters have the same value in the entire volume of the greenhouse,
– due to the lack of empirical data no effect of energy screens was taken into account,
– impact of the ground on the heat and mass transfer was neglected, because in the tested facility, cultivation was carried out on coconut fiber mats covered with white foil,
– evaporation from the greenhouse cover and crops was neglected, because in modern greenhouses a condensate is drained from the cover, and when cultivation is maintained properly, retting on plants should not take place.

Heat transfer model

Considering the equipment of the object, changes in air temperature inside the greenhouse can be presented in the form of the heat balance equation:

$$\frac{dT_{wew}}{d\tau} = \frac{1}{\rho_{wew} c_{wew} V_{sz}} \left(Q_{oslona} + Q_{s.grzewczy} + Q_{radiacja} - Q_{went} - Q_{transp} + Q_{kond} \right) \quad (\mathrm{K \cdot s^{-1}}) \quad (1)$$

where:

- T_{wew} – air temperature inside the greenhouse, (K)
- ρ_{wew} – air density inside the greenhouse, (kg·m^{-3})
- c_{wew} – specific heat of air inside the greenhouse, (Jkg^{-1}·K^{-1})
- V_{sz} – greenhouse volume, (m^3)
- $Q_{osłona}$ – heat flux exchanged between the interior and the cover, (J·s^{-1})
- $Q_{s.grzewcz}$ – heat flux from heating pipes, (J·s^{-1})
- $Q_{radiacja}$ – heat flux supplied from solar radiation, (J·s^{-1})
- Q_{went} – heat flux exchanged through the ventilation, (J·s^{-1})
- Q_{transp} – heat flux exchanged by plant transpiration, (J·s^{-1})
- Q_{kond} – heat flux supplied by condensation, (J·s^{-1})

Heat balance components are heat fluxes supplied to the greenhouse: due to condensation of water vapor on the cover, from heating pipes, from solar radiation and heat fluxes exchanged during ventilation, and as a result of plant transpiration. Heat transfer through the cover may take place in both directions.

Most of convective heat fluxes exchanging between different parts of the greenhouse and the air inside the greenhouse depend on the heat transfer coefficients and the temperature difference between the elements surface and the air. These fluxes describe the following equations:

– for convective heat exchange between the air inside the greenhouse and the cover:

$$Q_{oslona} = \alpha_{oslona} A_{oslona} \left(T_{oslona} - T_{wew} \right) \quad (\mathrm{J \cdot s^{-1}}) \quad (2)$$

where:

- α_{oslona} – heat transfer coefficient through the cover, (W·m^{-2}·K^{-1})
- A_{oslona} – cover surface, (m^2)
- T_{oslona} – cover temperature, (K)

– for convective heat exchange between the air and the heating pipes:

$$Q_{s.grzewczy} = \alpha_{s.grzewczy} A_{s.grzewczy} \left(T_{s.grzewczy} - T_{wew} \right) \quad (\mathrm{J \cdot s^{-1}}) \quad (3)$$

where:

- $\alpha_{s.grzewczy}$ – heat transfer coefficient of heating pipes, (W·m^{-2}·K^{-1})
- $A_{s.grzewczy}$ – heating pipes surface, (m^2)
- $T_{s.grzewczy}$ – heating pipes temperature, (K)

– for convective heat exchange through ventilation:

$$Q_{went} = \alpha_{went} A_{went} \left(T_{zew} - T_{wew}\right) \quad (\mathrm{J \cdot s^{-1}}) \tag{4}$$

where:

α_{went} – heat transfer coefficient between the air inside the greenhouse and its environment, ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$)

A_{went} – vent sufrace, ($\mathrm{m^2}$)

T_{zew} – outside air temperature, (K)

Heat flux supplied from solar radiation is expressed by following simplified relation (Tap, 2000):

$$Q_{radiacja} = A_{sz}\, 0{,}7\, Rad \quad (\mathrm{J \cdot s^{-1}}) \tag{5}$$

where:

Rad – solar radiation density, ($\mathrm{W \cdot m^{-2}}$)

From analysis of the results of simulation studies of the greenhouse follows that, in this case value 0.7 in the equation (5) is too high and was lowered to the level of 0.55.

Determination of the heat transfer coefficients α is a complex task. The reason for this is primarily a large number of time-varying factors that affect the value of coefficients. In this study, the heat transfer coefficients are calculated on the basis reported in the literature information models (Bot, 1983; Zwart, 1996), i.e. experimentally determined relationship between the temperature difference of the elements and the air temperature in the greenhouse and characteristic values. These coefficients are expressed by the following formulas:

– heat transfer coefficient between the air and the inner side of the cover (Zwart, 1996):

$$\alpha_{oslona} = 1{,}7(\cos\varphi)^{0{,}33} \cdot \left(T_{wew} - T_{oslona}\right)^{0{,}33} \quad (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{6}$$

where:

φ – slope of the roof, (º)

– heat transfer coefficient between the air and the upper heating pipes, which are located above the plants (Bot, 1983):

$$\alpha_{s.grzewczy\ 1} = 1{,}28\, A_{s.grzewczy\ 1}^{-0{,}25} \cdot \left(T_{s.grzewczy\ 1} - T_{wew}\right)^{0{,}25} \quad (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{7}$$

– heat transfer coefficient between the air and the lower and vegetative heating pipes, when the pipes have a diameter of 51 mm and are located in the area of plants growth and under the cultivation gutters (Bot, 1983):

$$\alpha_{s.grzewczy\ 2} = 1{,}99\, A_{s.grzewczy\ 2} \cdot \left(T_{s.grzewczy\ 2} - T_{wew}\right)^{0{,}32} \quad (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{8}$$

– heat transfer coefficient between the air inside the greenhouse and its surroundings through natural ventilation (Kurpaska, 2007):

$$\alpha_{went} = \rho_{wew} \cdot c_{wew} \cdot \Phi_{went} \quad (\mathrm{W \cdot m^{-2} \cdot K^{-1}}) \tag{9}$$

where:
Φ_{went} – air flow rate through ventilators, (m·s^{-1})

taking into account density and specific heat of the air inside the greenhouse, and air flow rate through ventilators. The simplified relation presented in the work by Tap (2000) is used in the present work to calculate the air flow rate through ventilators

$$\Phi_{went} = \left(\frac{\sigma \cdot K_z}{1 + \chi \cdot K_z} + \zeta + \xi \cdot K_n \right) \cdot v_{zew} + \psi \quad (\mathrm{m \cdot s^{-1}}) \tag{10}$$

where:
K_n – opening degree of ventilators on the windward side, (%)
K_z – opening degree of ventilators on the leeward side, (%)
v_{zew} – outside wind speed, (m·s^{-1})
$\sigma,\chi,\zeta,\xi,\psi$ – constants, the value of which amounts to: σ=7.1708·10^{-5}(%$^{-1}$), χ=0.0156(%$^{-1}$), ζ=2.7060·10^{-5}(-), ξ=6.3233·10^{-5}(%$^{-1}$), ψ=7.4·10^{-5} (m·s^{-1})

Air flow rate depends on the degree of opening vents on the windward side K_n and lee side K_z as well as on the outside wind speed v_{zew}.

The last two heat fluxes Q_{transp} and Q_{kond} included in the heat balance are latent heat. One of them is heat Q_{transp} lost through transpiration of plants (11), when due to plant metabolism the water passes from the liquid phase into the gaseous one.

$$Q_{transp} = r_0 A_{liscie} M_{transp} \quad (\mathrm{J \cdot kg^{-1}}) \tag{11}$$

where:
r_0 – heat of vaporization or condensation, (J·kg^{-1})
$A_{liście}$ – leaf area, (m^{-2})
M_{transp} – mass flux absorbed by plants through transpiration referred to m^2 of the greenhouse area (kg$_{pary}$·m^{-2}·s^{-1})

The second source of the latent heat is the condensation on the cover. By condensation of water vapor, heat is released to the environment:

$$Q_{kond} = r_0 A_{oslona} M_{kond} \quad (\mathrm{J \cdot kg^{-1}}) \tag{12}$$

where:
M_{kond} – mass flux from the condensation (kg$_{pary}$·m^{-2}·s^{-1})

Mass exchange model

Water vapor content of the air inside the greenhouse is an important environmental parameter, which determines the proper development of a crop. It is also used to assess the risk of diseases and undesirable pest development.

A model describing the changes in the water vapor content of the air inside the greenhouse is based on the mass balance equation. The primary source of water vapor in the balance equation is plant transpiration. Water vapor in the air inside the greenhouse is reduced as a result of condensation on the inner side of the cover. Mass transfer due to ventilation can take place in both directions depending on the conditions inside and outside the greenhouse. Mass balance equation takes the following form:

$$\frac{V_{sz}}{A_{sz}}\frac{df_{wew}}{d\tau} = M_{transp} - M_{kond} - M_{went} \tag{13}$$

where:

A_{sz} – greenhouse area, (m^{-2})
f_{wew} – water content of the air inside the greenhouse, ($g \cdot m^{-3}$)
M_{went} – mass flux due to ventilation, ($kg_{pary} \cdot m^{-2} \cdot s^{-1}$)

In this study to determine the transpiration of the plants a regression model presented in the work (Kurpaska, 2006) was applied. It was developed to determine the water demand of greenhouse tomatoes, taking into account controllable factors of the surrounding climate, i.e. solar radiation *Rad*, air temperature inside the greenhouse T_{wew} and vapor pressure deficiency *VPD*.

$$M_{transp} = \frac{1}{120}\left(0{,}0025 \cdot Rad + 0{,}098 \cdot T_{wew} - 0{,}143 \cdot VPD + 0{,}05\right) \ (g \cdot m^{-2} \cdot s) \tag{14}$$

where:

VPD – vapor pressure deficit, (Pa)

In order to simplify the developed mass exchange model it was assumed that the temperature of inner side of the cover is calculated according to the following equation (Kurpaska, 2007):

$$T_{oslona} = 0{,}4T_{zew} + 0{,}6T_{wew} \ (K) \tag{15}$$

where:

T_{oslona} – cover temperature, (K)

Whereas condensation of water vapor on the inner side of the cover is expressed by the relation (Tap, 2000):

$$\begin{cases} M_{kond} = m_1 \left| T_{wew} - T_{oslona} \right|^{m_2} \left(f_{wew} - f_{\max wew} \right) & \text{gdy} \quad f_{wew} > f_{\max wew} \\ M_{kond} = 0 & \text{gdy} \quad f_{wew} \le f_{\max wew} \end{cases} \quad (\text{g·m}^{-2}\text{·s}) \qquad (16)$$

where:

$m_1 \left| T_{wew} - T_{oslona} \right|^{m_2}$ – mass transfer coefficient,
m_1 i m_2 – fixed parameters of the mass transfer coefficient,
$f_{max.wew}$ – the maximum water content of the air inside the greenhouse (g·m^{-3}).

Reducing or increasing (to a lesser degree) the water vapor content of the air inside the greenhouse is also carried out through ventilation. The amount of water vapor removed from the greenhouse is described by the following formula:

$$M_{went} = \Phi_{went} \left(f_{wew} - f_{zew} \right) \quad (\text{g·m}^{-2}\text{·s}) \qquad (17)$$

where:
f_{zew} – water content in the outside air, (g·m^{-3})

The air flow rate through ventilators is calculated from the relationship (10) presented in the part of the work on heat balance.

Computer model and simulation results

Models of heat and mass transfer in the air inside the greenhouse, which were described earlier, were implemented in MATLAB/Simulink software. Figure 1 shows a schematic representation of the developed computer model of heat and mass transfer in the air inside the greenhouse.

The developed computer model was used to perform simulations, which led to the conduct of daily changes in temperature and humidity inside the greenhouse. Waveforms of input variables of the simulation model shown in Figure 1 were determined by experimental investigations. Figure 2 and figure 3 show exemplary results of these simulations for four consecutive days, as well as the values of the analyzed parameters obtained in the course of experimental tests in the greenhouse. The simulations carried out with a computer model were used for carrying out graphical and statistical validation of the model.

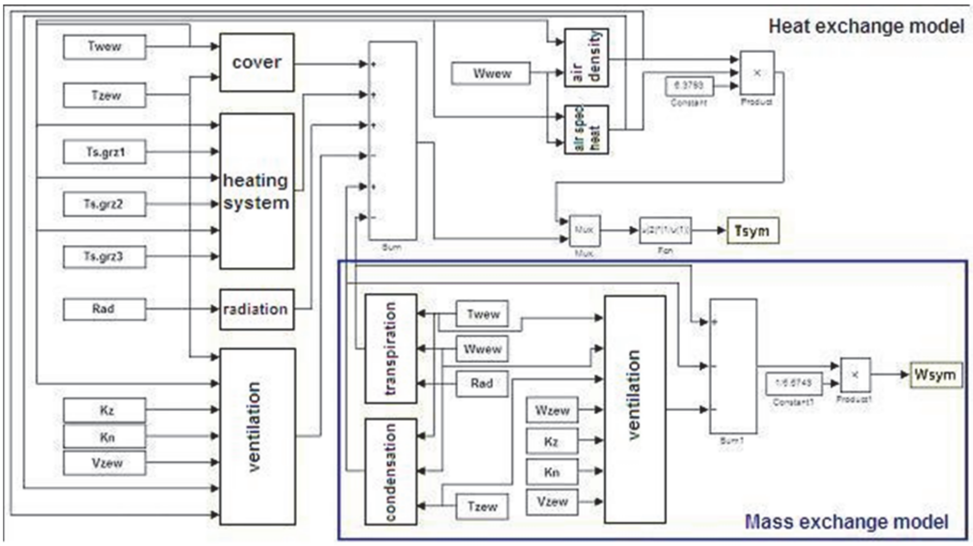

Figure 1. Schematic representation of the computer model of heat and mass exchange in air inside greenhouse. Symbols: W_{wew} *– relative humidity of air inside greenhouse (%),* W_{zew} *– relative humidity of air inside greenhouse (%),* T_{sym} *– air temperature inside greenhouse obtained as a result of computer simulations (°C),* W_{sym} *– humidity of air inside greenhouse obtained as a result of computer simulations (*$kg_{pary} \cdot m^{-3}_{powietrza}$*)*

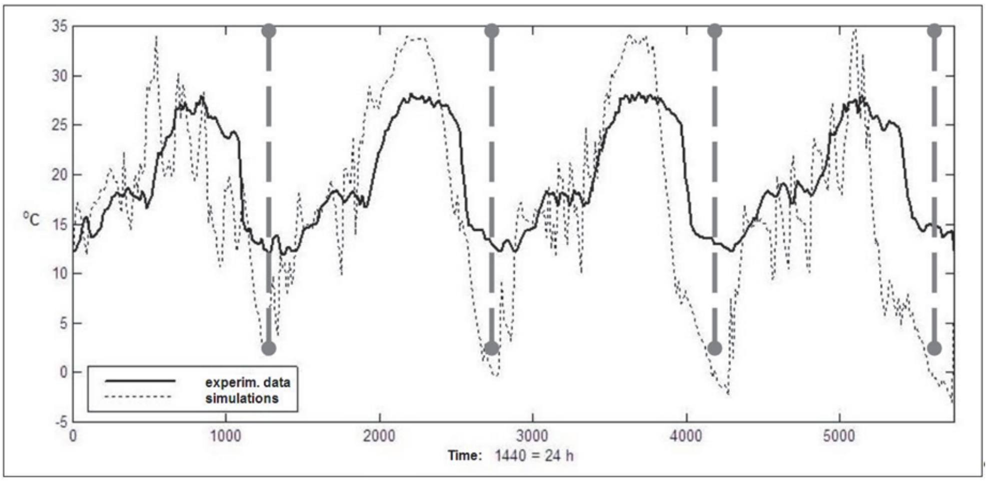

Figure 2. Air temperature changes inside greenhouse obtained during measurements and simulation research

Analysis of simulation results allows statement of logical correctness of the developed model. It also enables the identification of critical points of failure to adjust the model. It was found out that in this case the moment is the sunset, marked on the charts with a vertical line ●━ ━●. This indicates the strong correlation and sensitivity of microclimate inside the greenhouse on the amount of heat supplied to the object due to sun radiation.

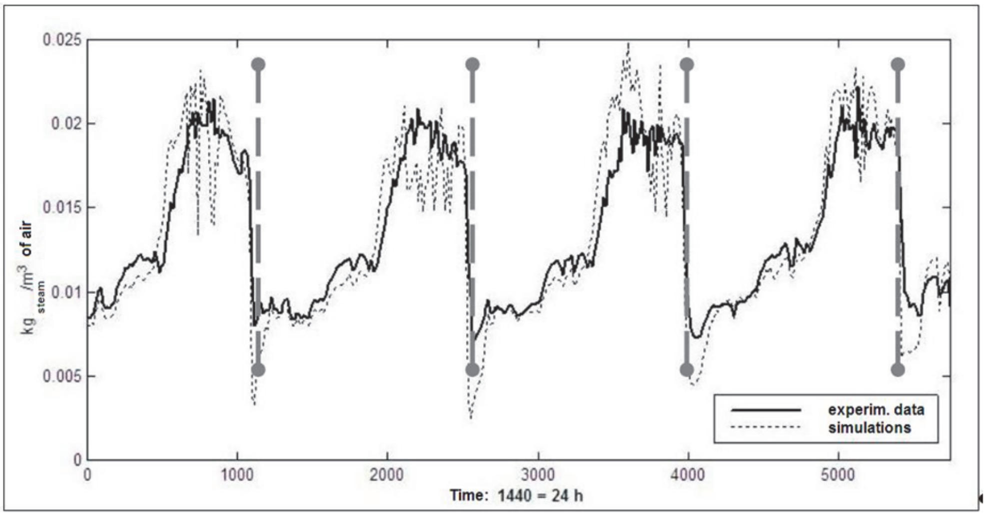

Figure 3. Changes of air humidity inside greenhouse obtained as a result of measurements and computer simulations

For statistical verification of the developed model a determination rate was used (Makać and Urbanek, 2010):

$$R^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y})^2 - \sum_{i=1}^{n}(y_i - Y_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}; \quad R^2 \le 1 \tag{18}$$

where:

y_i – are the values of the selected features obtained from measurements,

Y_i – the corresponding values determined from the model.

If the value of determination rate is closer to 1, the better is consistency of data from the model with empirical data. For the heat exchange model the determination rate (for example four days presented in fig. 2 and 3) was 0.87. Whereas for mass exchange model the determination rate was 0.97.

Conclusions

The accuracy of the heat transfer model is mainly affected by the simplification degree and by omitting other heat fluxes in the model. This applies in particular to the heat exchanged between solid elements of the greenhouse and the air inside the greenhouse by radiation. None of these heat fluxes in the developed model may explain the discrepancy between the data obtained during the simulation and data obtained from experimental investigations in the period just after sunset. Whereas a better fit of the mass transfer model may result, inter alia, from smaller number of process variables, compared to the amount of variables involved in the heat exchange process. The developed mathematical model and a computer model created on this basis provide valuable information about the complex system, which is a greenhouse. The ability to perform a variety of simulation enables, among others, to analyze the sensitivity of the system to individual parameters changes. In order to use the developed model e.g. for control purposes, it requires to be more detailed.

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MODEL PROCESU WYMIANY CIEPŁA I MASY W POWIETRZU WEWNĄTRZ SZKLARNI

Streszczenie. Celem pracy było opracowanie matematycznego modelu wymiany ciepła i masy w powietrzu wewnątrz wielkogabarytowej szklarni, w której prowadzona jest towarowa uprawa roślin. Podczas formułowania modelu wykorzystano m.in. modele opisane w literaturze i wyniki badań eksperymentalnych. Opracowany model matematyczny został zaimplementowany do programu MATLAB/Simulink, a symulacje przeprowadzone z udziałem modelu komputerowego wykorzystano do przeprowadzenia graficznej i statystycznej walidacji modelu. Analiza wyników symulacji pozwala na stwierdzenie logicznej poprawności opracowanego modelu, a także umożliwia określenie punktów krytycznych niedopasowania modelu. Na dokładność opracowanego modelu wymiany ciepła wpływa przede wszystkim stopień jego uproszczenia. Aby opracowany model mógł być wykorzystany, np. do celów sterowniczych, wymaga większego uszczegółowienia.

Słowa kluczowe: szklarnia, mikroklimat, model matematyczny, wymiana ciepła i masy