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BUCHAREST

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Faculty of Building Services Engineering

Thermo-technics and Thermal Equipment Department

DOCTORAL THESIS

Summary

Energetically Aspects related to the Microclimate in Protected Areas

*Applications in Healing and Acclimatization
Chambers*

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1. Introduction

In specialized protected crop areas for seedling production, the values of the parameters characterizing the microclimate in these locations must be observed with utmost precision, as young plants are vulnerable to their unpredictable fluctuations. By monitoring and predicting the variation of the microclimate factors, it's guaranteed the optimal development, with a high survival rate of the seedlings.

The main objective of this study is to analyze the variation of microclimate factors in the healing and acclimatization chambers of grafted vegetable seedlings during the specific technological phase. *Callus inducing* or *healing* refers to process of healing of the area where the two components of the grafted plant were sectioned, namely the graft and the rootstock. The main parameters of the microclimate that influence the development of seedlings are relative humidity, temperature, intensity of light radiation, speed of air currents and the level of CO₂ concentration.

2. Contents of doctoral thesis

The first part of the study presents the most important concepts related to cultivation in protected areas generally, as well as notions related to the entire process of vegetable seedlings grafting. Then, it's presented the evolution and the current stage of knowledge of researches oriented towards the analysis of the influence of microclimate factors on the healing process of grafted seedlings, their survival rate and their further development. Subsequently, it is highlighted the main energetic issues specific to protected crop areas and to the thermo-technical processes that occur in these areas, but also in the callus induction chambers during the process of healing of the grafted seedlings or during their acclimatization period before planting them in crop fields. It is likewise presented the main thermophysical parameters specific to the healing chambers, namely temperature, relative humidity, light radiation intensity and carbon dioxide concentration. Then, the research protocol for measuring the variation of the main microclimate factors in an experimental healing tunnel is presented. This is followed by the analysis and interpretation of the results of these measurements, carried out during the healing process of several grafted seedlings. The next stage of the research, presented in this paper, consists in the proposal of a numerical modeling concept of the thermo-technical processes that occur in the callus induction and acclimatization chambers. Further, the data obtained by numerical modeling were compared to those obtained from experimental measurements, aiming at validating the proposed numerical model. This analysis shows that the proposed numerical model is validated. The conclusions will also show that, by means of such a model, validated, depending on the external environmental conditions, on the cultivation type and on the location type, it is possible to act in real time to adjust the microclimate factors, reducing the decision of the human factor, which may often be delayed or even wrong. At the same time, it is shown that such a model lays the foundations for the design and development of automated multifunctional premises, which may be used either to heal the grafted plants, or to acclimatize seedlings before their planting in the field or in

greenhouses, without interfering with the constructive solution of the site. In the last part of the thesis, the activities of dissemination of the partial results obtained throughout the doctoral research are mentioned.

3. Energetic issues specific to protected areas

After presenting the theoretical aspects related to the grafting of vegetable seedlings and after making the overview of the researches made worldwide as concern the analysis of the microclimate in protected areas, several energetic issues specific to protected areas intended for growing vegetables are presented. The microclimate of a greenhouse is the result of heat and mass exchanges between air layers and solid surfaces (walls, roof, various structures, crop leaves), between the different air layers, between the air from the inside and from the outside of the greenhouse. The mechanisms of these mass and heat transfers consist in conduction, convection and radiation (Pieters and Deltour, 1997). Figure 1 schematically shows the mass and heat flows that occur between the different surfaces inside greenhouses.

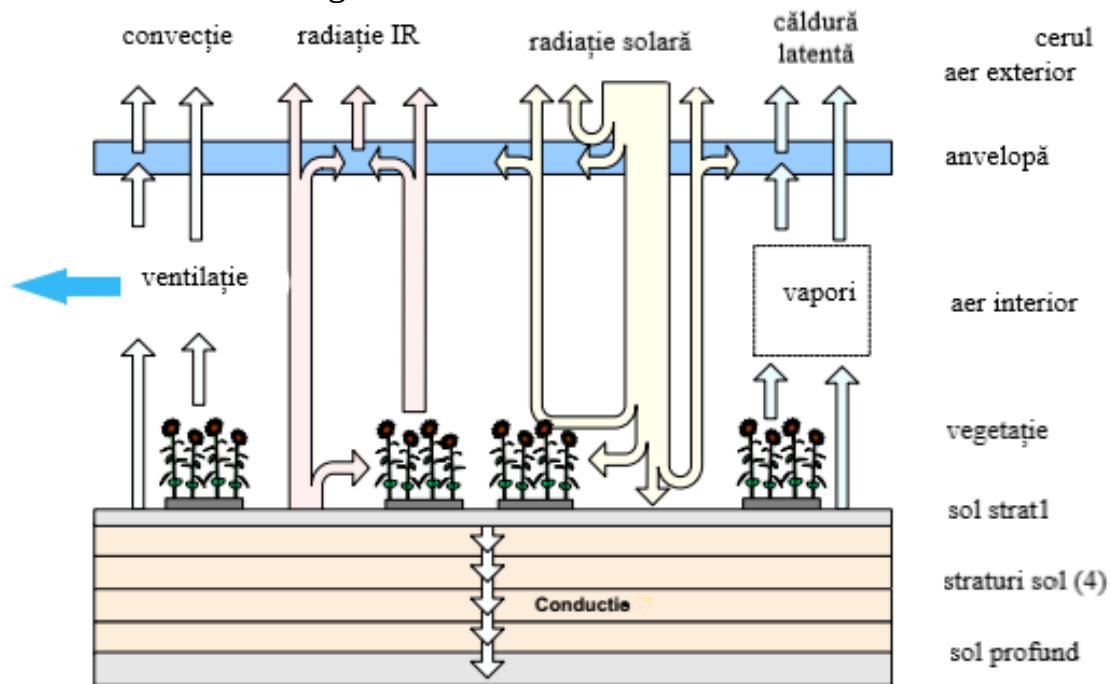


Fig. 1: Exchanges of heat and mass that occur in greenhouses

When analyzing the energy exchanges in greenhouses, it may consider that there are 7 horizontal layers between which these exchanges take place (see Figure 1). Therefore, the microclimate in the greenhouse is the result of heat and mass exchanges between these layers. The interactions between layers include heat transfers through the processes of conduction, convection, sun and heat radiation, as well as mass transfers through latent heat. The heat exchanges of the air inside the greenhouse occur by convection with the greenhouse envelope, with the vegetation in the greenhouse, with the soil, with the heating system (if any) and by the exchange with the exterior air, by diffusion and ventilation. For a crop, sun radiation, the radiative exchange with the envelope, with the soil and with the greenhouse equipment, the convective exchange with the proximal air and the

exchange of latent heat during the process of evapotranspiration are of utmost importance. For the soil, the accumulations and losses of energy are produced by absorption of solar radiation, by radiative exchange with the envelope, with the crop itself and with the equipment installed in the greenhouse, through the convective exchange with the greenhouse air and through the convective exchange with the underground layers of the soil. Considering the complexity of the heat and mass transfer processes occurring in greenhouses and solariums, the analysis of the energy balance may be made separately for the soil, for the crop, for the volume of the interior air and for the envelope. Two types of solid surfaces are usually encountered in greenhouses: the walls of the greenhouse, which are generally made of plastic foil, and the surface of crop leaves. In the proximity of these surfaces, the air flow cannot be considered to have zero viscosity, even if the velocities are close to zero. This viscosity generates a dynamic layer in the contact area with solid surfaces, an area where the impulse is dissipated by friction. If there is a difference in temperature between walls or leaves and the air, then a boundary heat layer is formed, which depends essentially on the dynamic boundary layer. Moreover, if there is a difference in humidity between walls or leaves and the interior air, a boundary layer is formed, generated by this difference in vapor concentration, which overlaps the other two previous boundary layers in the immediate proximity of the wall or of the leaves. Defining temperature and concentration gradients helps establishing with precision the heat or mass transfer rate between air and leaves or wall. Various correlation formulas are deduced from fluid flow equations, adapted to consider the boundary layer conditions, by means of various dimensionless criteria (Schlichting, 1955) which are defined by means of the characteristic flow conditions. Consequently, the macro-model is still valid to determine the energy and mass balance of walls and leaves in the area of interest. However, these formulas are not valid for the entire crop, because of the interaction between the various layers of air that flow vertically. Thus, in 1993, Schuepp (1993) shows that the relations for the laminar flow at leaf surface is valid when the boundary layer becomes turbulent on the side of the leaf facing the soil. As regards the numerical model proposed in this paper, the movement of air flows and the distribution of temperature, of relative humidity and of CO₂ concentration are generated strictly by the vertical density gradient caused by the heat transfer through free convection, from the lower surface of the heating chamber to the air existing inside the chamber. The predominant surface of capturing solar radiation is the lower surface of the location (the one with the alveolar trays with seedlings and the free one between the trays) and it's considered that this is the only surface able to capture sun radiation. The walls are subject to the condition of getting a convective thermal flow triggered by the inside and outside temperature differences.

4. Energy balance in protected crop areas

The thermophysical processes occurring in protected crop areas are in an energy balance with the exterior and interior environment of the greenhouses. Fernandez (Fernandez and Bailey, 1992) proposes the following equation for the energy balance inside greenhouses:

$$\dot{Q}_i + \dot{Q}_s = \dot{Q}_v + \dot{Q}_e + \dot{Q}_{anv} + \dot{Q}_{stoc} \quad (1)$$

where $\dot{Q}_i$ is the energy produced by the additional heating system of the greenhouse, $\dot{Q}_s$ is the energy of sun radiation, $\dot{Q}_v$ is the energy lost through ventilation, $\dot{Q}_e$ is the energy lost through leaks, $\dot{Q}_{anv}$ is the energy lost by heat transfer through the envelope, and $\dot{Q}_{stoc}$ is the energy stored in the various components of the greenhouse, all of them expressed in W. Hanan believes that the amount of solar energy used in the process of morphogenesis is minimal, and it may be neglected when analyzing the energy balance (Hanan, 1998); likewise, most energy transfers are related to the transformation of water from its liquid state to vapor and vice versa. A large amount of energy is absorbed by the soil which then conveys to plants and to the other elements in the greenhouse. The same is done by each of the other elements, respectively the plants absorb energy, which they later convey by IR radiations to the soil and to the constructive elements, to the envelope. Plants also lose energy through evapotranspiration. The air exchanges energy with all the elements in the greenhouse, and the envelope absorbs a large amount of solar energy; it conveys part of it back to the atmosphere, and the other part inside the greenhouse.

The energy flows in a healing chamber exposed to solar radiation inside a greenhouse are shown schematically in Figure 2 (Miles et al., 2016).

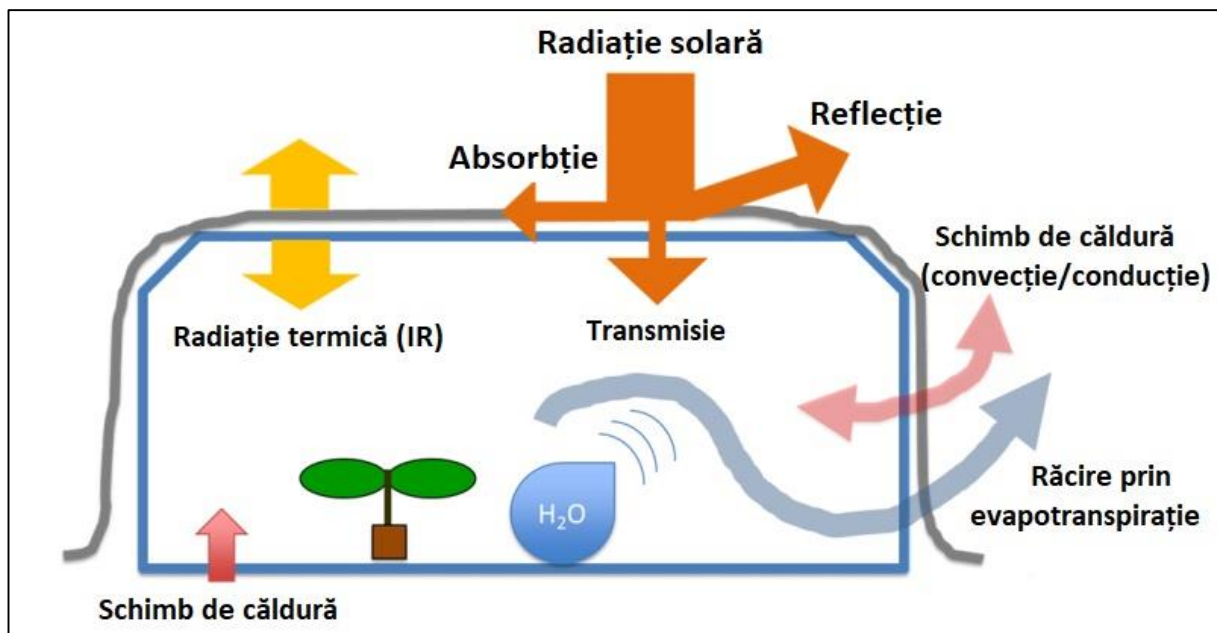


Fig. 2: Energy flows in a tunnel-type healing chamber, (Miles, 2016)

5. Thermophysical parameters specific to healing chambers

The main factors characterizing the microclimate from the protected crop sites are: temperature, relative humidity, light radiation intensity and CO₂ concentration. The differences between the parameter values defining the microclimate inside and outside the protected vegetable cultivation areas are generated mainly by the following 4 elements (Popovski, 1997): 1. *solar radiation*: its main component is UV radiation, which is able to go through the envelope almost without any loss; this radiation is reflected by the plants and by the various equipment installed in the locations, and only part of them are able to

go back through the envelope, while the remaining radiation is preserved inside the location, causing the increase (rise) of temperature; 2. *ventilation*: air velocity inside the protected areas is much lower than outside, and the heat transfer phenomenon differs between the two environments; 3. *plant density*: it significantly influences relative humidity and CO₂ concentration inside locations, and the mass transfer process differs in the two environments; 4. the existence of *heating systems*: these are able to modify some of the energetic features of the microclimate inside the chambers. The recommended values for the microclimatic parameters in the healing chambers are: temperatures in the post-grafting period must be between 23°C/20°C (day/night) or 25°C/18°C (day/night), and temperature values of 30°C/15°C (day/night) are considered high, respectively low for the healing process; the ideal humidity levels are between 70% and 90% during the healing period, according to the crop variety; the intensity of light radiation must have a density of active photosynthetic photon flow (*PPFD*) between 400 and 700 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$; the CO₂ concentration must exceed 900 ppm, thus eliminating the inhibition of the photosynthesis process by O₂.

6. Experimental analysis of processes occurring in healing chambers

In order to evaluate the various microclimate parameters during seedling healing and to identify the best microclimate conditions, but also their management strategies, during the doctoral stage, two measurement phases were carried out, the first phase between May 13-19, 2018, and the second phase between May 17-22, 2019, inside the research micro-greenhouse of HORTING Institute, in an experimental healing tunnel consisting of several sections with the dimensions $L = 1.8 \text{ m}$, $w = 1.5 \text{ m}$ and $h = 1.0 \text{ m}$.

During the first phase, the measurements were carried out in 4 independent sections. In each of the 4 compartments, 9 alveolar pallets were placed, with 104 seats for nutrition cubes. At this phase, 4 densities of seedlings per each compartment were chosen: 347 seedlings/m², 173 seedlings/m², 83 seedlings/m² and 37 seedlings/m². During the experiments, measurements of the main microclimate factors were made, namely temperature, relative humidity, light radiation intensity and CO₂ concentration, outside the micro-greenhouse, inside the micro-greenhouse and inside of every healing section. The following measuring devices were used to carry out the measurements: USB-Data Loggers MicroLite was used to measure the relative humidity; a Testo 535 portable analyzer was used to measure the CO₂ concentration - the measurements were made 1 hour after sunrise, at noon (at 1 p.m.) and 1 hour before sunset; a HD 2102.2 Data Logger photo-radiometer + LP 471 PAR probe were used to measure light radiation intensity; a LM-8102 multifunctional measuring device was used to measure sun radiation intensity outside and inside the micro-greenhouse.

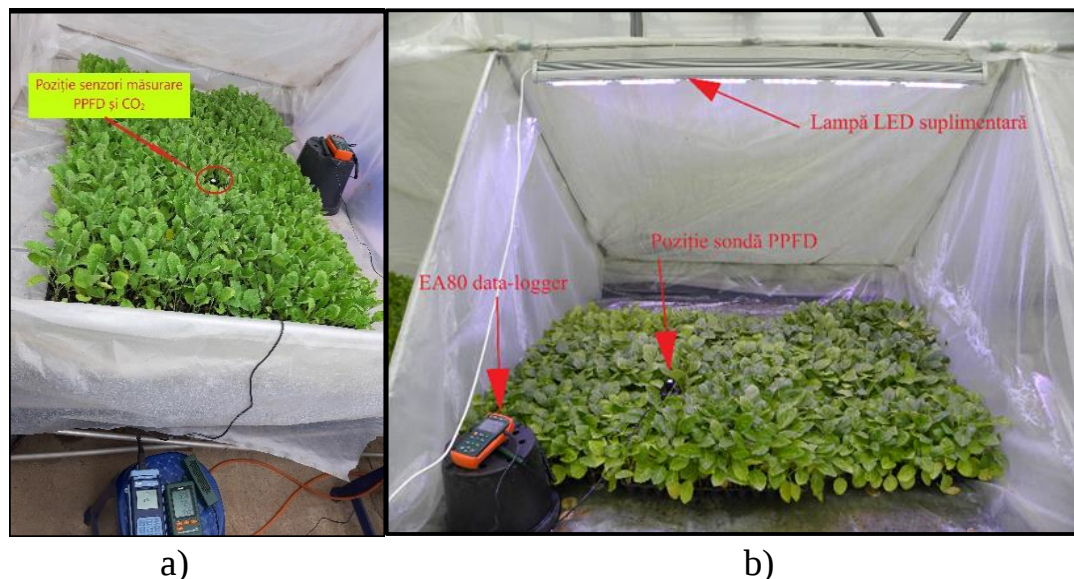


Fig. 3: The sensors' placement: a) at the first phase of the measurements;
b) at the 2nd phase

During the second phase, in the same location other experimental measurements were made. This time, two sections of the experimental healing tunnel were used. Alveolar pallets with seedlings were placed in each compartment and their density was of 347 plants/m². The difference between the two measurement sessions is that, during this stage, in one of the sections, on its upper side, an additional LED lighting element was set up, with the following features: white LEDs emitting a light flow of 4000 K, blue LEDs emitting in wavelength $\lambda = 460$ nm, and red LEDs with $\lambda = 660$ nm. The LED lamp for additional lighting was programmed to operate daily between 04:20 and 20:20, namely to turn on one hour before sunrise and to turn off about one hour after sunset. For measurements, the following devices were used: EA80 data-loggers to measure CO² concentration, temperature and relative humidity in the two sections; SD800 data logger to measure CO₂ concentration, temperature and relative humidity in the micro-greenhouse; LP471 data-logger + PAR-LP probe to measure light radiation intensity inside the sections; VantagePRO2 Plus weather station used to measure temperature, relative humidity and intensity of sun radiations outside the greenhouse.

7. Results, discussions and interpretations

7.1. The values of the parameters measured during the first phase were analyzed and interpreted. Their variation pattern helps establishing microclimate management strategies in healing areas. The values of temperature and relative humidity are shown graphically in Figure 4 and Figure 5.

It may notice that the temperatures in the 4 sections, as well as inside the micro-greenhouse, are similar to the variation of exterior temperature. In terms of thermodynamic processes, this was to be expected. In terms of microclimate factor management inside the micro-greenhouse and in the healing tunnels, it may observe that there is no efficient system to monitor and remedy the influence of

microclimate conditions in the external environment on temperatures in the healing tunnels.

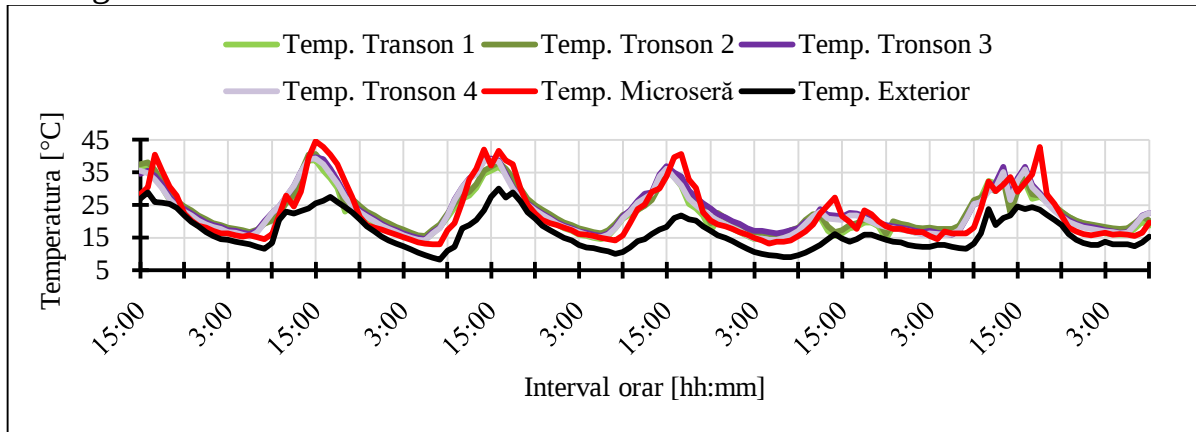


Fig. 4: Variation of temperature in the 4 sections, inside and outside of the micro-greenhouse

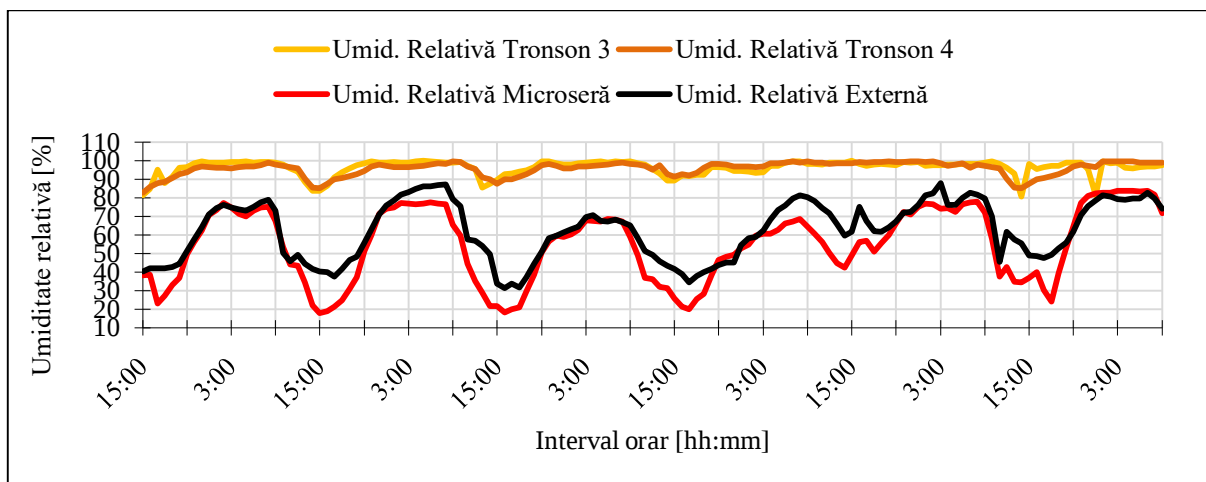


Fig. 5: Variation of relative humidity in the sections, inside and outside of the micro-greenhouse

In Figure 6, it may notice that the variation of temperature in the micro-greenhouse and in the external environment does not significantly influence the relative humidity in the healing areas. The variation of relative humidity in the healing areas is mainly caused by the evapotranspiration process occurring during photosynthesis.

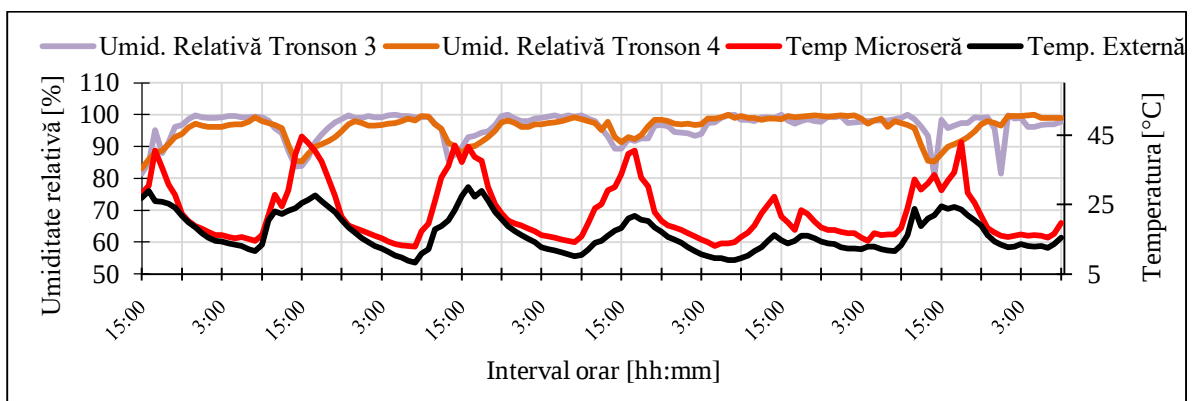


Fig. 6: Variation of relative humidity in the sections 3 and 4, of the temperature in the micro-greenhouse and of external temperature

The intensity of light radiation directly influences the photosynthesis process and therefore the CO₂ concentration. Figure 7 shows that, on sunny days, when the value of light radiation intensity (PPFD) in the section is high, the photosynthetic activity was very intense and the value of CO₂ concentration was low.

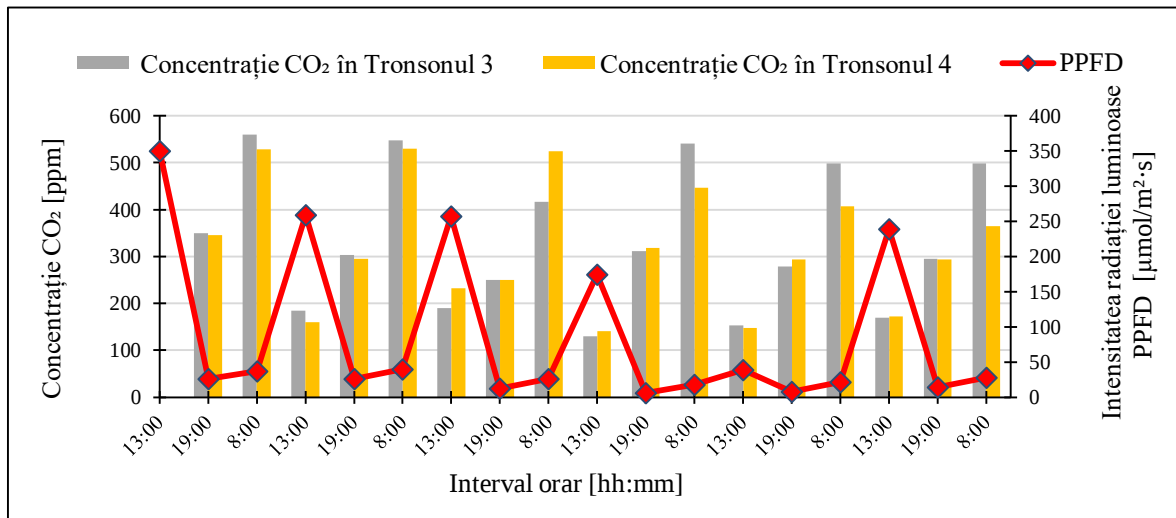


Fig. 7: Variation of CO₂ concentration and of light radiation intensity

7.2. The values of the parameters measured during the *second phase* have also been analyzed and interpreted. Following this analysis, it has been found that the thermo-technical processes that develop in the healing tunnel generate a dynamic variation of the microclimate parameters. These parameters interact between them and are influenced by the seedlings biological processes during their healing period; on their turn, these biological processes influence the dynamics of thermo-technical processes inside the healing areas. It is obvious that the temperature rises while the intensity of light radiations increases. Even if the heat generated by the LED lamp is low, a rise in temperature is noticed in the additionally lighted section. Nevertheless, this difference of temperature between the 2 sections is influenced more by the temperature values from the micro-greenhouse than by the temperature emitted by the additional lamp. It may also notice that, at higher values of light radiation intensity, the CO₂ concentration decreases as a result of the increase in the intensity of the photosynthesis process, which is a CO₂ “consuming” process. Figure 8 shows how relative humidity is influenced by the increase of light radiation intensity: the higher the value of light intensity, the higher the intensity of the photosynthesis process. Or, an intense photosynthesis process materializes through a high evapo-transpiration process, therefore entailing the increase of relative humidity in the healing chamber. This increase occurs until relative humidity comes close to the saturation point, while evapotranspiration stagnates and tends to stop.

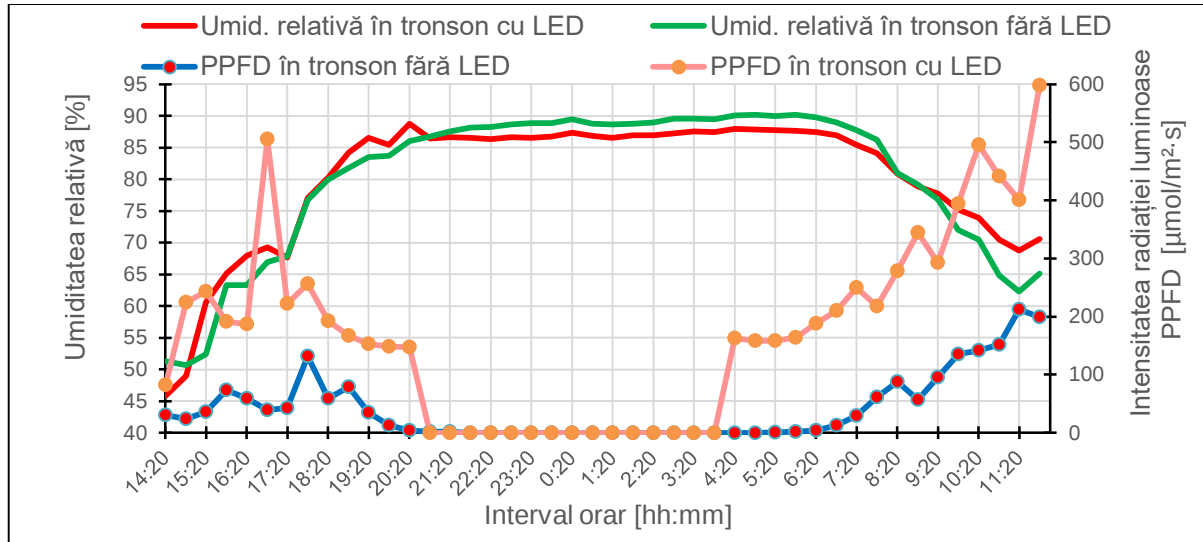


Fig. 8: Influence of light radiation intensity on relative humidity

8. Numerical modelling of processes in the healing chambers

Due to the complexity of the phenomena occurring in the healing chambers, the amount of information required to fully quantify the variables of microclimate factors depends on both the intensity of the thermophysical processes that develop and on the level of accuracy of the measuring instruments that are used. However, an analytical approach to the system of differential equations describing these processes is very difficult. The numerical simulation of these thermophysical phenomena may entail the development of a predictive model of their variation, versatile, which could be used in any external weather condition, at any time of the year and in any geographical location. Likewise, numerical modelling techniques may also provide an effective means of accurately quantifying climate variables in the healing chambers. For the numerical modelling of the thermo-technical processes that are developed inside healing chambers, it has been decided to use the COMSOL Multiphysics software package. The heat transfer module of this software, used to model the processes that occur in the healing chambers, supports all the basic heat transfer mechanisms, including heat transfer through conduction, convection and radiation (both radiation between two surfaces and between a surface and the surrounding environment). The numerical investigation was made for only one healing section. In order to solve the differential equations using the finite element method, the analyzed area was divided into small-sized elements. Consequently, by successive iterations, it is possible to determine the values of microclimate parameters, such as temperature, pressure, velocity vectors, etc. Taking advantage of the double symmetry of the healing tunnel geometry, in order to facilitate the calculation, the choice has been made to solve the equations for a quarter of the real area, taking two limits as planes of symmetry. The two planes of symmetry (longitudinal and transverse) were considered not only in terms of geometry, but also in the solving of the equations, as they represented delimitation conditions. In order to make the numerical simulation, the transfer equations were solved strictly in the fluid (air) area, and, this case, the geometry represents the "empty" part of the site, without walls or plants, which constitute the boundaries of the area. The decision has been

made to solve the heat transfer and impulse transfer equations (the movement of air currents). The movement of air currents and the distribution of temperature, relative humidity and CO₂ concentration are generated strictly by the vertical density gradient due to heat transfer by free convection, from the lower surface of the healing site to the air inside the location. The predominant surface of capturing solar radiation is the lower surface of the location (that with the seedlings alveolar trays and the free one between the trays); this has been considered to be the only surface able to capture sun radiation, as the walls have as a limiting condition the convective heat flow determined on the base of inside and outside temperature differences. The values of the temperature in the exterior of the site, as well as of the heat flow in the lower part of the healing area, measured during the experimental determinations, were considered boundary conditions in non-stationary regime in the numerical simulation.

8.1. Results, discussions and interpretations

Following the simulation, the maximum velocity reaches about 0.12 m/s and manifests mainly at the center of the healing chamber. In the proximity of the vertical and oblique wall of the healing chamber, it may observe that there is an area where velocity has a very low value and the same may be noticed in the proximity of the seedling alveolar trays. Figure 9 shows the flow lines resulting from the simulation.

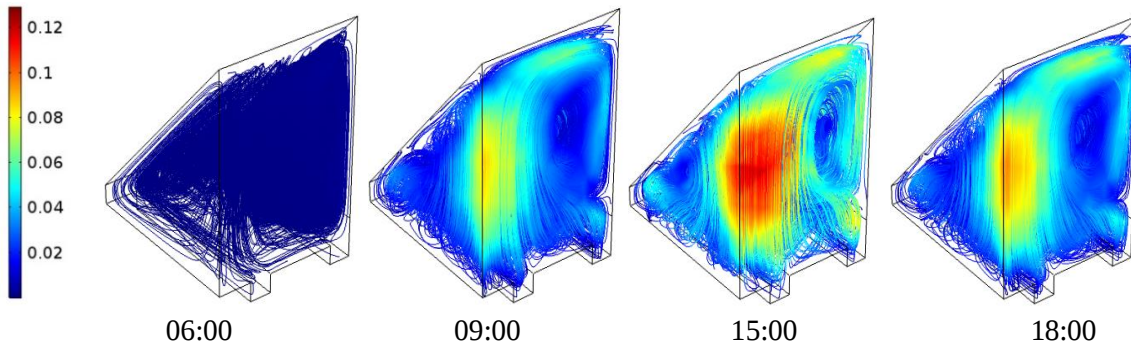


Fig. 9: Flow lines

At this point, it may distinguish with greater clarity the areas in the immediate proximity of the walls, where velocities are low, compared to those of the central area of the healing tunnel. The fact that flow lines have a higher density in the central area of the tunnel leads to conclude that the other parameters of the microclimate inside the location, respectively CO₂ concentration, temperature and relative humidity, do not have equal values in the entire volume of air existing in the healing tunnel. Consequently, solutions are required, in order to equalize the values of microclimate factors in the entire volume of the tunnel. Figure 10 shows the temperature fields resulting from the simulation, which have the same input data as for the simulation of the variation of air velocity fields inside the tunnel. It may notice that, in the areas close to the alveolar trays, where the velocity of air currents is not very intense, the temperature is higher, which has a negative impact on the healing process and on the development of seedlings, particularly as the calculated maximum temperature was of 43.8°C.

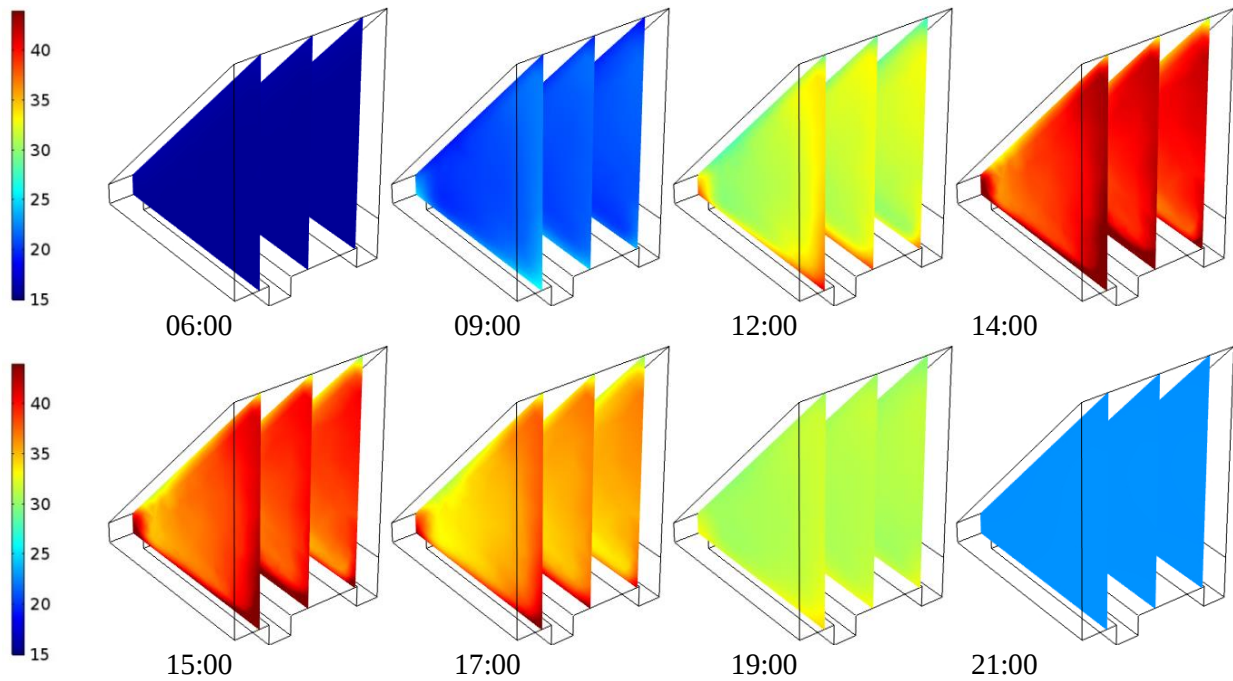


Fig. 10: Temperature fields, in °C, at various moments

Figure 11 shows the calculated values of the variation of CO₂ concentration in the same simulation conditions established to determine the variation of air current velocity and of temperature. It's observed the same aspect as in the case of temperature: due to the low values of the air flow velocity, the CO₂ concentration varies with an unequal distribution inside the tunnel. These unequal distributions of CO₂ concentration and high values of temperature, as well, are not the best conditions for the healing period of the grafted seedlings. For a plants survival rate of 95% -100%, it is imperative to have the same microclimate conditions in the whole volume of the healing tunnel, particularly in the alveolar trays area.

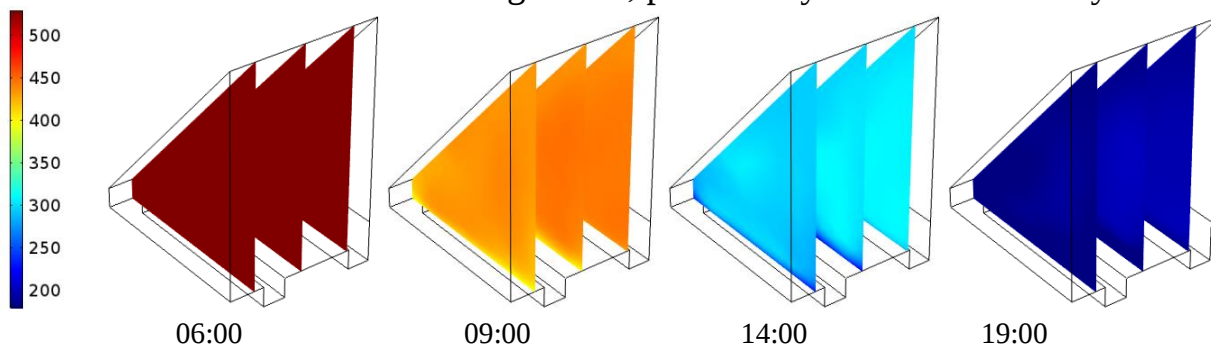


Fig.11: CO₂ concentration fields in ppm, vertical **planes**, for various moments

8.2. Validation of the numerical model

To see if the proposed numerical model is correct, the measured values were compared, for the same position of the measuring device sensors, respectively just above the seedling alveolar trays, with the calculated values of the parameters. This case, the values of temperature, relative humidity and CO₂ concentration were compared. Graphical representations of these values are shown in Figure 12.

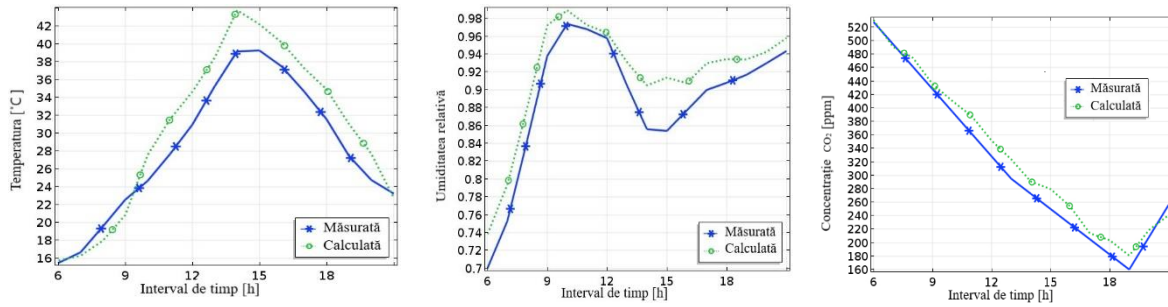


Fig. 12: Variation of temperature, relative humidity and CO₂ concentration in the calculation field

It is observed that the calculated values have the same tendency of variation as the measured values. The average squared error calculated for temperature validation is of 2.84°C, the average squared error calculated for the relative humidity is of 3.1% and the average squared error calculated for CO₂ concentration is of 18.98 ppm. Therefore, the values of the average squared errors calculated for the variation of the microclimate factors in the healing tunnel validate the proposed numerical model.

9. Conclusions

Since the technological phases to obtain grafted seedlings are relatively short, the fluctuations of microclimate factors may have important effects on the quality and quantity of the yield. This is why a recommended method would be to use areas where special microclimate conditions may be provided during the healing period. The advantages of using an artificial environment are mainly the predictability of yield indicators and the standardization of seedling quality, due to the constancy and uniformity of microclimate conditions in this type of areas. The numerical model designed to predict the evolution of the microclimate premises in healing chambers proposed in this research has been validated, therefore the proposed solution is correct. Likewise, the proposed numerical model may be used for a series of activities such as the management of microclimate conditions inside healing areas, assessment of results provided by existing areas or design of healing rooms where the management of microclimate factors may be done in real time, without the involvement of the human factor.

As the production of grafted seedlings in Romania has acquired a considerable importance and their growing period, respectively March, April and May, is an interval with large fluctuations of external natural climate factors, the researches carried out during this study aimed at achieving a numerical model able to predict the parameters of thermodynamic processes occurring in the healing chambers, both according to the external environmental conditions and to the interaction of plants with the internal environmental factors. This model only analyzes the variation of the microclimate parameters, but it cannot specify the best values at any time of the day. To improve these predictions, the model must be tested for more environmental conditions. At the same time, a future research must consider the interaction of plants with the microclimate factors because each crop has different rates of photosynthesis that interact differently with the microclimate in the healing chamber. As a consequence, there are many data that must be considered during the assessment process and in order to predict with accuracy

the internal climate in the healing and acclimatization chambers. Real-time monitoring of information related to plant morphogenesis and variations in microclimate factors should provide information that would entail a minimum disturbance in plant development and in the internal environmental conditions. In this regard, interdisciplinary research must be developed in order to implement a biological model of growing plants, considering the environmental parameters, so that it should be possible to establish in real time the best policy for controlling and predicting the values of microclimate parameters in the healing and acclimatization chambers. The optimization of the constructive and functional parameters of the healing and acclimatization premises implies the development of interdisciplinary researches in the horticultural field, technical engineering, informatics technology, etc.

10. Personal contributions and capitalization of results

Through the documentary study that I underwent at the beginning of my doctoral internship, which consisted in analyzing over 150 specialized articles from the country and from abroad, I was able to make an overview of the current status of researches. At the same time, this documentary study stood as the reference point for the directions aimed at by subsequent theoretical and experimental researches presented in this paper. Another highly important outcome of the documentary research is that, both nationally and internationally, till nowadays, no research has been carried out with the purpose to analyze the thermo-technical processes that occur in healing chambers, which provides utter originality to this paper. Another aspect of genuineness of this thesis consists in the concomitant analysis of the variation of the most important microclimate factors in the healing/acclimatization chambers, namely temperature, relative humidity, light radiation intensity and carbon dioxide concentration. Then, based on the experimental measurements that have been made, a numerical model for calculating the evolution of microclimate factors was proposed. This numerical model may also be considered as a novelty in the field. So far, all the research carried out in this direction focused on analyzing the microclimate of protected crop areas, considering *a priori* that the thermophysical processes occurring in the healing and acclimatization locations are identical to those in greenhouses.

During the stages of this doctoral study, the partial results that I have obtained were periodically disseminated, by participating in various national and international scientific events such as: *International Congress on Food Technology 18-19 March, Athens – Greece*; *8th International Conference on Energy and Environment CIEM 2017 - UPB Bucharest / 19 - 20 October 2017*; *IX International Symposium on Soil and Substrate Disinfestation (SD 2018), Heraklion, Crete, 9-13 September 2018*; *1st Conference of the UTCB Doctoral School, Bucharest, Romania, din October 26, 2018*; *Greensys 2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses, 16th – 20th June 2019, Angers, France*; *2nd Conference of the UTCB Doctoral School, Bucharest, Romania, October 25, 2019*

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