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DYNAMIC CLIMATE MODEL OF A GREENHOUSE

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ABSTRACT

Greenhouses are more and more used nowadays, irrespective of the climatic condition of an area, in order to provide favourable environmental conditions for the growth and development of plants. In addition to giving protection from the effects of wind, rain and snow, the temperature inside the greenhouse is increased during the day by solar radiation. As the rate of plant growth is doubled for a 10 K rise in temperature up to a certain limit, higher temperatures are important for the economic production of commercial crops in greenhouses, and some pretentious species require greenhouses to be heated at night as well as during the day. To predict the temperatures which occur naturally in a greenhouse, and the energy needed to achieve a desired temperature, requires an understanding of its thermal behaviour. This, in turn, requires knowledge of the ways in which energy is transferred throughout a greenhouse. Simulation of the thermal aspects of a greenhouse is a powerful tool in predicting and assuring the proper environmental conditions for under glass grown plants. It can be asserted that technical solutions can improve the actual negative economic situation of agricultural geothermal projects in Romania. Simulation is a proper approach to many of the problems encountered there, which influence the design of greenhouses and, thus, the utilization of geothermal energy in greenhouse heating. Simulation enables the investigation of the changes in climate and other influencing parameters, and the demonstration of the possibilities of the geothermal heating installations in greenhouse heating.

In this paper the development of a dynamic climatic model of a greenhouse is described. The actual greenhouse is planned as a research greenhouse at the University of Oradea. The model includes the effects of solar radiation, heating (with both a soil surface heating system and an underground heating system in use when the outside temperature is low), ventilation, infiltration, evaporation, and condensation.

1. MODELLING IN HORTICULTURE - A SHORT HISTORY

Modelling has played a major role in horticultural and agricultural research for many years. Horticulture is based on crops of higher value and with more stringent quality constraints and often requires more sophisticated technical input and management than agriculture. In recent years, the impact of environmental considerations and input costs have further increased such needs. Thus, commercial horticulture has increasingly required the close control of greenhouse temperature, when to open the ventilators and when to apply pesticides or fertiliser. Most horticultural modelling systems are aimed at scientists and study models rather than end-user models. Consequently, the distribution of models to horticultural industry often requires considerable extra programming effort to make them sufficiently user friendly. Although both scientists and growers require access to models of the same systems, their use of them may be quite different. The model described in this paper is a study model intended for scientific research. The advanced technology of greenhouse horticulture is reviewed by Hanan (1998). His work is often used and referred to here, but for original references see his book.

A major obstacle in using models for forecasting is that appropriate meteorological data are not always readily available. Most of the biological processes involved depend on temperature but some also depend on radiation, rainfall, evapotranspiration and humidity. Some forecasting procedures can be used successfully with long term weather records but others need data collected during the growing season. In a research environment, simulations are often built independently for different aspects of a crop, such as growth habits, temperature adjustment, CO_2 enrichment, etc. In this paper, a typical summer and a typical winter day in Oradea, Romania, are simulated. Other more extreme weather conditions could be easily simulated by the model.

2. BACKGROUND INFORMATION - MAIN ASPECTS OF MODELLING A GREENHOUSE

2.1 State-of-the-art control and the objectives of a dynamic greenhouse model

The greenhouse, its crop and the management thereof is a system. A model is a simplified representation of this system. The mathematical methods and the complexity in solving these models become an art that only someone deeply involved can successfully use. Seginer (1993) outlined some approaches to the problem of control determination for climate control:

a) The traditional approach where experiments are designed to test a range of suggested set points rules. While this method has been most common, interaction and complexity of climate control has increased to the point that the method is too expensive, requiring an extensive testing facility. Setpoints derived from such studies are, according to Seginer, incapable of weighing short-term, conflicting interests (e.g., simultaneous ventilation and CO_2 injection). Examples would be investigations of crop response to different temperatures imposed in a number of chambers or greenhouse sections.

b) The expert system approach where rules are extracted by communication with an expert grower.

c) A learning system (pattern recognition approach), where the state of the environment and the actions of the expert grower are monitored. The data obtained are used for automatic rule formation. This could be considered the pattern employed by Sigrimis (1989) in which the variables were "normalized" (range zero to one) and the values required were obtained by recording actual system data over a 24-hour period. These were then used as the required parameters that could be "tuned".

d) A system model approach, where mathematical algorithms are used in optimization schemes to produce individual control decisions. This approach is actively pursued by many.

When it comes to actual models, there is a plethora, including: static model, steady-state model, black box model, dynamic simulation model, mechanistic model, stochastic model, heuristic model, descriptive model, explanatory model, state-variable model, etc. In this paper the dynamic simulation model will be presented, being the model used for modelling the greenhouse. The method is to reproduce the greenhouse climate response to one or more variables such as temperature, solar radiation, ventilation, etc. The basis of the dynamic simulation model is the transform of the static equations into non-steady state or "dynamic" equations. The static models are a set of equations relating the various aspects of heat loss, heat input, ventilation, humidity, condensation, infiltration etc., that can be solved for an instant in time when, essentially, the system is in equilibrium. Static models are called "steady-state" models. Equations are based upon physical laws. Static models do not involve time; in contrast, dynamic models consider changes with time. With the help of the computer it is possible to turn static equations into a dynamic process since a new set of conditions can be calculated each time the computer cycles through its run time.

Simulation is an inexpensive process for studying climate or crop response without the cost of building a greenhouse and testing crop growth within it. This is the aim of the report, to make an estimation of the response of the system to the climatic conditions in Romania before the greenhouse is built and to estimate the energy consumption. The number of variables that influence growth make actual testing very expensive (refer to Seginer´s type 1 approach). The results of simulation can be run in a short time, and model validity can be compared with what happens under real conditions if the investigator feels it necessary to do so.

One of the goals of horticulture production in greenhouses is to increase the sustainable income of the grower. The investment costs for greenhouses as well as labour and energy costs are much higher compared with conventional plant production. This can be balanced out only with better utilization of the yielding potential of plants, higher labour productivity and high energy efficiency. Higher plant productivity and quality in combination with a reduction of pollution and energy use, require a better control of the environment. Temperature, air humidity, CO_2 concentration and light intensity are controlled in commercial greenhouses. The set of momentous environmental factors inside the greenhouse affecting crop growth and development is referred to as the greenhouse climate. The application of more advanced algorithms will lead to improvement in the control of greenhouse climate.

In this paper, the climate optimization problem in a Venlo type glass greenhouse (planned to be built at the University of Oradea, Romania), is studied with respect to the thermal behaviour of geothermally heated greenhouses. The experimental greenhouse at the University of Oradea has not been built yet, and the present report will be a useful tool in choosing the control system for it. The results obtained with the simulation system will also be helpful in convincing many other greenhouse owners from Oradea and other parts of Romania, that geothermal water can be used for greenhouse heating, and that the most economical way to save energy and improve production is to use properly designed high technology control systems.

2.2 Heating system for greenhouses

Direct use is one of the oldest, most versatile and also most common forms of utilization of geothermal energy. Space heating, agricultural applications and aquiculture are the best known and most widespread forms of utilization. The most common application of geothermal energy in agriculture is in greenhouse heating, which has been developed on a large scale in many countries. The reasons for choosing geothermal energy in this sector are:

a) Good correlation between the sites of greenhouse production areas and low-enthalpy geothermal reservoirs;
b) The fact that greenhouses are one of the largest low-enthalpy energy consumers in agriculture;
c) Geothermal energy requires relatively simple heating installations, but advanced computerised installations can later be added for total conditioning of the inside climate in the greenhouses;
d) The economic competitiveness of geothermal energy for greenhouse heating in many situations.

As with other uses of so called "alternative energies", it is not possible to make a general statement that greenhouse heating is the optimal form of geothermal application. Each situation must be evaluated separately, and local factors play a decisive role in any decision-making (Popovski, 1993). At the moment, the out-of-season, or controlled climate production of vegetables and flowers can rely on good technology. Various solutions are available for obtaining optimum growth conditions, based on the optimum growth temperature of each plant. There are basically seven different geothermal heating systems which are applied to greenhouses (Rafferty and Boyd, 1992):

1. Finned pipe
2. Unit heaters
3. Fan coil units
4. Soil heating
5. Cascading
6. Bare tubing
7. Combination of the above

The choice of heating system type is not dictated by engineering considerations such as the maximum use of the available geothermal resource or even the most economical system, but on grower preference. Grower preference may be based strictly on past experience and familiarity with growing crops with that system. It may also be influenced by factors such as the type of crop, or potential disease problems. Some crops, such as roses and mums, require closely controlled humidity and a considerable amount of air circulation to prevent leaf mildew. If a radiant floor system is used, auxiliary circulating fans will be required. Tropical and subtropical potted plants, on the other hand, may require high humidity and higher soil temperature. In this case, a radiant under the bench system will be preferred, perhaps combined with an overhead air system for snow melt, and to obtain the maximum sunlight during winter months in areas of high snow fall. Certain flowering plants may require shading to control blooming, thereby enabling the grower to market at the most opportune time. The type and location of the shading cover can affect the placement of heating and air handling equipment and, perhaps, the type of heating. All these things should be taken into consideration, and the heating system designer should maintain close communication with the grower in the selection of type and placement of heating devices.

2.3 Climatic data for Romania

Because of its position on the southeastern portion of the European continent, Romania has a climate that is transitional between temperate and continental. Climatic conditions are somewhat modified by the country´s varied relief. The Carpathians serve as a barrier to Atlantic air masses, restricting their oceanic influences to the west and centre of the country, where they make for milder winters and heavier rainfall. The mountains also block the continental influences of the vast plain to the north in Russia, which bring frosty winters and less rain to the south and southeast. In the extreme southeast, Mediterranean influences offer a milder, maritime climate. The average annual temperature is 11°C in the south and 8°C in the north. Rainfall, although adequate throughout the country, decreases from west to east and from mountains to plains. Some mountain areas receive more than 1,000 mm of precipitation each year. Annual precipitation averages about 635 mm in central Transylvania, 521 mm at Iasi in Moldova, and only 381 mm at Constanta on the Black Sea.

2.4 Current greenhouses agriculture in Romania and the potential role of geothermal energy

The exploration and research of geothermal resources began in Romania in 1962-1965. The first geothermal wells were drilled in the Western Plain (Oradea, Felix, Călacea and Timisoara areas). The completion and experimental exploitation of over 100 wells in the past 20 years, enabled the evaluation of exploitable heat resources from geothermal reservoirs. The proven reserves (with the already drilled wells exploited by downhole pumps) are about 200,000 TJ for 20 years. At present, over 200 wells have been drilled which show the presence of geothermal resources. The drilling of most of the wells was funded by the Romanian government as part of the Geological Research Program. The drilling was carried out almost exclusively by the Romanian Foradex S.A. Company. The total installed capacity of the existing wells for energetic use is 320 MW_t (for a reference temperature of 30°C). At present, only 137 MWt are used from 60 wells which produce hot water in the temperature range of 55-115°C. For 1994, the annual energy utilisation from these wells was about 1,900 TJ (45,000 toe), with a load factor of 63%. More than 80% of the wells are discharged in artesian flow and 18 wells require anti-scaling chemical inhibition. The main energetic uses of geothermal energy are:

a) Space heating and hot water preparation for domestic use, 53%;
b) Greenhouse heating, 34%;
c) Industrial process heat (wood drying, milk pasteurisation, flax and hemp processing), 11%;
d) Fish farming, 2%.

About 40 wells are used for balneological and recreational purposes. The total flow rate from these wells is over 360 l/s and the water temperatures are in the range of 35-65°C. In 1995, the average flowrate was 275 l/s, with an annual utilisation of 870 TJ. Geothermal water is currently used in 16 thermal spas that have a treatment capacity of over 850,000 people per year. Geothermal water is also used in 24 open pools and 7 indoor swimming pools. In 1995, the total energy savings in balneology was about 21,000 toe.

Before 1990, Romania was one of the most powerful protected crop production countries in the social-communist Eastern Block and one of the pioneers in geothermal energy application for heating greenhouses (more than 40 ha). However, the process of the state economy system transition influenced negatively the conditions for running this business which resulted in a significant decrease in production and stopping the development process:

a) Most of the projects are rather old and nearly abandoned because of the lack of market due to the low quality of the products (using low technology equipment);
b) Obsolete technologies in use are far behind those developed in EC countries. Reconstruction and improvements are necessary in most of the projects; a good solution has to be proposed in the proper use of the available energy including a high technology control systems;
c) Equipment in use (particularly for the regulation and control of the heat supply) is very old fashioned and cannot fulfill the demands of intense and competitive production.

It can be asserted that technical solutions can improve the actual negative economic situation of agricultural geothermal projects in Romania. Simulation is a proper approach to many of the problems encountered here which could influence the design of greenhouses and, thus, the utilization of geothermal energy in greenhouse heating. Simulation enables the investigation of climate changes and other influencing parameters, and the demonstration of the possibilities of geothermal heating installations in greenhouse heating.

2.5 The University of Oradea geothermal system and greenhouse demonstration project

The University of Oradea was established as a state university in 1990, on the basis of the Higher Education Institute founded in 1963. It comprises more than twelve departments in different fields. Those related to geothermal energy are mechanical engineering, electrical engineering, energy engineering, environmental protection and medical science.

Inside the university campus, a geothermal well was drilled in 1981. The initial artesian flow rate was about 35 l/s with a well head temperature of 87°C. At present, the flow rate is 30 l/s and the well head temperature is 85°C. Geothermal water is used for district heating of university buildings, to provide them with hot tap water, and to produce electricity in a pilot binary power plant which is an experimental one used for testing. The return geothermal water, used for the district heating system and electric binary power plant, is proposed for use in a complex of greenhouse heating, two swimming pools and two aquaculture ponds. This is called cascaded usage, and was chosen for educational and research purposes.

A greenhouse demonstration project has been planned at the University of Oradea, composed of a complex of 4-6 small production units of 200 m^2, complete with different production technologies for characteristic vegetable cultures and different geothermal heating technologies, accommodated to the use of low-temperature heating fluids, local harsh winter climate and requests of the cultivators. A small unit is also planned for young plant production and a simple small laboratory for following the quality production and supply materials. For the complex of the intended greenhouses, the geothermal water will be used for both space and hotbed heating. Hotbed heating has a significant role not as a heating system but as a technology for growth, consisting of a specific way of heating plants through the soil. The greenhouse will be extremely useful in experimental work for the students from the horticultural department of the university and for research work in growing different kinds of plants and out-of-season plants. The greenhouse produce can be used at the university´s canteen or sold on the market.

The climatic model described in this paper could potentially be an important part of this demonstration project. The project is conceptualized by specialists from the University of Oradea, in collaboration with specialists from other institutions. The purpose of the project is to demonstrate the technical, technological and economical advantages of modern greenhouse constructions using locally available geothermal energy, in comparison with old fashioned built ones which use fossil fuel energy. This project (Figure 1) should also give an orientation for the technical and economical feasibility of the development of geothermally heated protected crop cultivation in Romania, introducing computer system control of the greenhouse heating. The data logging used for observing the heating process of the greenhouse, enables measuring and monitoring changes of all relevant energetic and technological data under different climate and exploitation conditions. The collected data will be evaluated and elaborated in order to estimate the quality of the chosen technologies and techniques. An accurate control of the factors which influence the "internal" or greenhouse climate (required for optimal plant development) reduces energy consumption and it is known that greenhouses are one of the largest energy consumers in agriculture. For countries like Romania, with an economy in transition, proper usage of available energy with less waste is one of the most important objectives.

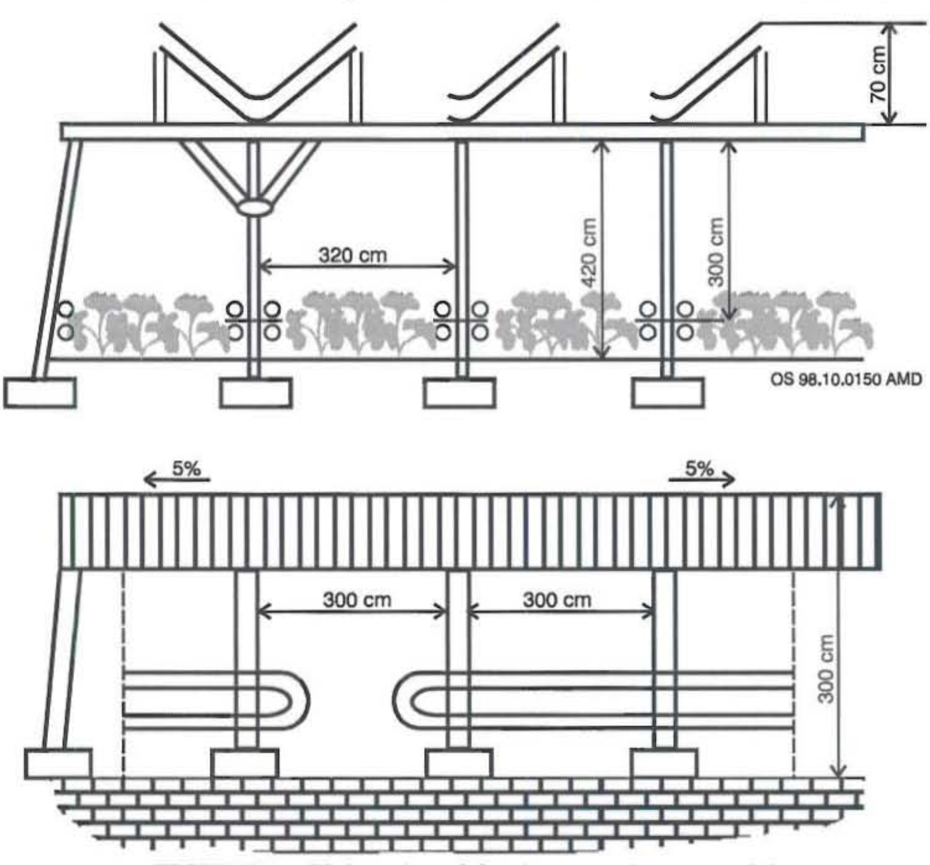

FIGURE 1: University of Oradea greenhouse model

The proposed greenhouse is a Dutch Standard NEN3859 type, sometimes regarded as the "Venlo" standard (Spelman,1988; Spek,1985), being considered the "standard" design in European countries (Figure 2). It is probably the world's most widely used and copied greenhouse design. The Venlo type greenhouse consists of a steel superstructure in modules of 4 x 6.4 m which permit 1 m wide glass, 4 mm thick. It is located above the soil, all the spans having the same structure and dimensions (18x50 m). The greenhouse is built as a metallic structure on a continuous concrete base. All the elements of the metallic structure are made of laminated zinc coated steel profile (I-shape). There are three rows of metallic posts, nine metres between each, which hold an array of metallic trusses, each 18 m wide with a maximum height of 6 m and a minimum height (at the eave) of 3 m. Each span has a central entrance, 2 metres wide, at both ends and several side entrances, each of them having sliding doors. Paved alleys are built within the greenhouse, in order to provide good interior access inside the spans.

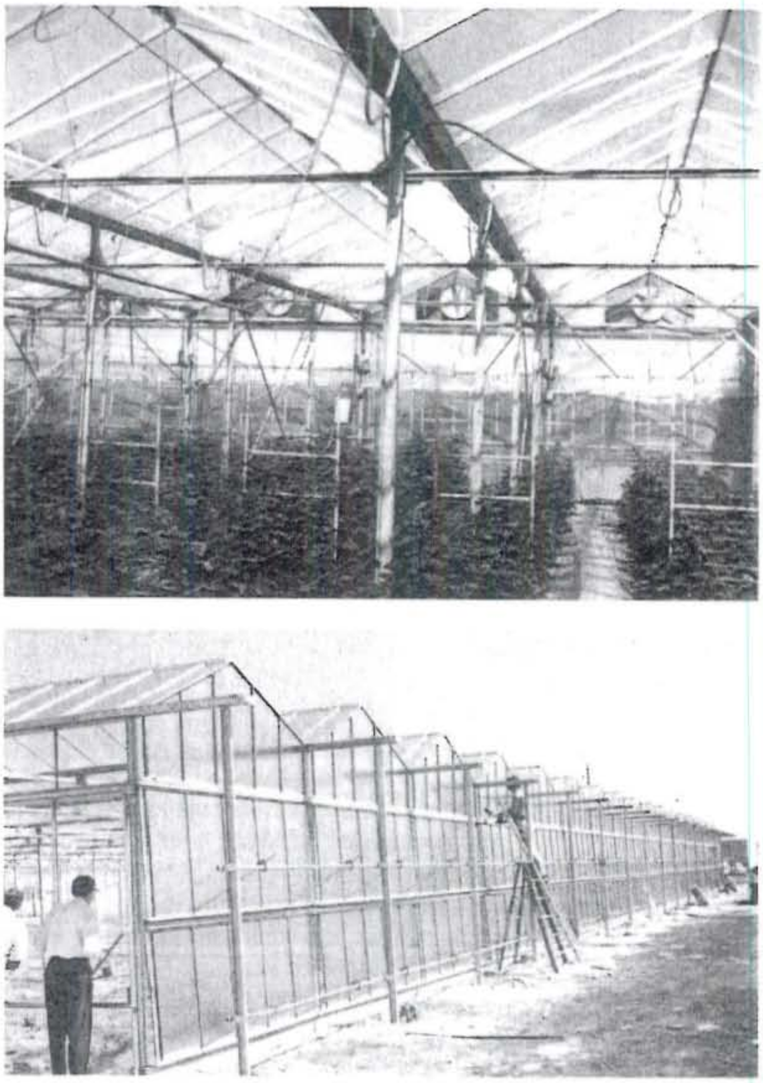

FIGURE 2: Venlo type greenhouse (Hanan, 1998)

3. THE GREENHOUSE MODEL

3.1 The greenhouse effect

The difference between the greenhouse climate and outside weather (sometimes called the greenhouse effect) is mainly caused by two mechanisms:

a) The first is the envelope of air: the air in the greenhouse is stagnant due to the enclosure. So the exchange of greenhouse air with the surrounding (outside) air is strongly decreased compared to the air outside the envelope. Moreover, local air velocities are small compared to that in the open. The reduction of the air exchange (or ventilation) directly affects the energy and mass balances of the greenhouse air while smaller local air velocities affect the exchange of energy, water vapour and carbon-dioxide between the greenhouse air and the greenhouse inventory (crop, soil surface, enclosure and heating system).

b) The second is the mechanism of radiation: the inward shortwave radiation (direct from the sun and scattered from the sky and clouds) is decreased due to light interception by the opaque and transparent components of the greenhouse while the long wave radiation exchange between the inside and the outside of the greenhouse is changed due to the radiative properties of the covering materials. Glass as the covering material leads to the mouse trap theory: glass is (partly) transparent for the incoming shortwave radiation and opaque for the longwave radiation emitted from the interior, so the energy is trapped. However, this effect is of minor importance in explaining the increased air temperature in the greenhouse, therefore, equating the greenhouse effect with the mouse trap theory is misleading. Nevertheless, the radiative effects are indispensable to describe the greenhouse climate because they directly affect all energy balances and, therefore, the inside temperature.

3.2 Greenhouse heating design and climate control

Due to harsh winter temperatures in European countries, during the winter, spring and autumn, it is necessary to heat the greenhouse space and also the greenhouse soil. The heating system will therefore, be a combination of a ground surface located heating system and a soil heating system.

3.2.1 Surface heating system design

The heating system located on the soil surface has the purpose of heating both the air and ground of the greenhouse. The system of pipes is located on the ground surface between the plant rows or directly in the plant rows of the greenhouse. The pipes can be arranged in unit loops but also with a parallel system of two or three pipes in a loop. This heating system has a good and fast response to short-lasting changes in temperatures on the outside. The influence to the soil temperature below the installation is small; inside air movement is well directed and the air also has a convenient velocity for most of the cultures. This kind of heating system has a positive influence on most of the known plants cultures with an earlier harvest, better yield and good quality of products. In the winter, because the top leaves of the plants are not protected against the cold, solar radiation can be used and an additional higher positioned heating system, specific for colder climates.

In the soil surface heating system design, plastic pipe of 40 mm diameter with a heat transfer coefficient $k_p = 11.52$ W/m^{2}K is assumed. Besides the soil surface heating system, a soil heating system is in use and supplies about 60% of the total heat requirement.

The necessary surface of the heating elements depends on the heat requirements of the greenhouse and influencing factors of the heat transfer from the heating system to the greenhouse interior. A simplified equation is used for the calculation of the necessary surface of the heating system elements (Popovsky, 1990)

$$A_{hs} = \frac{Q_{hs}}{k_p(T_{hs} - T_{\in})} \qquad (1)$$

where A_{hs} = Surface of the heating elements [m^2];
k_p = Heat transfer coefficient of the pipe material [W/m^{2}K];
T_{hs} = Mean temperature of the heating elements [K];
T_{in} = Temperature inside the greenhouse [K];
Q_{hs} = Heat requirements of the greenhouse [W].

In the equation above, the mean temperature of the heating elements, T_{hs} can be calculated as the arithmetical mean value of the heating elements:

$$T_{hs} = \frac{T_e + T_r}{2} \tag{2}$$

In Equation 2, T_e and T_r are respectively the temperatures of the heating fluid entering the heating installation and the return temperature of the heating fluid. Considering that the temperature of the fluid entering the pipe is about 80°C and the return water is about 60°C, the temperature of the heating elements T_{hs} is 70°C. The inside temperature T_{in} is considered 30°C.

All the elements in the equation above being known, the surface of the heating system is

$$A_{hs} = \frac{55000}{11.52\times(70-30)} = 119\ m^2 \tag{3}$$

The area of the pipe, considering that the length of the pipe is $l = 50$ m, is given as

$$A_p = \pi \times \phi_p \times l \tag{4}$$

According to the calculation, $A_p = 6.28$ m^2. The number of necessary pipes is given by the ratio between Equations 3 and 4

$$n = \frac{A_{hs}}{A_p} \tag{5}$$

Consequently, 19 pipes are needed. The number of pipes can be increased if the soil heating system cannot supply enough energy. The soil heating system has a temperature limit in order to avoid an overheated floor.

3.2.2 Soil heating system design

This system generally involves using the floor of the greenhouse as a large radiator. Tubes, through which warm water is circulated, are buried in the floor of the greenhouse. Heat from warm water is transferred through the tube to the soil and, eventually, to the air in the greenhouse. In the past, tube materials were generally copper or steel. Because of corrosion and expansion problems with these materials, nonmetallic materials have seen increasing application in recent years. The most popular of these is polybutylene. This material is able to withstand relatively high temperature (up to 80°C) and is available in roll form for easy installation. PVC piping is only available in rigid form and is limited with respect to temperature. A soil heating system is preferred by many operators because it results in very even temperature distribution from floor to ceiling and does not obstruct floor space or cause shadows. However, its ability to supply 100% of the heating requirements of a greenhouse depends on a rather mild climate and a low inside design temperature. This is caused by the nature of the heat transfer in the system. As a result, this system is generally employed in conjunction with another system such as a surface heating system.

The soil heating system consists of pipes located at 50 cm below the soil surface at 40 cm intervals. The pipes used are corrugated, 20 mm in diameter. Return geothermal water from the surface heating system will be used. In this way, the inclination towards deposition is avoided as the return water is quite clean and free of chemicals. The system is oriented towards keeping constant temperature around the plant root system. This type of heating is very positive for a list of vegetable and bulbous flower cultures, and also for an earlier harvest and lower heat consumption.

Designing the soil heating system the same procedure was followed as for the surface heating system, considering the temperature of the water at the input of the system to be the return water temperature from the surface heating system. As was mentioned previously, the soil heating system is used for covering about 60% of the total heat required. The total heat required for greenhouse heating is considered to be about 135 kW; hence the soil heating system has to supply about 80 kW.

The surface of the heating system elements can be defined by the following equation:

$$A_{shs} = \frac{Q_{shs}}{K_{pl} \times (T_{hs} - T_2)} \tag{6}$$

where Q_{shs} = Total heat supplied by the soil heating system [W];
k_{pl} = Heat transfer coefficient of the pipe material [W/m^{2}K]; = 10.17 W/m^{2}K;
T_2 = Temperature of the soil (heated by the soil heating system) at the depth where the pipes will be buried [°C]; assumed to be T_2 = 25°C.

The temperature, T_{hs}, is the same as in Equation 1 and assumed to be 70°C, giving A_{shs} = 174.8 m^2.

The pipe area is given as

$$A_{sp} = \pi \times \phi_{sp} \times l \tag{7}$$

For the length of the pipe, l = 50 m, and with ϕ_{sp} = 0.02 m, the area of the pipe becomes A_{sp} = 3.14 m^2.

The number of necessary pipes for the soil heating system is calculated in the same way as for the soil surface heating system.

$$n_s = \frac{A_{shs}}{A_{sp}} \tag{8}$$

Using the data presented above in Equation 8, it was found that 57 pipes are needed to cover 60% of the total heat demand. If this amount is too big to cover the soil area, then the pipes can be mounted in double loops or the diameter of the pipes can be increased (see Figure 3).

3.2.3 Ventilation system of greenhouse

To promote good growth of plants, greenhouses require heating during the winter, but equally important they require ventilation during summer days. This is required for three reasons:

- to limit the greenhouse temperature;
- to remove water vapour transpired by the plants;
- to replace the CO_2 used in photosynthesis.

To limit the greenhouse temperature, the least

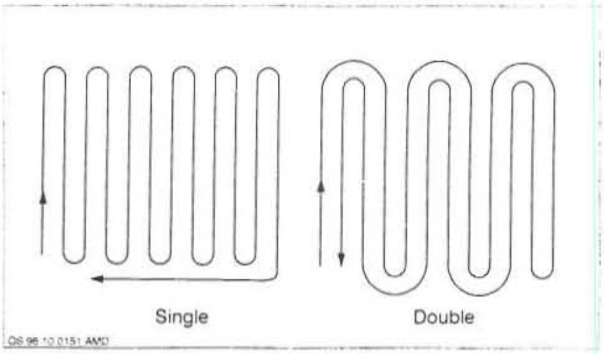

FIGURE 3: Single or double loop pipe arrangement

expensive method used is natural ventilation, caused by pressure differences or natural buoyancy forces through ventilators arranged on the top of the structure, on the sides, or both. Air movement and mixing within the greenhouse has a direct influence on the energy exchange of the vegetation. This aspect of wind velocity over the canopy versus the ventilation exchange rate for the structure is not adequately treated in the energy balances described in the literature. But the ventilator operation is very important, especially for pretentious plants grown in the greenhouse. Air movement and slight temperature drops under critical conditions can provide favourable conditions for disease development such as powdery mildew epidemics, powdery mildew conidia, etc. Therefore, it is important that the ventilator be designed correctly and the rate of ventilation controlled adequately.

For climate conditions in Romania, natural ventilation will be used as in the Dutch Venlo type greenhouses. The ventilation will occur by opening windows on the roof of the greenhouse. According to Smith (1988), the ventilator area should be about 16% of the total floor area. Natural ventilation is obtained by opening ventilator panels in the roof of a greenhouse. The hot internal air passes out through the opening by a combination of natural and forced convection, and is replaced by colder outside air which enters through the lower parts of the same ventilator apertures. Forced convection is produced by the wind, consequently the speed and the direction of the wind affects the rate of ventilation.

In calculating the water vapour change through the greenhouse due to ventilation, it was assumed that the total area of the ventilator is 16% of the floor area (144 m^2) as is typical for this type of greenhouse. The water vapour flow is given as

$$F_v = w \times r_{vent} \times k_v \times A_v \tag{9}$$

where w = Wind speed [m/s];
F_v = Water vapour flow due to ventilation [m^3/s];
r_{vent} = Opening of the ventilator, takes values of 0-1;
k_v = Slope of the curve showing the ventilation flux divided by wind speed variation (ϕ/w) with the percent of the ventilator opening (Hanan, 1998; Figure 4-67); $k_v = 0.266$;
A_v = Area of the ventilator [m^2], = 144 m^2.

The amount of water vapour exchanged is

$$D_{wvent} = F_v \times (X_{ain} - X_{aout}) \tag{10}$$

In Equation 10 X_{ain} and X_{aout}, respectively, represent the absolute humidity of the air inside and outside the structure. In order to calculate the absolute humidity, Equations 30 and 64 (see later), respectively, were used.

3.2.4 Control equipment

In order to maintain a constant temperature within the structure over both winter and summer, a PI (proportional-integral) controller and a P (proportional) controller are used. The PI controller is used for stabilizing the temperature inside the structure according to the variation of the flow through the heating system's pipes. The P controller is used for the ventilation part of the system.

In the heating system, the simulated value (T_{in}) is compared with a setpoint value. The value of the setpoint can be found according to plant preference inside the structure. The difference between the setpoint and the controlled value (T_{in}) generates an error (*ER*). The error is applied to the PI controller which generates an output (*m*, the flow rate through the pipes). The value of the controller output is changed at a rate proportional to the integral of the error signal. This output is applied to the heating system through a control valve in order to make the error signal zero. The P controller is considered rather slow and inaccurate, but it can be used in many cases. The P controller is used for the ventilators, acting in opening and closing the window according to the inside temperature changes. The setpoint of the controller is set slightly above the heating system's setpoint and is compared to the controlled value of the system (T_{in}). The error of the P controller is applied to the P controller which generates the output of the control system (rate of opening or closing the window). The output value increases ventilation in order to keep the error signal close to zero.

4. MAIN MODEL PARAMETERS

4.1 Selection of model main parameters and the model equations

In contrast to outdoor production, the growing conditions in greenhouse cultivation can be influenced by a number of interconnected factors. For example, the temperature and air humidity can be regulated by means of ventilators, humidifiers and a heating system; the CO_2 concentration of the air can be increased by means of flue gasses or pure CO_2. In the most sophisticated greenhouses, it is possible to influence the level and duration of solar radiation by means of screens and/or supplementary lighting. Also, for many crops it is nowadays feasible to control the root environment with respect to temperature and the availability of water and nutrients. Among the factors which influence the greenhouse climate and which interact with each other are light, temperature, ventilation, infiltration, condensation, humidity, etc. A few interventions such as heating, ventilating, and shading act preferentially on one particular parameter but also modify several others. For example, heating affects temperature but also affects saturation deficit, and ventilating affects both temperature and saturation deficit, (vapour pressure deficit, which is considered the difference between saturation and actual vapour pressure, $VPD=e_{s(T)}(1-RH)$), and also modifies the CO_2 concentration.

In the problem of climatic set point determination, one has to consider and to integrate the following two parameter classes describing

a) The situation outside the greenhouse, expressed through air temperature, humidity, solar radiation, direction and intensity of the wind;
b) The inside situation that we want to evaluate through quantitative measures of air temperature, humidity, ventilation, soil temperature and, from the heating system relieved energy.

In order to achieve the most rational decision in controlling the parameters influencing the greenhouse climate, it is important to consider not only the requirements of the plants but also the cost of providing heat. This economic factor has to assure a minimal spending in energy consumption. This paper focuses only on the climate issue with respect to temperature, humidity and condensation estimations. Other important components of the optimal production problem such as carbon dioxide concentration and nutrition are not considered here.

4.1.1 The heat balance through the structure

In solving the climate control problem, it is necessary to take into account various parts of the greenhouse and the greenhouse contents. This includes the heat balances and the response of the crop, the greenhouse air, the cover of the structure and the greenhouse soil. The hemisphere above the greenhouse also influences the energy and mass exchanges. The heat balance of the greenhouse is a multidimensional quantity which consists of heat transfer and mass exchange to and from the greenhouse environment. The parameters involved in the physical process of the greenhouse are in an energy balance with the environment and, all together, are in an energy balance with the greenhouse environment.

The physical processes involved in estimating the greenhouse climate, can be schematised according to Figure 4. The heat balance according to Figure 4 can be expressed:

$$Q_{total} = Q_{gain} - Q_{loss} \tag{11}$$

where Q_{total} = Total energy balance (net energy change) [W];
Q_{gain} = Amount of energy entering the greenhouse [W];
Q_{loss} = Amount of energy leaving the greenhouse [W].

4.1.2 Heat gain through the structure

Determination of the greenhouse´s heat demands (gains), for different external and internal climatic conditions, means the determination of all the heat transfers of the energy balances of climate parameters. They depend upon the values of the heat transfer coefficients, temperature and humidity differences between the external and internal climate, property of materials, radiation, shape factors, and on the characteristics of the plant canopy inside the greenhouse, characteristics of the heating and cooling installations, etc. Some of the factors mentioned above are constant or nearly constant and they can be determined easily by calculation. Others depend on temperature and humidity changes, which means they have to be determined for changeable or so-called dynamic conditions. Solar radiation and external air temperature change their values without depending on the internal climate conditions. But the internal climate conditions change under the influence of the external climatic factors.

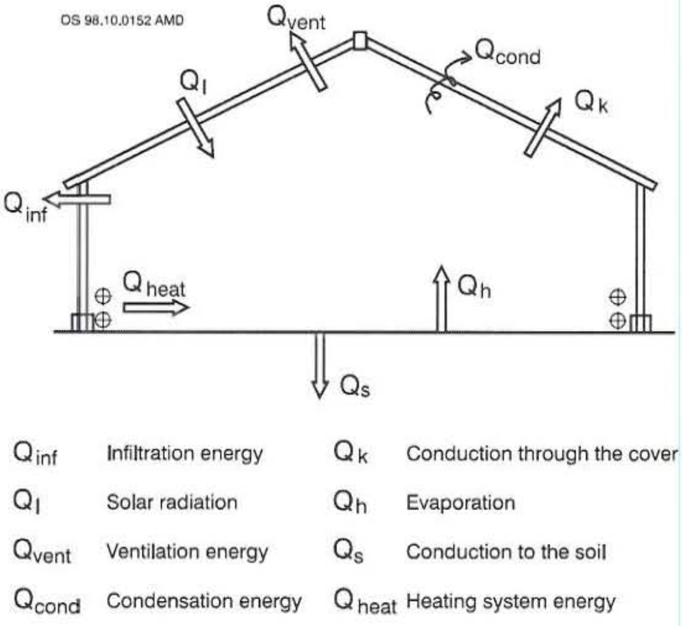

FIGURE 4: Energy transfer through the greenhouse structure

The amount of energy entering the greenhouse is

$$Q_{gain} = Q_h + Q_l + Q_w \tag{12}$$

where Q_h = Energy produced inside the structure by the heating system [W];
Q_l = Heat gain of income solar radiation [W];
Q_w = Heat transfer due to transpiration within the structure [W].

4.1.3 Heating system

The heating system, as was mentioned previously in the description of the heating system design (see Chapter 3.1.1), consists of the heating system on the surface of the soil and the heating system of pipes buried under the soil. This kind of combination heating systems in greenhouses appears in moderate and colder regions. Two main factors determine the use of combined heating systems for greenhouse heating:

a) To lower the investment cost by introducing cheap solutions for covering the brief peak load requirements of the greenhouse;

b) To protect the plants against the impact of cold radiation of the atmosphere and environment during periods of very cold external temperatures.

$$Q_h = Q_{hs} + Q_{shs} \tag{13}$$

where Q_{hs} = Heat gain from the heating system on the soil surface [W];
Q_{shs} = Heat gain from the heating system buried in the soil [W].

The soil surface heating system

For calculating heat loss through the pipes of the heating system, the length of the pipe was divided into five 9 m sections. The heat loss at the output of each section was calculated, then the total heat loss through the length of the pipe. For the simulation, in order to assure the required temperature for plant growth (12-28°C), 60 pipes of 40 mm were chosen for both the soil and surface heating systems. The total heat supplied by the soil surface heating system can be evaluated as

$$Q_{hs} = 60 \times dq_p \tag{14}$$

where dq_p = Heat transfer through the length of a pipe [W].

dq_{hs} can be defined according to the internal heat transfer equation

$$dq_{hs} = m \times C_w \times \Delta T \tag{15}$$

where m = Mass flow of fluid through the pipe [kg];
C_w = Heat capacity of the water [J/kgK], = 4180.0 J/kgK;
ΔT = Temperature difference [K].

For the simulation, with the length of the pipe divided into five units (Figure 5), the heat transfer will be defined by the equation below, where T_{h5} is the temperature of the hot water at the output of the heating system:

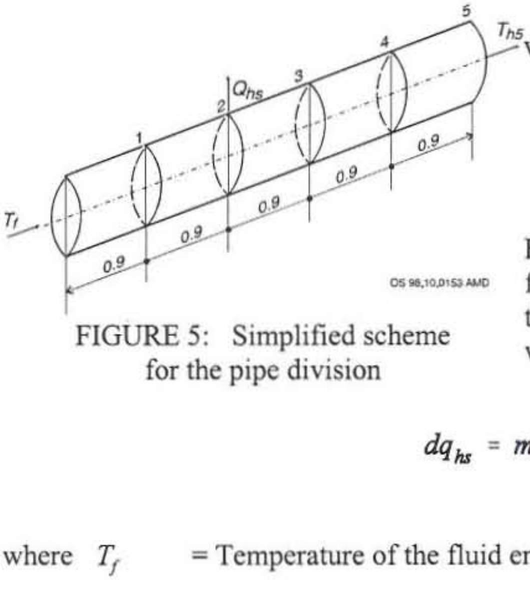

FIGURE 5: Simplified scheme for the pipe division

$$dq_{hs} = m \times C_w \times (T_f - T_{hs}) \tag{16}$$

where T_f = Temperature of the fluid entering the pipe [K], assumed to be 60°C.

The following equation is used for the calculation of the temperature at the output of the pipe:

$$T_{hf} = T_{h(i-1)} - dT_{h(i-1)} \tag{17}$$

where i = 1,...5 is the number of sections in which the pipe was divided.

The temperature loss through the pipe is given by the following equation, for all five sections of the pipe:

$$dT_{h(i-1)} = \frac{k_p \times (T_{h(i-1)} - T_{in}) \times dA}{m \times C_w} \tag{18}$$

where k_p = Thermal conductivity of the pipe material [W/m^{2}K],
for present case, plastic pipe of ϕ = 40 mm, and K_p = 11.52 W/m^{2}K was chosen;
T_{in} = Temperature inside the structure [K];
dA = Area of one section of the pipe [m^2], given by $dA = \pi\ \phi_p\ dl$.

The total length of the structure is l = 50 m, and the length of the pipe was considered to be 45 m, hence the length of the first section is dl = 9 m.

The heat supplied by the soil surface heating system is about 175 kW during a normal winter day, according to the simulation data. This heat is not enough to cover the heat demand through the structure; therefore the soil heating system was also considered.

The soil heating system

For modelling the soil heating system, it was assumed that the pipes cover the whole length of the soil mass in the same way as for the surface heating system. The heat transfer through the pipe was calculated according to the following equation:

$$Q_{shs} = 40m(T_f - T_{h5s}) \tag{19}$$

In the equation above, T_{h5s} is the temperature at the output of the soil heating system. 40 pipes of 0.02 m diameter were chosen. The temperature of the fluid through the pipes, T_f, is the temperature of the return hot water from the soil surface heating system. The temperature, T_{h5s}, can be estimated in the same way as for the soil surface heating system, using the equations below:

$$T_{his} = T_{h(i-1)} - dT_{h(i-1)} \tag{20}$$

$$dT_{h(i-1)} = \frac{k_{pl}\,(T_{h(i-1)} - T_2)\,dA}{m\,C_w} \tag{21}$$

where k_{p1} = Transfer coefficient of the material of the pipe [W/m^{2}K], here k_{p1} = 10.17 W/m^{2}K;
i = 1, ...5, the number of sections, the pipes were divided into.

In order to calculate the temperature of the five small units, the temperature T_2 of the soil was calculated

$$T_2 = \int_0^t [(\frac{K_s(T_1 - T_2)2}{z_1 + z_2} + \frac{K_s(T_B - T_2)2}{z_2 + z_3} + \frac{Q_{ug}}{A_s})\frac{1}{C_{ps}}\frac{1}{z_2}]\,dt \tag{22}$$

where C_{ps} = Heat capacity of the soil [kJ/m^{3}K];
z_i = Thickness of one layer [m];
A_s = Surface area of the soil [m^2];
T_1, T_2 = Temperatures at the centre of each layer [K];
T_B = Temperature at the bottom of the soil layers [K].

According to the simulation results, this heating system supplies 35 kW during a normal winter day.

With both soil surface and soil heating systems in use, in winter during the day when solar radiation is also available, an indoor temperature of 28°C can be reached; during the night, the temperature is about 15-17°C.

4.2 Solar radiation

Solar radiation is one of the most important environmental factors for plant growth. Radiation is generated from a material close to a black body. Solar radiation received at the earth's surface varies with the season because of the geographical relationship between the sun and the earth. Therefore, it is important to calculate how much of this energy can be used at a given place on the earth at a certain time of year. Coverings can improve the temperature environment by increasing inside temperature, but cannot enhance the solar radiation level. Shading to decrease the solar radiation level is sometimes important, but in most cases, the most important problem is minimizing the reduction of solar radiation due to coverings.

The sun is the largest source of energy in our system; we can receive from the sun an equivalent of 5700 K if temperature is calculated from sun radiation. The direct solar radiation received on a flat surface of unit area (normal to the radiation beam) just outside the earth's atmosphere is called the solar constant, I_o. The value of this constant varies, as it is an indicator of the energy that reaches the earth, and its value was established after many observations over the years. When solar radiation passes through the atmosphere around the earth, some parts of the solar radiation are absorbed and others are reflected. Therefore, the solar radiation received on the earth's surface consists of direct and diffuse radiation. Direct radiation is that which comes directly from the sun, and diffuse is that which is reflected into the atmosphere and comes from all directions of the sky. In this report, only direct solar radiation was considered, as it plays the most significant role in heat transfer between greenhouse and sun. For calculation, the following simplified equation was used:

$$Q_l = I \times \tau \times \gamma \times A_c \tag{23}$$

where τ = Light transmission of the greenhouse cover for solar radiation [-]; according to Popovski, (1993), $\tau = 0.7$, in a conventional greenhouse τ varies daily and seasonally with the sun's angle and orientation of all the cover surfaces. In this model, the angle effect was ignored and the average daily value of τ is used;

γ = Constant of the proportion of the solar radiation entering the greenhouse, useful to increase internal temperature; γ is in the range of 0.3-0.7; a value of 0.4 was chosen.

A_c = Surface of the greenhouse, [m^2]; for most greenhouses the solar radiation entering a wall is partially offset by that leaving the opposite wall; so the area used in Equation 23 is the area of greenhouse cover;

I = Intensity of incoming solar radiation.

The following equation was used in estimating the solar intensity, I, [W/m^2]:

$$I = I_o \sin(\omega(t - \varphi)) \tag{24}$$

where I_o = Solar constant [W/m^2], in our case 1800 W/m^2;

φ = Argument of the sinusoidal variation of solar energy [sec];

ω = Frequency of periodic change in solar radiation over 24 hours [rad]; given as $2\pi / 24$.

For the negative part of the sinusoidal variation, the solar energy is considered equal to zero (see I_{win} and I_{sum} on the plot).

As day length is different during summer and winter, different equations were considered for solar energy evaluation (see Figure 6 for the variation of solar radiation in winter and summer).

During the summer, daylight is assumed to last for fourteen hours. The sun is considered to rise at 7 o´clock in the morning and set at 21, the equation for the solar radiation is given by Equation 25. For winter time, daylight was assumed to last for 10 hours, sunrise is considered at 7, setting at 17. Equation 26 describes the solar radiation in winter.

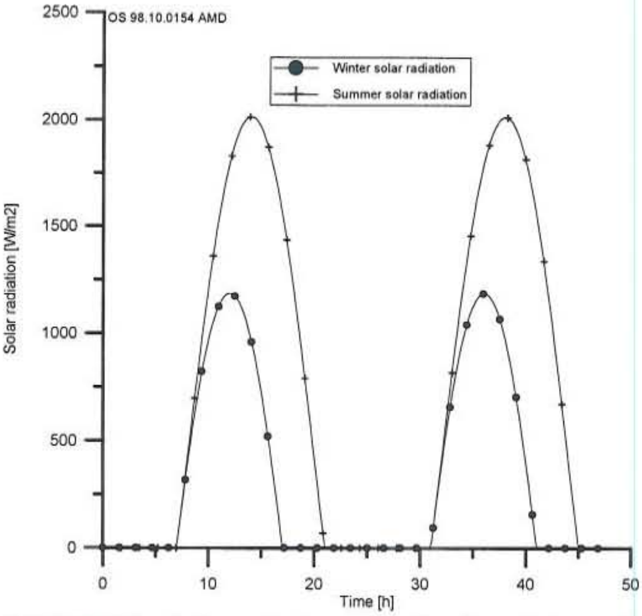

FIGURE 6: Solar radiation variation for winter and summer

$$I_{sum} = I_o \sin(\omega(t-8)) + I_o \sin\omega \tag{25}$$

$$I_{win} = I_o \sin(\omega(t-6)) + I_o \sin\omega \tag{26}$$

4.3 Evapotranspiration

Transpiration or evapotranspiration is assumed to occur from substomatal cavities in the leaves of vegetation and or from below the soil surface. The heat exchange due to it can be estimated as

$$Q_w = H_w \times LAI \times A_f \tag{27}$$

where LAI = Leaf area index, for a full canopy covered floor, $LAI = 4.0$. It represents the amount of vegetation in the greenhouse. With it, the leaf stomatal resistance (r_v) is converted to crop canopy resistance;

H_w = Latent heat exchange due to transpiration [W/m^2].

The latent heat exchange, H_w , is given by the following equation:

$$H_w = \frac{\rho Cp}{\gamma_1 r_v} \times (e_{sin} - e_{ain})$$

where γ_1 = Psychrometer constant [Pa/C]. According to Hanan (1998, Tables 5-32) the psychrometer constant and the slope of saturated vapour pressure curve are regarded as weighting factors that determine the partitioning of the radiant energy between evaporation (latent heat) and convection (sensible heat). The psychrometer constant takes different values according to the air temperature variation. For the simulation it is a table defined variable;

r_v = Resistance of leaves and stomata to heat transfer [m/s]. It can be assumed constant and its values were chosen according to Hanan (1998, Tables 5-33). This is a plant constant, and its value varies from hundreds to thousands of m/s;
e_{ain} = Vapour pressure of the air inside the greenhouse [Pa];
e_{sin} = Vapour pressure at saturation at T wet bulb, [Pa].

For the simulation, e_{ain} was considered variable during 24 hours according to the outside temperature (conform Hanan, 1998), given by the following equation:

$$e_{ain} = \frac{X_{ain} \times P}{(X_{ain} + \varepsilon \rho_a)} \tag{29}$$

where P = Atmospheric pressure [Pa], 101.3 kPa at sea level;
ε = Ratio of molecular weights of water and air [-], 0.622;
X_{ain} = Mass of vapour per unit volume of the air inside the greenhouse [kg/m^3];
ρ_a = Density of the dry air, 1.292 kg/m^3.

and X_{ain} is given by

$$X_{ain} = \frac{M_{wt}}{V_{ginf}} \tag{30}$$

where M_{wt} = Total amount of vapour exchange through the structure [kg];
V_{ginf} = Volume of air change rate per unit cover area, [m^3 / m^2 hr].

4.4 Energy loss through the greenhouse

The amount of energy leaving the greenhouse can be estimated according to the following equation:

$$Q_{loss} = Q_k + Q_s + Q_{cond} + Q_v + Q_{inf} \tag{31}$$

where Q_k = Heat loss due to "conductive" heat loss [W];
Q_s = Heat loss due to conduction to the greenhouse soil [W];
Q_{cond} = Heat loss due to condensation [W];
Q_v = Heat transfer due to ventilation [W];
Q_{inf} = Heat transfer due to infiltration [W].

4.4.1 Conductive heat transfer

The word"conductive" is written in quotation marks because it is not only conductive but consists of all the heat transfers through the greenhouse cover from the internal to external air, conductive heat transfer through the covering material, and radiative heat transfer. It is possible to calculate it by using the following empirical equation:

$$Q_k = h \times A_c (T_{in} - T_o) \tag{32}$$

where T_o = Temperature outside [K];
h = Conductive heat transfer coefficient [W/m^2];
A_c = Area of the cover of the greenhouse [m^2];
T_{in} = Inside air temperature [K].

In American literature, standard works provide heat transfer coefficients for the most common claddings, leaving the impression that such values are constants (Hanan, 1998). Aside from thermal conductivity of the material itself, the heat transfer coefficient (h) of any material is not constant and varies markedly with conditions inside and outside the structure. Other factors changing the transfer coefficient (h) are conditions within and outside the greenhouses in regard to convective heat transfer. This has been examined by numerous investigators (Bot, 1983). Outside the structure, heat loss is commonly assumed to increase linearly with increasing wind speed. Others have provided data to show non-linearity with considerable variations among cladding materials as a function of wind speed. It is assumed that the heat transfer coefficient between cover and outside air of the Venlo glass house is a function of wind speed (Bot, 1983). In the equation below, the heat transfer coefficient combines both the effects of convection, conduction and thermal radiation. This coefficient does not account for infiltration or air through the cracks and interstices around the panes or door of the greenhouse. For the simulation, the heat transfer coefficient is calculated with the following equation, where w is the wind speed [m/s]:

$$h = 2.8 + 1.2w \tag{33}$$

4.4.2 Heat loss to the soil

Heat flow in the soil is complicated because heat flow is associated with water flow. In most cases (Takakura, 1993) it is sufficient to consider heat flow using apparent thermal conductivity, which includes the effect of water flow. Then the heat flow in the soil is similar to that in a solid body. In simulation the flat ground is divided into three even layers in depth and the temperature at the centre of each layer is T_1, T_2 and T_B, respectively. Temperature T_B at the bottom layer is a boundary condition and the temperature at the surface of the ground is considered the temperature inside the greenhouse.

According to the energy balance equation, the energy change in time dt in the soil is expressed by dQ/dt, and it is converted to temperature change using the thermal properties of the mass

$$\frac{dQ}{dt} = C_p \times \rho \times \frac{d\theta}{dt} \tag{34}$$

In conduction heat transfer, the energy balance can be written as

$$C_p V_s \frac{dT_1}{dt} = K_s A_s \left(\frac{2(T_{in} - T_1)}{dz} + \frac{T_2 - T_1}{dz}\right) \tag{35}$$

$$C_p V_s \frac{dT_2}{dt} = K_s A_s \left(\frac{(T_1 - T_2)}{dz} + \frac{T_B - T_2}{dz}\right) \tag{36}$$

where C_p = Heat capacity of the soil [kJ/m^{3}K];

V_s = Volume of the soil layer [m^3];
dz = Thickness of one layer [m];
A_s = Surface area of the soil [m^2];
k_s = Soil thermal conductivity [J/smK], for the simulation considered to be 1.52 J/smK;
T_1, T_2 = Temperatures at the centre of respective layers [K];
T_B = Temperature at the bottom of the soil layers [K].

The above two equations are in differential form; they can be rearranged in integral form

$$T_1 = \int_0^t \left(\frac{K_s 2(T_{in} - T_1)}{dz\,dz\,C_p} + \frac{K_s(T_2 - T_1)}{dz\,dz\,C_p} \right) dt \tag{37}$$

$$T_2 = \int_0^t \left(\frac{K_s(T_1 - T_2)}{dz\,dz\,C_p} + \frac{K_s(T_B - T_2)}{dz\,dz\,C_p} \right) dt \tag{38}$$

Because the layers of the soil considered are shared unevenly, the depth dz will be different for all three layers. In this case the equations for the two temperatures will be

$$T_1 = \int_0^t \left(\frac{K_s 2(T_{in} - T_1)}{(z_0 + z_1) C_p z_1} + \frac{K_s 2(T_2 - T_1)}{(z_1 + z_2) C_p z_1} \right) dt \tag{39}$$

$$T_2 = \int_0^t \left(\frac{K_s 2(T_1 - T_2)}{(z_1 + z_2) C_p z_2} + \frac{K_s 2(T_B - T_2)}{(z_2 + z_3) C_p z_2} \right) dt \tag{40}$$

For winter time, in the equation for temperature T_2, the temperature gain from the soil heating system is added

$$T_2 = \int_0^t \left(\frac{K_s 2(T_1 - T_2)}{(z_1 + z_2) C_p z_2} + \frac{K_s 2(T_B - T_2)}{(z_2 + z_3) C_p z_2} + \frac{Q_{ug}}{A_s C_p z_2} \right) dt \tag{41}$$

For simplification, it was assumed that heat loss in the soil occurs between the surface of the soil and the first layer, so the temperature difference will be $(T_{in} - T_1)$. Temperature T_2 was calculated for a better evaluation of the temperature deeper in the soil mass.

$$Q_s = \frac{k_s}{Z_1} \times A_s \times (T_{in} - T_1) \tag{42}$$

4.4.3 Heat loss due to condensation

Whenever the inside cover surface temperature, T_c, is below the dewpoint of the inside air (the dew point is the temperature to which unsaturated air must be cooled to produce saturation, that is, $e_{ain} = e_{sin(T)}$), water will condense. The formation of a water layer results in energy transfer. Condensation usually increases due to the lower temperature of the cover. As 1 kg of water requires $2.47\text{x}10^6$ J to convert liquid to vapour (latent heat of vaporization), this same amount will be released upon condensation at the inner cover surface. The equation for heat transfer due to condensation can be

$$Q_{cond} = C \times i_{sv} \times A_c \tag{43}$$

where i_{sv} = Enthalpy of the saturated vapour [kJ/kg], for 20°C, the enthalpy is 2453.48 kJ/kg;
C = Condensed amount of water on the cover [kg/m^{2}s].

C can be calculated as

$$C = \frac{A_c}{A_f} 1.64\times10^{-3} (T_a - T_r)^{1/3} (X_{ain} - X_c) \tag{44}$$

X_{ain} = Ambient absolute humidity [kg/m^3];
X_c = Absolute humidity at the cover [kg/m^3];
T_a = Virtual temperature of the air [K];
T_r = Virtual temperature of the cover surface at T = inside cover temperature [K].

The virtual temperature of the air inside the greenhouse can be estimated according to the following equation:

$$T_a = \frac{T_{in}}{1 - \frac{e_{ain}}{P} \times (1 - \varepsilon)} \tag{45}$$

where P = Atmospheric pressure [kPa], which is 101.3 kPa;
ε = Ratio of the molecular weights of water and air, 0.622;

The virtual temperature of the cover surface, T_r, at the inside cover temperature, T_c [K], is given as

$$T_r = \frac{T_{cover}}{1 - \frac{e_{ain}}{P} \times (1 - \varepsilon)} \tag{46}$$

and T_c as

$$T_c = T_{in} - \frac{T_{in} - T_0}{3} \tag{47}$$

The equation above is an estimation of the temperature of the cover surface inside the greenhouse. For a 4 mm thick glass cover, the heat transfer coefficient due to conduction is similar in magnitude to the heat transfer coefficients due to convection on the cover inside and outside the structure. The conduction and convection heat transfers may be represented as a resistance network, with the resistance connected in series, and for a small thickness of the greenhouse cover the overall heat transfer coefficient is estimated as

$$k = \frac{1}{\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}} \tag{48}$$

where k_1, k_2, k_3 are the heat transfer coefficients at the surface of the cover outside the greenhouse, of the glass, and at the surface of the cover inside the structure, respectively. Considering that all these coefficients are roughly equal, it is easy to notice that the heat at the cover surface is shared in three equal parts. In this way, Equation 47 was found.

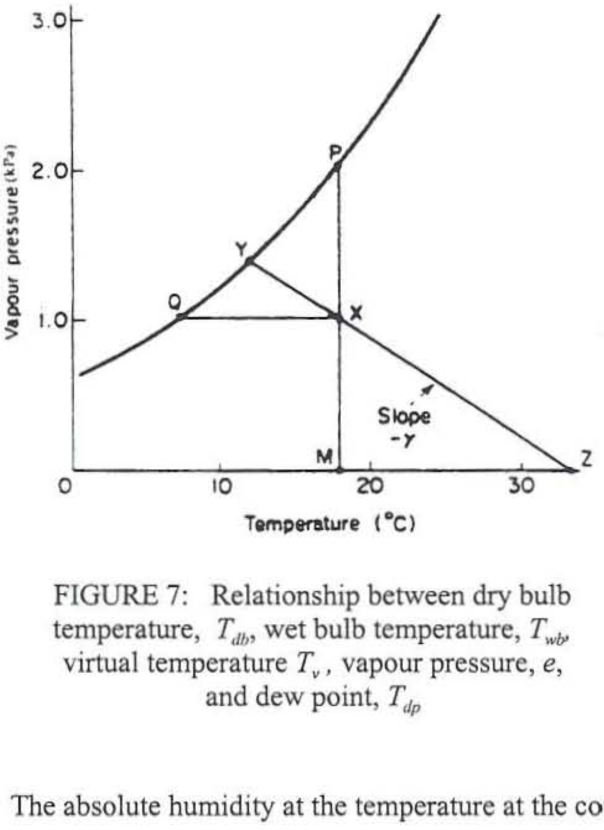

FIGURE 7: Relationship between dry bulb temperature, T_{db}, wet bulb temperature, T_{wb}, virtual temperature T_v, vapour pressure, e, and dew point, T_{dp}

In order to define the virtual temperatures used in Equations 45 and 46, the psychrometric chart (Figure 7) can be used. This chart gives the relationship between dry bulb temperature, T_{db}, wet bulb temperature, T_{wb}, virtual temperature, T_v, vapour pressure, e, and dew point, T_{dp}.

According to Hanan (1998, Figures 5-77), the relationship between the parameters can be described in the way that at a temperature T = 18°C and a vapour pressure e_a of 1 kPa (point X), a wet bulb thermometer will be cooled under standard conditions to point Y (12°C). This is the lowest air temperature that can be obtained by cooling the system with a fan-and-pad cooling system. P represents the vapour pressure if the same amount of air were saturated at the same temperature (2.06 kPa). Q is the temperature to which the sample would have to be cooled to be saturated, T_{dp}, and Z is the virtual temperature of the sample, or the temperature to which air would have to be raised in order to have the same density as the moist air at 18°C (33.3°C).

The absolute humidity at the temperature at the cover inside the structure is given as

$$X_c = \frac{\rho_a \varepsilon e_{ac}}{P - e_{ac}} \tag{49}$$

where ρ_a = Density of the air, 1.292 [kg/m^3];
e_{ac} = Vapour pressure at the cover, [Pa].

The vapour pressure at the cover, e_{ac}, is defined as

$$e_{ac} = RH_c \times e_{sc} \tag{50}$$

where RH_c = Ratio of humidity at the cover inside the greenhouse [%]. When temperature at the cover is at the saturation temperature and water condenses, RH_c = 100%;
e_{sc} = Saturation vapour pressure, at the temperature of the cover inside the structure [Pa].

4.4.4 Heat loss due to infiltration

Infiltration represents energy loss due to the exchange of air through cracks. One of the most detailed investigations on infiltration was done by Okada and Takakura´s development (1973). According to these authors, infiltration rate can be based on the volume water vapour changed per unit cover area (roof and walls). This volume of water vapour is directly proportional to the wind velocity and the temperature difference from inside to outside the greenhouse (see also Equation 56).

Heat transfer due to infiltration can be estimated as

$$Q_{inf} = [(C_{p_a}(T_{in} - T_0) + L_v \Delta q)\rho_a V_{ginf}] A_g \tag{51}$$

where Q_{inf} = Heat transfer due to infiltration [W];
Cp_a = Specific heat of dry air [J/kgK] = 1.01×10^3 J/kgK;
L_v = Latent heat of vaporization [MJ/kg] = 2.45 MJ/kg;
Δq = Specific humidity difference, inside to outside, kg/kg moist air;
$V_{g\,inf}$ = Volume air exchange per unit cover area [m^3/m^2s].

$V_{g\,inf}$ is defined as

$$V_{ginf} = \frac{0.44w + 0.14\sqrt{\Delta T}}{3600} \tag{52}$$

where ΔT = Difference in temperature outside to inside [K];
w = Wind speed [m/s].

The specific humidity difference is defined by the following equation:

$$\Delta q = q_{in} - q_{out} \tag{53}$$

where

$$q_{in,out} = \frac{0.622\, e_{ain,out}}{(P - e_{ain,out}) + 0.622\, e_{ain,out}} \tag{54}$$

where e_{ain} = Vapour pressure of the air inside the structure [Pa];
e_{aout} = Vapour pressure of the air outside the structure [Pa].

and

$$e_{aout} = e_{sout} \times RH_{out} \tag{55}$$

In the equation above, RH_{out} is the relative humidity of the air outside the structure. It was defined for the simulation as a variable over 24 hours, taken from meteorological data. The element e_{sout} of the equation is the water vapour pressure at saturation which varies according to the wet/dry temperature of the air.

4.4.5 Heat transfer due to ventilation

The ventilation process is mainly the same as that for infiltration. The primary difference is that natural ventilation is used to deliberately lower the inside temperature whereas infiltration is a consequence of the failure of greenhouse building materials to form a hermetic seal. It is represented according to the following equation:

$$Q_v = (C_{p_a}(T_{in} - T_o) + L_v \times \Delta q)\,\rho_a F_v \tag{56}$$

where Q_v = Heat transfer due to ventilation [W];
F_v = Air flow due to ventilation [m^3/s]

and F_v is defined as

$$F_v = w \times r_v \times k_v \times A_v \tag{57}$$

where r_v = Percent of ventilator opening [%];
k_v = Slope of the curve representing the variation of the ventilation flux divided by wind speed as a function of the ventilator opening r_{vent}, [m^2/s]; according to Hanan (1998, Figure 4-67) k_{vent} = 0.266 m^2/s;
A_v = Ventilator area, [m^2], which, according to Smith (1988), should be about 16% of the floor area; for the case presented, A_v = 144 m^2.

4.4.6 Vapour balance

The water vapour from and inside the greenhouse can be transferred via infiltration, ventilation, transpiration and condensation. The total amount of water vapour exchanged through the structure can be described by the following equation:

$$D_{wch} = D_{winf,vent} + D_{we} + D_{wcond} \tag{58}$$

where D_{wch} = Total amount of water vapour change in the greenhouse [kg/s];
$D_{winf,\ vent}$ = Water vapour change due to infiltration and ventilation [kg/s];
D_{we} = Water vapour transfer due to transpiration [kg/s];
D_{wcond} = Amount of water vapour released by condensation [kg/s]

$D_{winf,\ went}$ is defined by

$$D_{winf,went} = (F_{inf} + F_{vent}) \times (X_{ain} - X_{aout}) \tag{59}$$

where F_{vent} = Air flow due to ventilation [m^3/s];
F_{inf} = Air flow due to infiltration [m^3/s];

and F_{inf} is defined by

$$F_{inf} = V_{ginf} \times A_g \tag{60}$$

The amount of water vapour transferred due to evaporation is given as

$$D_{we} = \frac{Q_w}{i_e} \tag{61}$$

where Q_w = Heat transfer due to transpiration [W];
i_e = Enthalpy of the moist air [kJ/kg].

The amount of water vapour released due to condensation can be estimated as

$$D_{wcond} = C \times A_c \tag{62}$$

where C [kg/m^{2}s] is the rate of condensation given as

$$C = \frac{A_c}{A_g} 1.64 \times 10^{-3} (T_a - T_c)^{1/3} \times (X_{ain} - X_c) \tag{63}$$

In Equation 64 the element X_{aout} represents the absolute humidity of the air outside the structure

$$X_{aout} = \frac{\rho_a \, \varepsilon \, e_{aout}}{P - e_{aout}} \tag{64}$$

As the quantities above are in derivative form defining the variation of the water vapour balance at time t, the equation must be integrated to find the total amount of vapour transferred through the greenhouse

$$M_{wt} = \int_0^t D_{wch} \, dt \tag{65}$$

where M_{wt} = Total amount of water exchanged through the greenhouse [kg].

The relative humidity, RH [%], in the greenhouse is defined by the following equation:

$$RH = 100 \times \frac{e_{ain}}{e_{\sin}} \tag{66}$$

4.4.7 Inside temperature

After determining the total mass and energy balance through the greenhouse, the inside temperature can be calculated according to the following equation:

$$\frac{dT_{in}}{dt} = \frac{Q_{total}}{V_g \rho C_p} \qquad (67)$$

where T_{in} = Temperature inside the greenhouse [°C];
Q_{total} = Total heat transfer of the structure [W];
V_g = Volume of the greenhouse [m^3];
ρC_p = Volumetric heat capacity of air 1200 J/m^3K.

4.4.8 Temperature control

It was mentioned previously that in order to assure a constant temperature inside the structure when the outside climate varies, the PI controller is used to adjust the flow rate of fluid through the heating system when the temperature is too low, and a P controller is used to reduce the inside temperature by opening the system ventilator.

4.4.9 Heating system control

The output of the PI controller can be given as

$$m = K \times (ER + Integral) \qquad (68)$$

where m = Flow rate of the heating system, [kg/s];
ER = Error of the PI controller, = $SP - T_{in}$; i.e. the difference between the set point (SP) and the controlled value, T_{in}.
K = Controller proportionality constant;
$Integral$ = Integral of the error signal which is defined as

$$Integral = \int_0^t \frac{ER}{TI} dt \qquad (69)$$

where TI = Integral controller constant [s];
IC = Initial condition of the integrator, [-].

There are several ways to determine the constant of such controllers considering the performance criterion i.e. to keep maximum deviation (error) as small as possible, achieve a short settling time, minimize the integral of the error until the process has settled to its desired point.

4.4.10 Ventilation control

The output of the P controller used for the ventilator is given as

$$ER1 = SP_1 - T_{in} \qquad (70)$$

$$r_{vent} = ER_1 \times K_p \qquad (71)$$

where SP_1 = Set point for the controlled parameter T_{in} [°C];
K_p = Control proportionality constant.

In the P controller, the actuator (or regulator) is varied directly with the deviation from setpoint SP_1. The error, ER_1 , between setpoint and the actual output T_{in} is multiplied by the gain, K_p . On both PI and P controllers, it is necessary to consider some limits of the output generated by the controller. This is solved by considering regulators in the control system.

4.5 Brief description of ACSL

The software used for the greenhouse model is coded ACSL. Following is a brief description of ACSL. ACSL is abbreviation of A Continuous System Simulation Language. For the casual user, ACSL provides a straightforward, easy-to-use analytical tool for modelling dynamic systems. For the experienced programmer, ACSL provides access to many programming tools that speed program development. ACSL investigates the dynamic behaviour of physical systems described by sets of differential equations.

The simulation system consists of two parts: a model definition program and runtime analysis commands. The ACSL translator converts model definitions into FORTRAN simulation programs that use ACSL´s run time library to read and interpret commands interactively and perform the analysis of the model. The model definition part contains the mathematical specifications of the dynamics of a continuous system. The body of the model definition contains the initial conditions prior to running the simulation. The DYNAMIC section contains any number of DISCRETE and DERIVATIVE section. In the DERIVATIVE section, differential equations have to be included to determine the continuous time performance of the model. In ACSL, the differential equations are specified in integral form with ACSL´s integrator operator: INTEG. The ACSL translator not only converts the model definition in FORTRAN but also the model itself is analysed from the standpoint of being a simulation of a physical system (diagnostics can indicate problems such as syntax errors, missing parameters, unsortable code, etc.). During analysis, the translator builds a dictionary of all names appearing in the model, so that variables can be changed later, printed or plotted.

4.6 Implementation of model in continuous simulation

The models are classified in several categories. In order to understand how to build a model, the physical structure is the most important aspect to be considered. The models can be classified according to their structure in lumped or distributed models, steady state or dynamic models, and linear or non-linear models. To simplify the model, lumped models in which one variable is assigned to each object to express an average are often used. For example, normally one variable is used for the inside air temperature of the greenhouse. If there is a large temperature gradient in one object, more than two variables are assigned to one object such as the soil layer, even if the model is one-dimensional. The soil layer is divided into several layers, and in each soil layer, temperatures are defined separately. (See the temperatures of the soil, T_1 and T_2).

The simulation of either a linear or a non-linear system which is time-dependent (in other words dynamic and continuous) can be done using ACSL. A typical simulation-based analysis of the greenhouse climate evaluates the influence of the external and internal factors on the temperature inside the structure. The derivative section of the program contains many differential equations which determine the continuous time history performance of the model. Many factors can be analysed like variation in time of infiltration, ventilation, condensation, and humidity which strongly influence the inside climate.

Example of a model - vapour balance. The important point in the description of a model is that its basic concept is a flow of something. For example it can be heat, water vapour or carbon dioxide in the air. Therefore, the governing rule is the conservation of these components. Here the water vapour balance within the greenhouse will be examined. The model being a dynamic one, the values of variables describing the system behaviour change with time

$$\frac{dM_{wt}}{dt} = D_{we} - D_{winf,vent} - D_{wcond} \tag{72}$$

In the equation above, one can see that the total amount of water exchange through the greenhouse is in derivative form, so a function INTEG to integrate it according to time has to be used, available with other functions in ACSL. The INTEG operator causes state variables to be calculated according to an integration algorithm. To integrate the equation above, the Runge-Kutta integration algorithm was used, but other integration methods can be chosen such as Adams-Moulton, or Gear´s stiff. To calculate the time history of the water vapour change within the greenhouse, the integration of the equation in derivative form is performed over time from a known initial state.

$$M_{wt} = INTEG(D_{wch}, M_{wt}, IC) \tag{73}$$

where D_{wch} = Total amount of water vapour exchange [kg], defined as

$$D_{wch} = D_{we} - D_{winf,vent} - D_{wcond} \tag{74}$$

The first argument in the equation for M_{wt} is the derivative form of the water vapour exchange and the second term is the initial condition for M_{wt}. The rate of change (the derivative) of each component in Equation 72 is expressed in the program as an algebraic combination of the state vector components ($D_{winf,vent}$, D_{wcond}, etc.). The integration equations of the program form the model; other statements in the program support these equations or control the execution of the program.

5. SIMULATION RUNS FOR TYPICAL WINTER AND SUMMER CONDITIONS

5.1 The temperature variation inside the structure during winter and summer

As was explained before, the climate conditions inside the greenhouse are determined by the heat and mass transfer through the structure, external climate conditions, and the presence of a heating system. The grower may be unable to maintain optimal temperature because sunlight is low or the heating system´s capacity is insufficient. The temperature in the greenhouse will vary with the plant species and their requirements for good development. Following are some simulation runs showing typical variations in the greenhouse climate.

Inside temperature. For the simulation, inside temperature T_{in} was calculated according to the heat balance through the structure, i.e. the total heat exchanged through the greenhouse. Therefore, the temperature of the inside air is influenced by processes such as humidity, conduction, ventilation, infiltration and condensation that occur inside the greenhouse.

It can be seen in Figures 8 and 9 that the inside temperature follows a periodic shape, heavily influenced by solar radiation variation (I_{win}, I_{sum}). The inside temperature during winter varies from 14°C at night to 28°C during the day. In winter, in order to reach this indoor temperature, a soil surface heating system was considered in addition to soil heating. This indoor temperature was reached with the outdoor temperature varying from -8°C at night to 8°C during the day. For the simulation, the outside temperature was defined in a table, according to meteorological temperature data from Romania for a specific day in July for summer and a day in February for winter.

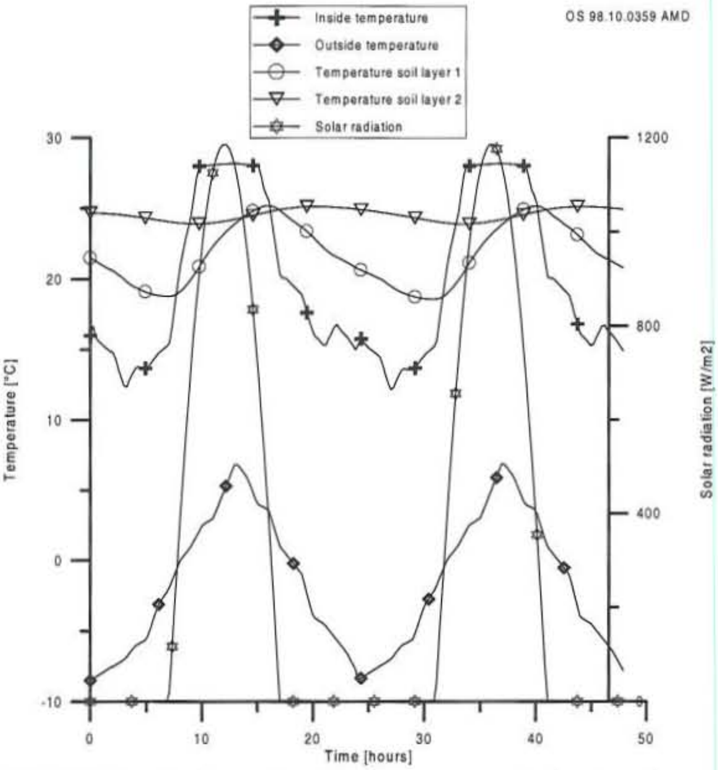

FIGURE 8: Inside and soil temperature variation in winter

Soil temperature. The soil temperature was also simulated. The soil was divided into three uneven layers, with temperatures T_1 *and* T_2 at the interfaces of the central layer and a temperature T_B at the bottom of the layers. For winter climatic simulation, temperature T_2 of the soil was considered the temperature supplied by the soil heating system to the greenhouse interior. For summer, temperature T_2 was considered the temperature of the soil layer at depth z_2. It can be seen on the plots, that both T_1 and T_2 follow a periodic shape variation. In winter, temperature T_1 at the surface of the soil varies from 19°C at night to 25°C during the day. During summer even if the soil heating system is not in use, temperatures T_1 and T_2 are increased by solar radiation during the day. Temperature T_1 at the surface of the soil varies from 22°C at night to 31°C during the day. Temperature T_2 considered at depth z_2 of the soil surface, varies from 21.5°C at night to 26°C during the day.

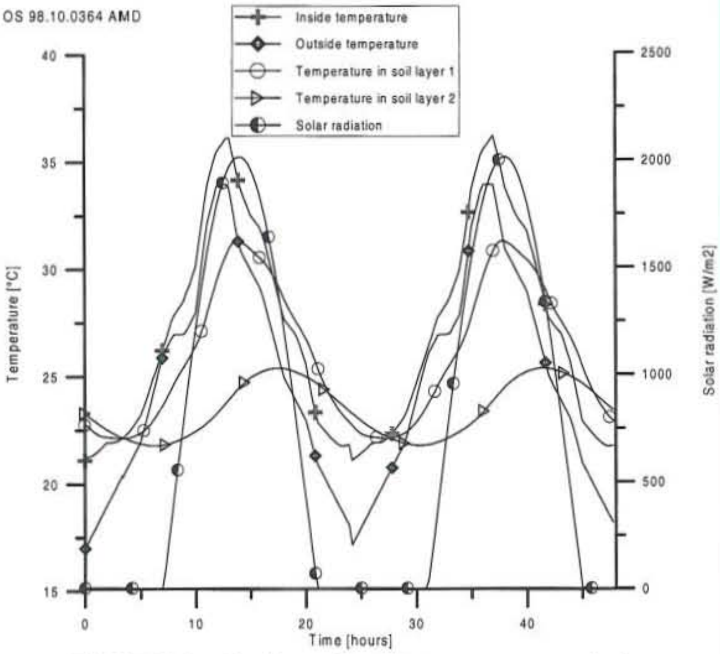

FIGURE 9: Inside and soil temperature variation during summer

5.2 Water vapour transfer through the structure and from evapotranspiration during winter and summer

In Chapter 4, mathematical equations for water vapour balance through the structure were presented. The water vapour transfer occurs from the greenhouse soil and structure to the air. This water vapour transfer is caused by factors such as infiltration, ventilation, humidity (transpiration), and condensation.

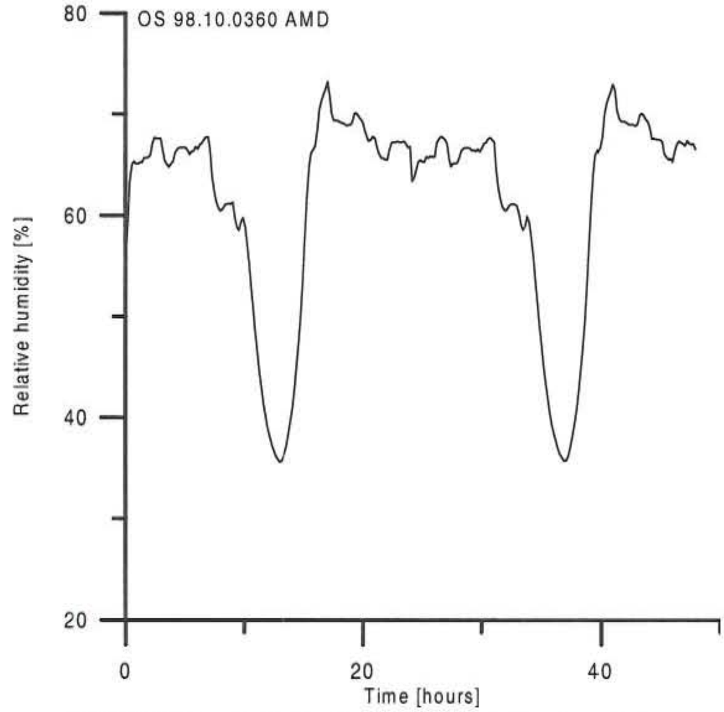

FIGURE 10: Relative humidity variation in winter

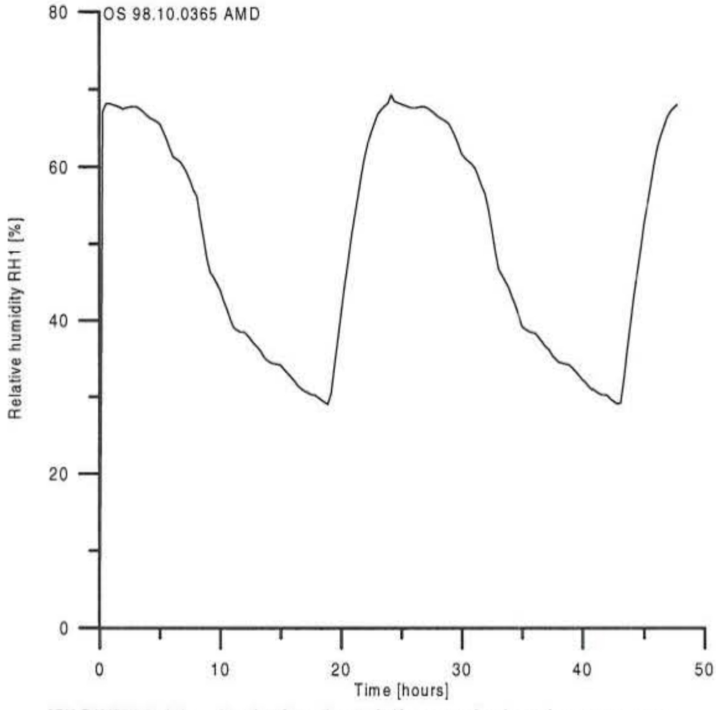

FIGURE 11: Relative humidity variation in summer

Relative humidity. One of the most important factors to be controlled is the relative humidity inside the structure (RH_I), as the atmospheric level of water vapour significantly influences growth and development of plants. The rate of growth, composition and form that a plant attains are, to a large degree, controlled by humidity. Humidity also has a direct effect on disease (high humidity causes mildew on plant leaves; low humidity dries plant roots and decreases the photosynthesis process). For the simulation it was assumed that the plants entirely cover the greenhouse floor (in this case the leaf area index is LAI = 4, which is used for converting leaf stomatal resistance to crop canopy resistance). The rate of humidity decreases when the temperature increases if the water content of the air is constant. In winter the relative humidity, RH, increases during the night up to 65% and during the day when solar radiation is present, the rate of humidity is decreased to 36% (Figure 10). During summer the situation is almost similar, the relative humidity increases during the night to 65-68% and decreases during the day to 30% (Figure 11). It should be noticed that during the summer, the lower humidity during the day is maintained for longer hours, as more solar radiation is available.

Water vapour transfer due to ventilation and infiltration. The direct exchange of air through the openings of the greenhouse is caused by ventilation and infiltration. The amount of water vapour released from the greenhouse due to ventilation is proportional to the outside wind velocity, and the surface area of the ventilator, the difference between the mass of vapour per unit volume of the outside and inside air. For the simulation, the ventilator was considered active during the summer as well as during the winter. Its opening is controlled by a P controller. According to the simulation data, the amount of water vapour released from the greenhouse is significant during summer, both night and day, if the inside temperature increases above ca. 32°C the P controller setpoint.

For the simulation, the ventilator area was considered 16% of the total floor area of the structure. The P controller opens the ventilator whenever the indoor temperature is higher than the P controller setpoint and closes the ventilators when this temperature is under the setpoint temperature. According to the simulation data, it can be seen in Figure 12 that during winter there is no water vapour exchange due to ventilation during the night, but during the day when the temperature inside is increased by solar radiation, the P controller opens the ventilator and a maximum amount of 3.8x10^{-2} kg/s of water vapour is released.

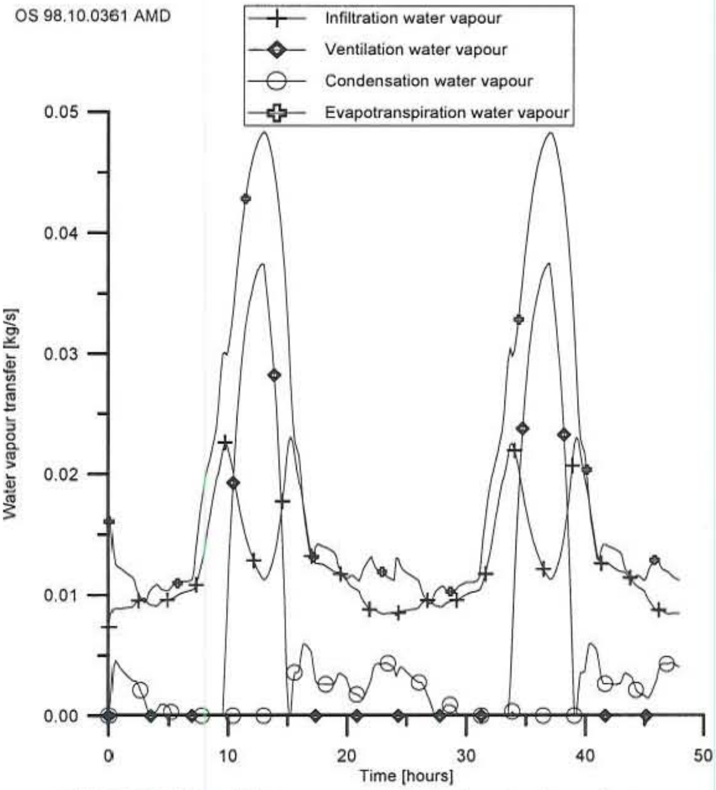

FIGURE 12: Water vapour transfer during winter

Water vapour exchange due to transpiration. The vegetation inside the structure can be considered a well-defined body that exchanges energy, mainly water vapour with the greenhouse air. The greenhouse climate and the plants interact in this respect. With no plants within, the greenhouse climate can be characterised as a hot and dry desert. With a crop, it is transformed into a humid and warm tropical climate. Therefore, the transpiration of the plant has a significant role on the inside climate condition. For the case described, it was assumed that the vegetative canopy completely covered the ground (the leaf area index, $LAI = 4.0$). The vapour exchange due to transpiration was estimated by considering the resistance of the plant to the transport of water to the surface of the leaves and the vapour pressure difference at saturation (at the surface of the cover) and of the inside air.

The simulation of the rate of transpiration inside the structure is required also by the fact that changes in transpiration will modify the energy balance of the interior; e.g., an increase in transpiration will result in cooling, in addition to modifying the water balance of the greenhouse.

It was assumed that the amount of water vapour released by evapotranspiration is in inverse proportion to the resistance of the vapour exchange from the plant to the inside air. It can be seen in Figure 12 that this transfer is rather significant. The water vapour released by transpiration follows a periodic shape variation, like solar radiation, most important during the day when solar radiation increases the rate of transpiration (4.8×10^{-2} kg/s during winter).

Water vapour exchange due to condensation. The greenhouse air changes energy as well as water vapour (condensation) to the inner surface of the cover and the cover exchanges energy to the outside air. Whenever the inside cover surface temperature is below the dewpoint of the inside air, water will condense. Condensation usually increases due to the lower temperature of the cover. In this case it is expected that the water vapour exchange due to condensation will be higher in winter than in summer. The quantity of the condensed water depends on air humidity and temperature. For the simulation, the amount of water vapour released by condensation to the cover of the greenhouse was defined by using the virtual temperature at the surface of the cover inside the structure and of the air inside the greenhouse. These temperatures depend on the temperature inside the structure and that at the cover, and on the water vapour pressure of the air inside the structure. According to simulation data no condensation occurs during summer (this means that the inside cover surface temperature is above the dewpoint of the inside air, this temperature being defined as the temperature at which unsaturated air must be cooled in order to produce saturation). During winter the amount of water vapour exchanged by condensation follows an irregular shape variation (Figure 12) more significant at night and especially when the sun sets with a 0.6×10^{-2} kg/s peak value. There is no condensation while solar radiation is available, and condensation increases again after the sun sets, being almost constant around 0.2×10^{-2} kg/s during the night.

5.3 Energy transfer through the structure during winter and summer

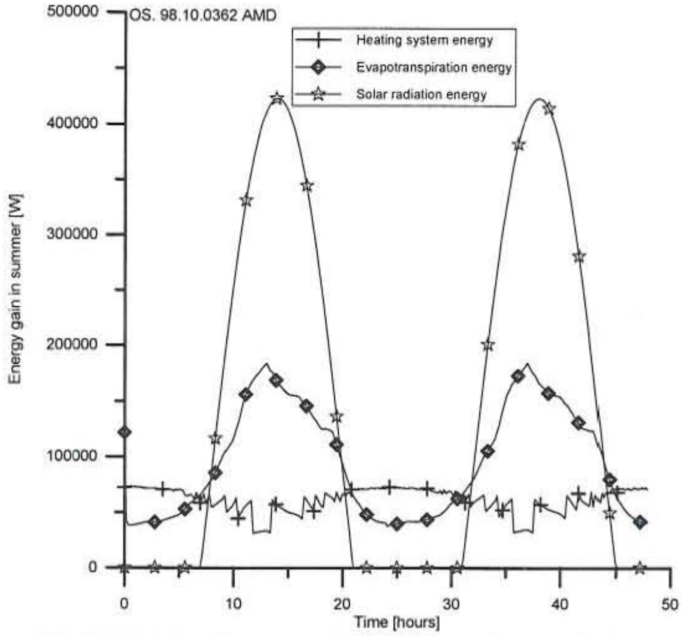

FIGURE 13: Energy gain in the greenhouse during summer

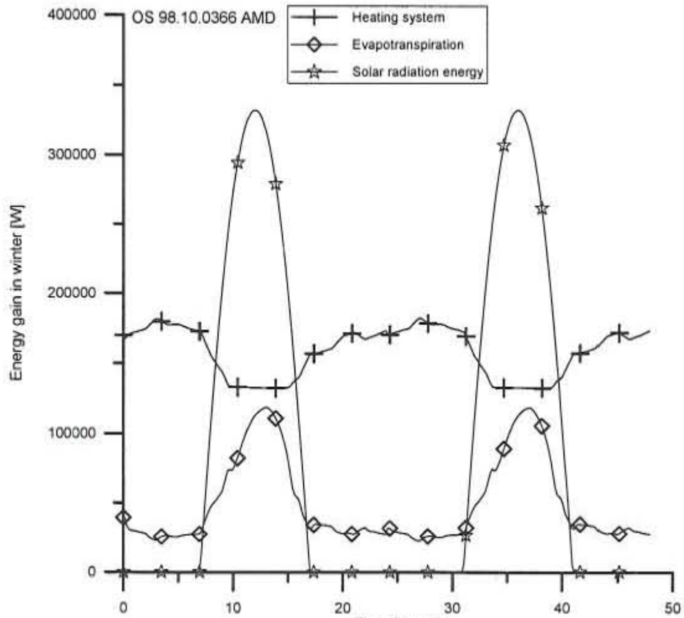

FIGURE 14: Energy gain in the greenhouse during winter

Heat gain through the greenhouse. For simulation it was considered that the heat gain to the greenhouse is due to solar radiation, heat from the heating system and heat transfer from evapotranspiration.

Simulation of solar radiation. As was discussed in Chapter 4, the solar radiation for the simulation was considered to vary as a sinusoidal function, considering that at the negative side of the variation the solar radiation is zero. The different length of day and of solar radiation availability during summer and winter were also considered. During summer the peak heat gain from the sun is about 400 kW (Figure 13), during winter it is about 330 kW (Figure 14). Solar radiation is an important influence on all the other heat exchanges through the greenhouse.

Simulation of heat gain from the heating system. Heat gain from the heating system plays an important role in maintaining the required indoor temperature. During the winter, the soil surface heating system was considered along with the soil heating system. In order to control the heat supplied by the heating system a, PI controller was used. It acts on the mass flow of water through the pipes of the heating system. The required heat is less during the day when solar radiation is available (peak value in winter is about 180 kW, and 70 kW in summer during the night).

Simulation of heat gain due to evaporation. Heat gain in the evapotranspiration process inside the structure follows a periodic variation similar to solar radiation. The transpiration process is more intense during the day due to the solar energy. According to the simulation data (Figures 13 and 14) heat transfer due to evapotranspiration varies between 20 kW to 120 kW in winter and between 40 kW to 180 kW in summer.

Heat loss through the greenhouse. Energy loss was estimated as a result of convection and conduction through the cover and the soil of the structure, condensation, infiltration and ventilation and was balanced with the heat exchange from the heating system, the solar radiation and the heat transfer from the plants to the inside air due to transpiration. The energy balance has an important role not only in maintaining a given temperature and humidity inside the structure, but also in designing the heating and ventilation systems and possibly even an evaporative cooling system.

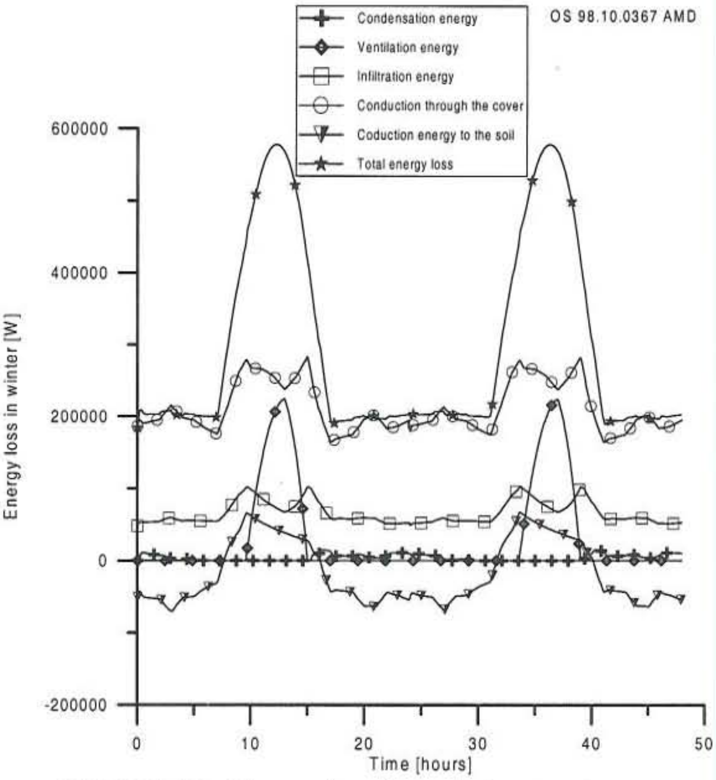

FIGURE 15: Energy loss through the greenhouse during winter

Simulation data of heat transfer due to conduction. According to the simulation (Figure 15), conduction heat transfer through the cover follows a periodic variation during winter. It can be seen on the plot (Q_k) that this amount of energy loss is high during the day (a maximum of 280 kW energy is lost) and not as high but still important during the night (200 kW). During summer, conduction heat transfer follows an irregular shape (Figure 16). The heat loss is higher during the day when solar radiation is available (around 18 kW) and very low during the night (about 10 kW). The explanation of less conductive heat loss in summer than in winter is found in the variation of influencing factors (low temperature difference and also low wind velocity).

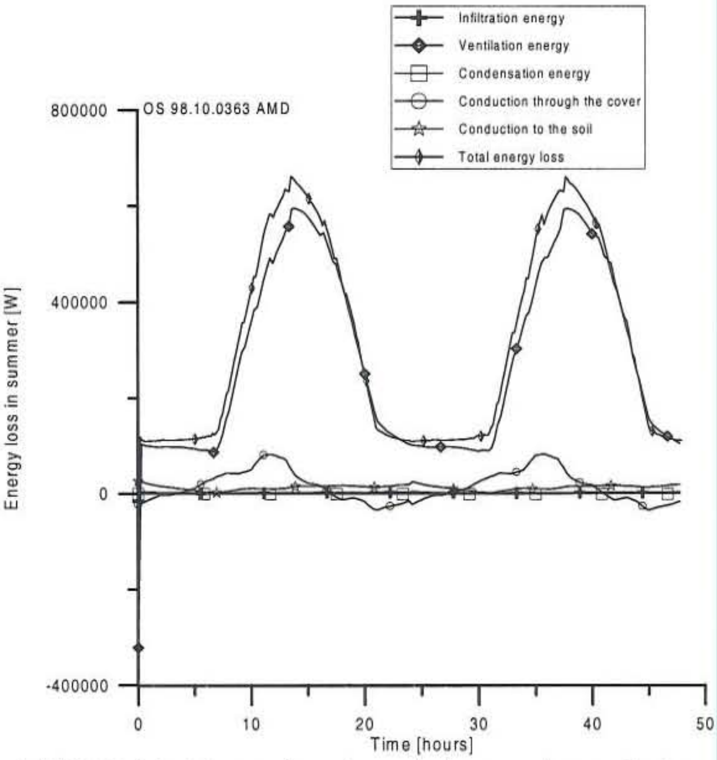

FIGURE 16: Energy loss through the greenhouse during summer

An important amount of energy is lost from the greenhouse interior to the greenhouse soil (Q_{soil}). Both in winter as well as summer (Figures 15 and 16), heat transfer follows a periodic shape variation increased during the day and decreased during the night. According to the simulation data, during winter a peak value of 60 kW can be reached. During the night, heat transfer to the soil is increased by the heating system which acts to supply more heat in order to maintain the required inside temperature. In summer the heat loss to the soil varies almost in the same way, more energy being lost during the day and less during the night.

Simulation data of heat transfer due to infiltration and ventilation. Heat transfer through the structure due to infiltration and ventilation was simulated. According to the simulation data, heat loss due to infiltration is more important in winter. It can be seen in Figure 15 that in winter, infiltration heat loss is almost constant during the night (50 kW), increases for several hours after the sun rises, and during the day. In summer, infiltration heat loss is rather constant both day and night (2-3 kW).

Heat transfer due to ventilation follows almost the same periodic shape variation as solar radiation (Figures 15 and 16). In summer, heat transfer due to ventilation increases as solar radiation increases, reaching a peak value of 600 kW. At night, the ventilator is opened as the indoor temperature is high enough due to the solar radiation accumulated during the day. In winter, the P controller acts on the ventilator, opening it only during day if the temperature inside is too high. According to the simulation data, this occurs for about five hours during the day when solar radiation is available. The maximum energy loss is about 220 kW.

Simulation data of heat transfer due to condensation. It is known that water will condense whenever the absolute humidity of the air inside the greenhouse is above the absolute humidity of the air at the cover surface temperature inside the structure. The amount of energy loss due to condensation is increased if the temperature of the cover is lower than the dewpoint temperature of the inside air. According to the simulation data, no condensation occurs in summer. In winter there is condensation at the cover of the structure, especially during the day. Heat loss due to condensation follows an irregular variation shape. The peak value of the heat loss is around 13 kW. Heat transfer due to condensation starts increasing after sunset. At night, it decreases again when the humidity and inside temperature gradually decrease.

With all these heat losses through the greenhouse, the total energy loss, Q_{loss} , follows a periodic variation, constant at night and increasing during the day. According to Figure 16, the peak value of heat loss in summer is reached at 1 p.m., around 660 kW. In winter, heat loss has the same periodic variation, peak value being reached at 12 p.m., about 580 kW (see Figure 15).

6. CONCLUSIONS

The climate model of the greenhouse described in this paper will play an important role in predicting the energy requirement and the proper design of the heating and ventilation systems for the greenhouse demonstration project proposed by the University of Oradea.

The simulation process can be extended to CO_2 concentration analysis, which has a critical role in the photosynthesis process of the plants. Together with some horticultural specialists from the University of Oradea, this analysis can easily be done. The model can also be extended to analyse the irrigation process within the greenhouse, for a better estimation of the relative humidity of the air inside the structure.

Simulation is an accurate method for the calculation of factors which influence the internal climate conditions in the greenhouse. This can help in finding techniques to improve the negative economic situation, not only for the greenhouse to be built at the University of Oradea, but also for other greenhouses in Romania. Simulation enables investigation of climate changes and other influencing parameters on the greenhouse climate, without the cost of building a greenhouse and testing the response of the plants within.

Before the experimental greenhouse for the University of Oradea is built, it is recommended to analyse the behaviour of the system under different climatic conditions in order to decide the energy consumption and the most economical heating system to be used in heating the greenhouse.

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