CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

FACULTY OF ENGINEERING

DEPARTMENT OF TECHNOLOGICAL EQUIPMENT OF BUILDINGS

DIPLOMA THESIS

MICROCLIMATIC CONDITIONS IN GREENHOUSES

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Department of Technological Equipment of Buildings

Faculty of Engineering

DIPLOMA THESIS ASSIGNMENT

Perez Barreto Pablo Antonio

Thesis title

Microclimatic conditions in greenhouses

Objectives of thesis

The aim of this diploma thesis is the evaluation and modelling of different microclimatic and operating conditions in greenhouses. The study should result in proposal of applications suitable for different climatic conditions.

Methodology

Based on the literature overview consider different conditions of production and evaluate suitable use and application of greenhouses in practical farming, mainly from the point of view of energy consumption, respecting the needs of cultivated crops. Use the methods of indoor microclimate modelling.

Outline of the structure

1. Introduction
2. Constructions and technological equipment of greenhouses
3. Winter and summer heat balance of greenhouse
4. Experimental measurement
5. Use and economy of greenhouses in different climatic conditions
6. Conclusions and recommendations for practical applications

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The proposed extent of the thesis

50 to 60 pages of text

Keywords

greenhouses; microclimate; plants; energy

Recommended information sources

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Nový, R. et al: Technika prostředí. ČVUT, Praha, 2000, 265 s.
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Prague February 1. 2013

DECLARATION

I herby declare that I have worked on my diploma thesis called "Microclimatic Conditions in Greenhouses." solely by myself with the help of the listed bibliography.

Prague on March 20th, 2013. ………………………………..

Acknowledgement

I would like to thank, in first instance, to my parents, who did everything to give me the possibility to study in Czech Republic. To my supervisor, Prof. Ing. Pavel Kic, DrSc., for his professional guidance in shaping of my research, his encouragement, major advices and recommendations which helped me with my diploma thesis, to Mr. Manuel Díaz Brito who was working with me in the greenhouses with the measurements and Fien Minnens who was the first to read this work, her critical comments improved the final quality significantly. I am very grateful to all people who supported my work by their help and advice.

GENERAL INDEX:

Figures:

Notation.

β_{ia}	Volumetric expansion coefficient of the inside air $\left[\frac{1}{K}\right]$
β_{oa}	Volumetric expansion coefficient of the outside air $\left[\frac{1}{K}\right]$
ε_{co}	Cover emissivity
ε_{s}	Soil emissivity
$F_{co\to co}$	Cover → Cover shape factor
$F_{co\to s}$	Cover → Soil shape factor
$F_{s\to co}$	Soil → Cover shape factor
$F_{s\to s}$	Soil → Soil shape factor
g	Gravity acceleration $\left[\frac{m}{s^2}\right]$
$Gr_{C,co\to ia}$	Cover → Inside air Grasshoff number $[-]$
$Gr_{C,co\to oa}$	Cover → Outside air Grasshoff number $[-]$
$Gr_{C,s\to ia}$	Soil → Inside air Grasshoff number $[-]$
$h_{C,co\to ia}$	Cover → Inside air convection coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$h_{C,co\to oa}$	Cover → Outside air convection coefficient $\left[\frac{W}{m^2\cdot K}\right]$
$h_{C,s\to ia}$	Soil → Inside air convection coefficient $\left[\frac{W}{m^2\cdot K}\right]$
HF_{co}	Measured heat flux through cover $\left[\frac{W}{m^2}\right]$
J_{co}	Cover radiosity $\left[\frac{W}{m^2}\right]$
J_{s}	Soil radiosity $\left[\frac{W}{m^2}\right]$
K_{ia}	Inside air conductivity $\left[\frac{W}{m\cdot K}\right]$
K_{oa}	Outside air conductivity $\left[\frac{W}{m\cdot K}\right]$
K_{s}	Soil conductivity $\left[\frac{W}{m\cdot K}\right]$
$L_{C,co\to ia}$	Cover characteristic length $[m]$
$L_{C,co\to oa}$	Cover characteristic length $[m]$
$L_{C,s\to ia}$	Soil characteristic length $[m]$
$Nu_{C,co\to ia}$	Cover → Inside air Nusselt number $[-]$
$Nu_{C,co\to oa}$	Cover → Outside air Nusselt number $[-]$
$Nu_{C,s\to ia}$	Soil → Inside air Nusselt number $[-]$
$Q_{K,s}$	Conduction heat from soil $\left[\frac{W}{m^2}\right]$
$Q_{R,co}$	Inwards cover radiation $\left[\frac{W}{m^2}\right]$
$Q_{R,s}$	Upwards soil radiation $\left[\frac{W}{m^2}\right]$
$Q_{R,co\to sky}$	Outwards cover radiation $\left[\frac{W}{m^2}\right]$
$Q_{C,s\to ia}$	Soil-air convection $\left[\frac{W}{m^2}\right]$
$Q_{C,co\to oa}$	Cover-outside air convection $\left[\frac{W}{m^2}\right]$
$Q_{C,co\to ia}$	Cover-inside air convection $\left[\frac{W}{m^2}\right]$
$Ra_{C,co\to ia}$	Cover → Inside air Rayleigh number $[-]$
$Ra_{C,co\to oa}$	Cover → Outside air Rayleigh number $[-]$

$Ra_{C,s \rightarrow ia}$	Soil → Inside air Rayleigh number $[-]$
σ	Stefan-Boltzman constant in $\left[\frac{W}{m^2 \cdot K^4}\right]$
SR	SR the incoming solar radiation in $\left[\frac{W}{m^2}\right]$
τ_{SRco}	Cover transmissivity for solar radiation
T_{co}	Cover temperature $[K]$
T_{ds}	Deep soil layer temperature $[K]$
T_{ia}	Inside air temperature $[K]$
T_{oa}	Outside air temperature $[K]$
T_s	Soil surface temperature $[K]$
ϑ_{ia}	Inside air kinematic viscosity $\left[\frac{m^2}{s}\right]$
ϑ_{oa}	Outside air kinematic viscosity $\left[\frac{m^2}{s}\right]$
z_s	Soil measured depth $[m]$

ABSTRACT

The study of heat transfer in a greenhouse is a tool for improving environmental management and efficiencies in this type of structures. The future improvement on the quality of cultivation and the control of pests are some examples of the use for this model. With the present research we will give the main technical parameters to characterize the greenhouse, and also an analysis of the behaviors of the inside air temperature, all heat fluxes involved in the heat transfer problem and how the solar radiation and outside air temperature affect the greenhouse climate. This study is focused on a specific location in CULS (Czech University of Life Sciences Prague). The simulation has been created and validated with the data acquired in the greenhouse from 20th to 27th of April 2012.

KEY WORDS: greenhouse, heat transfer, cover, soil, inside air, model, climate.

ABSTRAKT

Studie přenosu tepla ve skleníku je nástrojem pro kontrolu, řízení a úpravu vnitřního prostředí i zlepšování efektivity provozu v těchto stavbách. Zlepšení kvality pěstování i ochrany proti škůdcům jsou některé příklady využití tohoto modelu. Výsledky výzkumu shrnuté v předložené práci poskytují hlavní technické parametry charakterizující skleník. Dále je zde analýza průběhů teploty vnitřního vzduchu, všechny tepelné toky, kterými probíhá sdílení tepla a také je zde definováno, jak sluneční záření a teplota venkovního vzduchu ovlivňují vnitřní skleníkové klima. Tato studie vychází z výsledků získaných v konkrétní lokalitě; jedná se o ČZU (Česká zemědělská univerzita v Praze). Simulace byla vytvořena a ověřena s údaji změřenými ve skleníku v období od 20. do 27.dubna 2012.

KLÍČOVÁ SLOVA: skleník, sdílení tepla, zakrytí, půda, vnitřní ovzduší, model, klima.

1. Introduction.

A microclimatic model is a quantitative method to evaluate the interactions of climatic conditions as solar radiation, air temperature, soil temperature with the different materials and shapes of a greenhouse. This model gives predictions of the climatic behavior of the greenhouse like heat fluxes and temperatures of different parts inside the greenhouse as for example the flux of heat across the cover of the greenhouse or the temperature of the greenhouse internal air as many other variables. Also can evaluate others important parameters like ventilation and heating of the greenhouse in winter season.

The proposal model could be used as forecast of different variables in the greenhouse as were mentioned before. With this data is possible to evaluate, as for example, different irrigation cycles, ventilation routines, and heating preferences for any crops before planting. Then is also possible to evaluate economically the cultivation with the virtual data obtained, what means a reduction in cost of experiments.

As an introduction, should be explained what is a greenhouse as well as the operating principles. The historical production practices of agriculture in Czech Republic and the current situation will be detailed.

The methodology followed to develop a climate model heat transfer in a greenhouse without heating systems (the proper heating systems will be proposed on this thesis for the winter conditions of the location) is to characterize all the parameters governing the problem and propose mathematical equations that describe it. For that, from 20th to 27th of April of 2012 thermodynamic and heat transfer variables were measured inside the greenhouse, such as temperature, humidity, heat flux through surface, speed of the wind, etc. In that week there were many variations in weather conditions, so it could analyze the behavior of some other variables as they change. With all the information collected is design a mathematical problem, describing the real problem, is solved by EES (Engineering Equation Solver) obtaining different values. These values are compared with previously measured values to verify the validity of the mathematical model.

Then measured variables, the variables calculated by the model will be analyzed and compared with each other using the computational tool Excel.

1.1. Fundamental of greenhouse.

A greenhouse is a building in which plants are grown. These structures range in size from small sheds to very large buildings.

A greenhouse is a structure with different types of covering materials, such as a glass or plastic roof and frequently glass or plastic walls; it heats up because incoming visible solar radiation (for which the glass is transparent) from the sun is absorbed by plants, soil, and other things inside the building. Air warmed by the heat from hot interior surfaces is retained in the building by the roof and wall. In addition, the warmed structures and plants inside the greenhouse re-radiate some of their thermal energy in the infrared spectrum, to which glass is partly opaque, so some of this energy is also trapped inside the glasshouse. However, this latter process is a minor player compared with the former (convective) process. Thus, the primary heating mechanism of a greenhouse is convection. This can be demonstrated by opening a small window near the roof of a greenhouse: the temperature drops considerably. Thus, the glass used for a greenhouse works as a barrier to air flow, and its effect is to trap energy within the greenhouse. The air that is warmed near the ground is prevented from rising indefinitely and flowing away.

Although heat loss due to thermal conduction through the glass and other building materials occurs, net energy increases (and therefore temperature) inside the greenhouse.

Greenhouses can be divided into glass greenhouses and plastic greenhouses. Plastics mostly used are PEfilm and multiwall sheet in PCor PMMA. Commercial glass greenhouses are often high-tech production facilities for vegetables or flowers. The glass greenhouses are filled with equipment such as screening installations, heating, cooling, lighting, and may be automatically controlled by a computer.

1.2. Historical Production Practices of the Czech Republic.

Historically, agriculture has only played a very small role in the economy of the Czech Republic due to the small amount of natural resources present in the country (Food & Agriculture book). There were times throughout its history where the country had some positive production of crops. In the early 1930s, agriculture in the Czech Republic was well developed and a primary importer of crops from neighboring countries (Caski, 1999). After the socialist regime, the former Czechoslovakia was split into the current Czech Republic and Slovakia.

After this, agriculture took a turn for the worse by falling behind newer technologies and standards that were being developed in both Western and neighboring countries (Caski, 1999). As mentioned earlier, there was a time when agriculture was more abundant in the region, particularly vegetable production. A wide range of vegetables are sold at farmer's markets and along the roadsides. In addition, during the summer-fall months blueberries, cranberries, and other cane fruits are harvested in the wild and sold by the roadside. During the former socialist rule of Czechoslovakia, 5 or 6 major agriculture firms produced about 70% vegetables grown in the Czech Republic (Caski, 1999). Most of the crops produced during that time were onions, potatoes, cabbage, and root vegetables. These crops have continued to be important for the Czech economy along with a few added others. During the 1980s, the average consumption annually was estimated to be about 700,000 tons of vegetable per year for the entire country's population.

Greenhouse production was also more prominent in the Czech Republic at one point in its history. In 1984, 220 hectares (ha.) of greenhouses and 200 ha. of plasticulture were present in the nation at the time for creation of vegetables, seedlings, and flowers. During this era, there was somewhat of an interest in the practice of greenhouse growing.

However, by 1989 the number of greenhouses dropped dramatically down to around 64 ha (Caski, 1999). There were numerous reasons for the decrease in the number of the greenhouses in the Czech Republic. The primary reason was there were other warmer countries in Europe and North Africa that were more suitable for greenhouse production. Another reason was that the greenhouses were often inefficient and poorly made so they did not last long (Caski, 1999).

1.3. Current Production Statistics.

As stated previously, the total amount of land area used for crop production in the Czech Republic is 38.82% of the total land mass. This land is used for growing a wide variety crops for the Czech Republic. Not only, does it provide the population with a food source, but some are also becoming bigger commodities which may eventually lead to a source of income for the country.

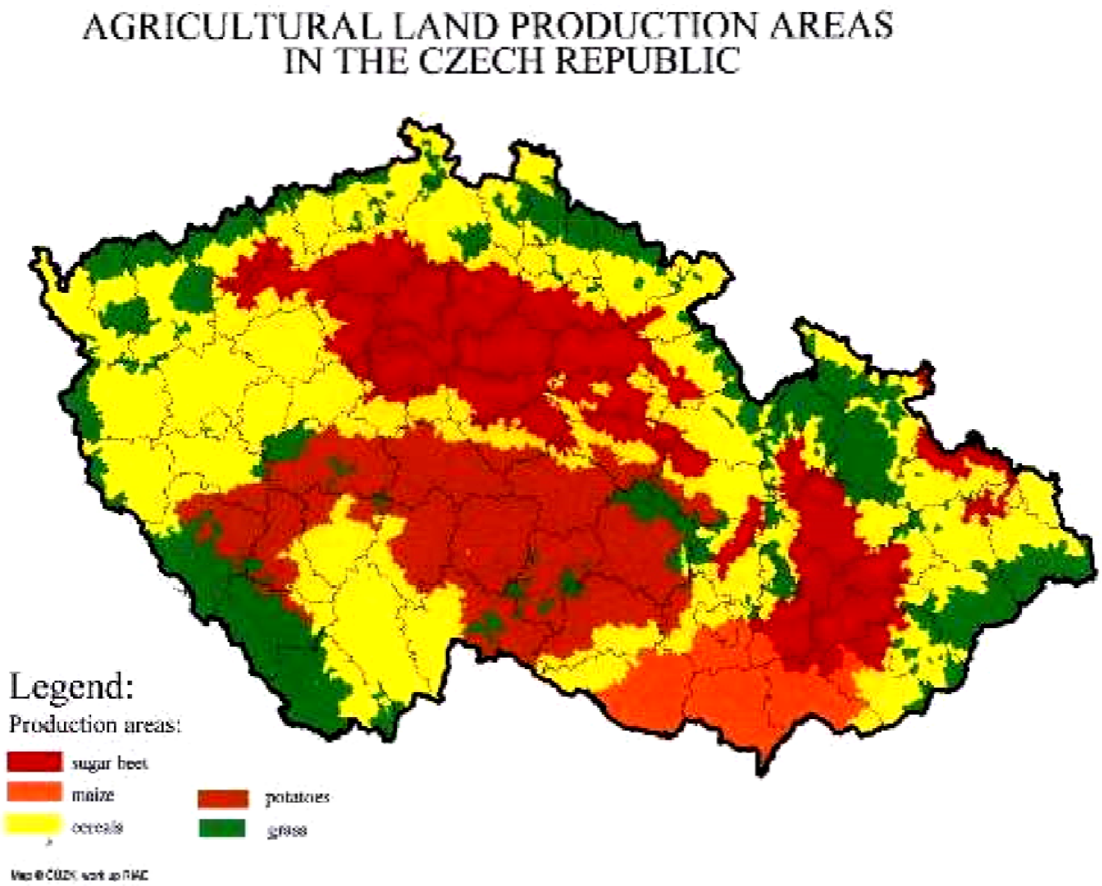

Figure 1.- Agricultural Land Production Areas in Czech Republic.

Current production statistics in the Czech Republic are somewhat varying. Overall, the country is an importer of several agricultural goods and they rarely are growing enough to be an exporter of any particular crop. However winter wheat, barley, corn, sugar beets, and corn are produced quite regularly to provide for the Czech population; the meat industry provides as well.

Winter wheat may also be produced abundantly enough to become a main export for the country as well. The *Figure. 1* show that the main crop produced in the country are cereals: wheat, barley and other similar grain species. The second most prevalent crop is sugar beets which are grown in the center of the country. The smallest amount of arable land is dedicated to the production of corn.

A few statistics for winter wheat, barley, and corn will be expressed from the year 1991. In that year, the Czech Republic produced 6200 metric tons (MT) of wheat with a steady increase over the past 30 years, 3790 MT of barley also with a steady increase, and 860 MT of corn with varying quantities over the past 30 years (Indexmundi, 2009). Looking at these numbers, it is obvious that the agricultural crop produced in the Czech Republic is that of wheat.

Another common commodity present in the Czech Republic is that of sugar beets, the Czechs use this product to produce a sugar that is then used to make rum. Fruits and vegetable production play a small role in the agricultural production of the Czech Republic. The main fruits produced are pears (Pyrus communis), apples (Malus sp.), cherries (Rhagoletis cingulata), and apricots (Prunus armeniaca) (Casaki, 2009). Potatoes also play somewhat of a large role for the country.

1.4. Current Production Practices.

Agriculture and crop production has never really been a primary source of revenue for the Czech Republic. However, more and more policies of sustainability are being introduced in order to help with the current production practices. The current farming structure consists of three categories: the first making up 38.7% of the agriculture business, belongs to cooperatives in an assortment of forms, based on mostly privately owned land leased from the companies. The second major forms of farming are incorporated privately-owned larger farms operating on leased land from the state or private owners, accounting for 35.4%. Finally, individual private farms account for 25.1% of agriculture land with the land they lease (Caski, 1999). This indicates that the majority of the country may eventually turn to larger run companies to do all of the agriculture crop production for the Czech Republic.

As of the 2008 year, organic farming has become increasingly important in the agriculture landscape of the Republic. In June of 2008, 7.84% of arable land was used for organic farming (Ministry of Agriculture, 2008). There was a steady increase from 2007 to 2008 with the number suspected to increase. The yearbook also stated that from year 2006 to 2007, the number of organic vegetable production was suspected to increase by 56%. This is an important concept considering organic production may lead to a more sustainable way to process food crops for the country making it appealing as a sustainable landscape. The most common crops produced organically in the country are common wheat, spelt, oats, and rye (Ministry of Agriculture, 2008). All of these are used as cereal products and are very important to the economy. Along with those cereals, field peas, carrots, cabbage, and greenhouse crops fall among the top products produced organically (Ministry of Agriculture, 2008). For the country, the appeal of these products can be seen through the abundance of them appearing in markets throughout the landscape. Organic farming in the Czech Republic does not stop at vegetable/fruit production but also involves livestock and domestic animal products. The top organically produced livestock are beef, sheep, cow's milk, and also chicken's eggs. Overall, the Czech Republic is taking several strides into becoming an organic crop producing country.

Fruit and vegetable production in the Czech Republic is also essential to the economy (fruit more so than vegetable). Production of vegetables has included almost 18 cultivars of main vegetables that take over 400 ha. to grow. Furthermore, some areas of the country are very adapted to growing vegetables in those regions. However, even with favorable areas that are able to grow vegetables there are still many details that need to be fixed in order to make vegetables a higher priority commodity in the country. These elements include the current vegetable production problems including: improving genetic material, improved crop production, and also improvement of packaging and shipping (Caski, 2007). Fruit, on the other hand, has become a very important commodity for the Czech Republic. Because most of the fruit grown there is in need of a temperate climate, fruit has become almost abundant enough to become a major export of the country (Caski, 2007). This could not only help the country transform from a leading importer to exporter but provide numerous jobs for people.

The current state of greenhouse and wholesale production is far from dominant but still present in the Czech Republic. Many of the greenhouses are owned by the government and were once connected to large power companies that offered warm water and electrical power from the plant (Jensen, 1995). The increasing strength of the Dutch floriculture industry has caused greenhouse production in the country to decrease. As of today, there are only about 20 ha. of greenhouses used in the Czech Republic to produce ornamentals (Jensen, 1995). As for wholesale growers, they are also there but very small in number. About 500 inexperienced, wholesale fruit and vegetable organizations registered with government in 1992. The reason why wholesalers are not making an impact on the economy is because the competition from bordering countries is making it hard to make a substantial difference between net imports and exports (Caski, 2007).

1.5. Objective.

This thesis main objective is to find a proper mathematical model for a selected greenhouse, adapting all parameters to it. With the obtained model, previously discussed reliability, computer based simulations can be run in order to get results for any supposed situation. Then these simulations would have a widespread range of objectives, changing any parameters desired to obtain theoretical results.

Another important part of the work done is the analysis of the measured data in the real greenhouse and the comparison between this real data and theoretical results obtained, which helps also to validate the proposed model. Some variables will be statistically analyzed with the aim of obtaining relations between them. In this section, with the parameters measured, other variables will be obtained through mathematical models in order to explain heat exchange processes in the greenhouse.

2. Constructions and technological equipment of greenhouses.

2.1. Descriptions: location, dimensions, general parts of the greenhouse, boundary conditions.

2.1.1. Location.

A real non-heated greenhouse located in Czech University of Life Sciences (CULS), Prague, was the object of this study. Look the overview of the university from Google maps (*Figure 2*) where the location of the greenhouse is shown in a blue circle.

Figure 2. Situation.

2.1.2. Dimensions

The overall length of the greenhouse is 24 meters, composed of 32 glass rows of 0,75 meters wide.

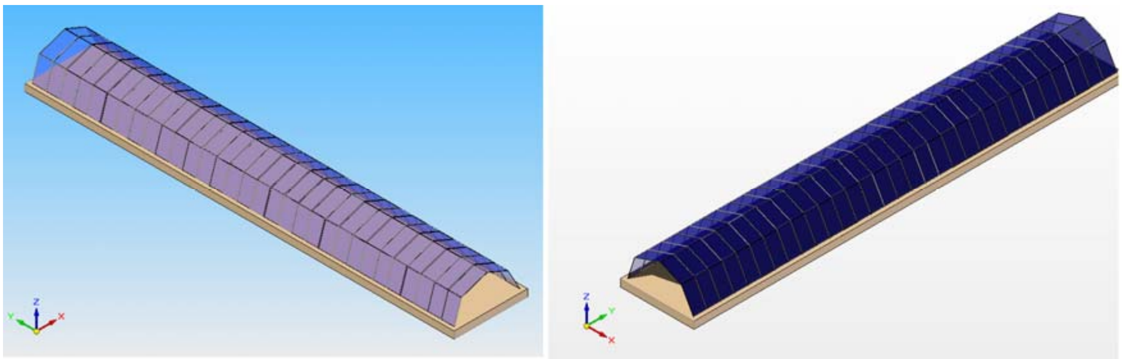

Figure 3. 3D view of the greenhouse.

The basic dimensions of the greenhouse side view or section are shown in the *Figure 4*.

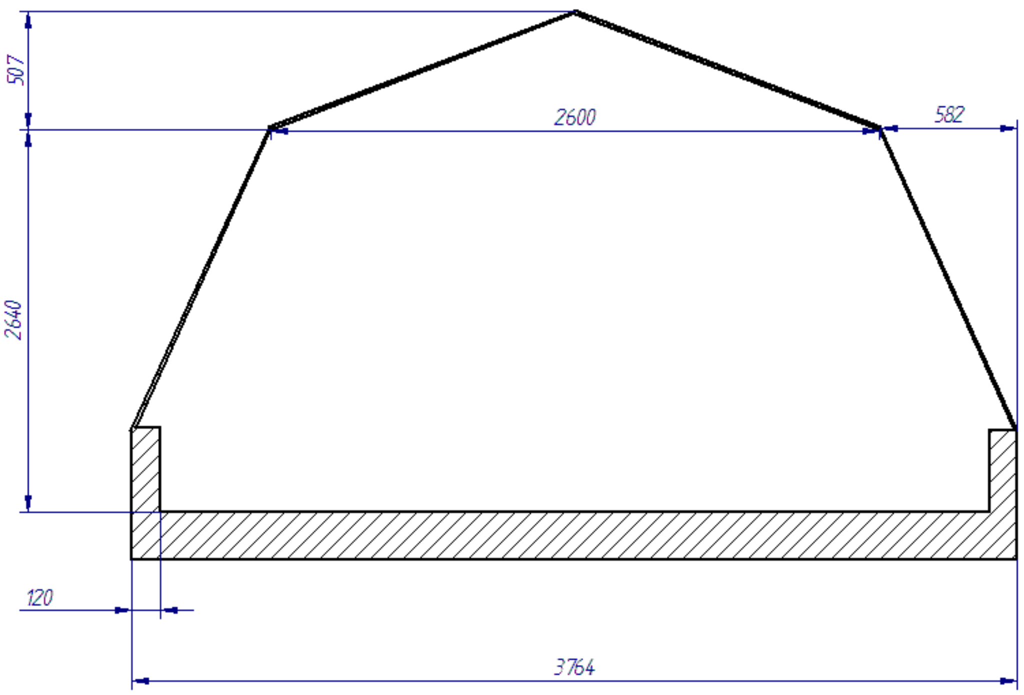

Figure 4. Section greenhouse.

2.1.3. General parts of the greenhouse.

In the present document several parts of the greenhouse are called many times. In this section they are described to clarify their nature.

Cover:

The cover is referred to the glass structure of the actual greenhouse. It is a protective screen between the inside and outside conditions of the greenhouse and it admit a big amount of solar radiation, creating the so called greenhouse effect.

Soil:

It is referring to the plant-clear corridor in the middle of the greenhouse, which properties are different from the growing medium. It is mainly composed of clay and sand.

Growing medium:

It is the ground surface in which plants are planted, presenting higher water contents than the soil. Its composition is a mixture of clay, sand and organic matter (manure).

Crop:

In the greenhouse are planted three or more different kinds of plants in this paper they are considered as only one crop altogether. All plants together are what is called crop.

Inside air:

The inside air is the enclosed volume by the greenhouse. For the thermomechanic assumptions it is supposed to be perfectly mixed or stirred, which means that there is no temperature gradient in it.

Figure 5. Greenhouse Pictures.

2.1.4. Boundary conditions.

The boundary conditions to our interest are only the outside air temperature and the solar radiation received from the sun, both measured in the mentioned station. On the other hand is also necessary like a boundary condition the temperature of soil in a deep of 9 cm. This last measurement of soil temperature was made by a thermo-couple. Also we count with ambient wind speed, atmospheric pressure and relative humidity data from a meteorological station but there is less important for the model.

Outside Air Temperature:

A homogeneous distribution of the outside air temperature all over the cover external surfaces is assumed. The influence of the outside air temperature into the internal conditions will be another point of the analysis that will be carried out.

Solar radiation:

The solar radiation is the main source of energy for the greenhouses. Its influences will be studied in the first section of the analysis chapter, organised in order of relevance.

Radiative properties of the cover will be explained too, as the effect of solar radiation passing through glass and warming a greenhouse is enormous, given that a greenhouse works by reducing airflow, isolating the warm air inside the structure so that heat is not lost by convection.

3. Winter and summer heat balance of greenhouse.

This section will explain step by step the mathematical model of heat transfer. We begin by arguing simplifications needed to use this method of calculation. Later we will verify the validity of the model by comparing actual data and data calculated by the model and a statistical analysis of results.

3.1. Assumptions.

The heat transfer model proposed need some simplification taken into account to help to solve the problem, modifying slightly the real situations but still obtaining reliable behaviors. In this section are listed all these conditions included in the model.

Firstly the generic assumptions for all the heat transfer problems:

- Conduction transfer is one-dimensional.
- Convection and conduction coefficients are constant.
- All surface temperatures are homogeneous.
- The inside and outside air temperatures are homogeneous.
- All heat exchanges are stationary.
- Greenhouse present symmetrical behavior.

The assumptions listed below are particular for the model proposed:

- The greenhouse is long enough to permit one-dimensional analysis
- Conduction through cover, due to its thinness, is negligible. Temperature inside cover and outside cover is the same.
- Vertical front and rear covers are negligible.
- The cover is made only from glass, steel supports are not considered.
- No coefficient has been included to account shading
- The cover surfaces are supposed to be only one summing all areas.
- Four angle geometry of the cover is simplified to one.
- The sky temperature can be approximated by the outside air temperature.
- Internal air has no temperature gradients.
- Internal air has no humidity gradients.

3.2. Summer Model.

The best way to shown how the reality works is by a simplification (*Figure 6*) about the reality. With *Figure 6*, we are ready to describe the basic equations who govern the problem.

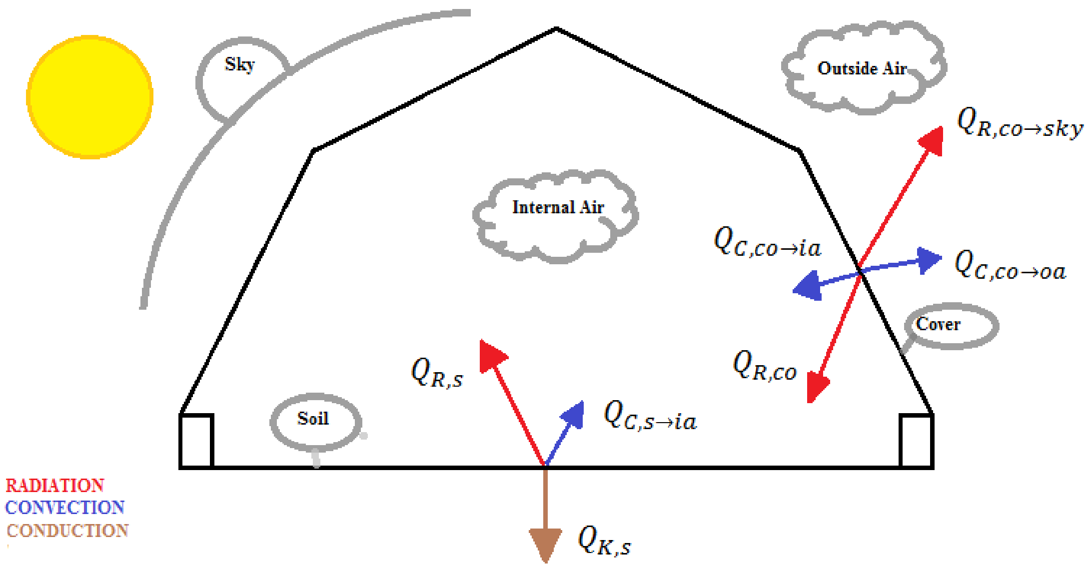

Figure 6. Greenhouse heat profile.

The three parts that are going to be object of the heat transfer model are the cover, the soil and the internal air. In the *Figure 6* we can see that the glass cover is exchanging heat by radiation to the ambient, or outside air, and towards the interior of the greenhouse facing the soil. Then it exchanges by convection to the outside air and the inside air. The soil surface will have only three heat flows, by radiation upwards, by convection to the internal air and by conduction towards underground layers of soil. The internal air would then be affected only by convection from the soil and cover surfaces in first approach, not including for the moment ventilation nor latent exchanges such as plant transpiration, evaporation or condensation.

3.2.1. Heat balances.

The *Figure 6* shown how can be described heat transfer balances for each surface and the inside air. That is, a balance for the cover, one for the soil and finally one for the inside air. These balances will be described below.

Soil surface

There are three heat exchanges, that govern the soil surface balance, go from the soil surface out, which means that summed they might have a value of zero.

$$\boldsymbol{Q_{C,s\rightarrow ia} + Q_{R,s} + Q_{K,s} = 0} \quad (1)$$

Where,

$Q_{C,s\rightarrow ia}$ → Convection exchange from the soil to the inside air.
$Q_{R,s}$ → Amount of radiation that leaves the soil.
$Q_{K,s}$ → Conduction heat that goes underground

Cover surface

Since we consider that the cover thickness is so low that the conduction through it can be neglected, all four arrows from the cover must be included in only one heat balance.

$$\boldsymbol{Q_{C,co\rightarrow ia} + Q_{C,co\rightarrow oa} + Q_{R,co\rightarrow sky} + Q_{R,co} = 0} \quad (2)$$

Where,

$Q_{C,co\rightarrow ia}$ → Convection exchange from the cover to the inside air.
$Q_{C,co\rightarrow oa}$ → Convection exchange from the cover to the outside air.
$Q_{R,co\rightarrow sky}$ → Radiation that leaves the cover towards the sky.
$Q_{R,co}$ → Radiation that leaves the cover inwards the greenhouse.

Inside air

As shown in the *Figure 6* is considered that the air is influenced only by convection from both soil and cover surfaces. These two convective exchanges must be complementary, or what is the same, their sum must result zero. It is assumed that no evaporation, condensation or plant respiration.

$$\boldsymbol{Q_{C,co\rightarrow ia} + Q_{C,s\rightarrow ia} + Q_{vent} = 0} \quad (3)$$

Where,

$Q_{C,co\rightarrow ia}$ → Convection exchange from the cover to the inside air.
$Q_{C,s\rightarrow ia}$ → Convection exchange from the soil to the internal air.
Q_{vent} → Ventilation through the open windows.

3.2.2. Heat fluxes.

Each of the heat fluxes introduced above has its own mathematical expression to obtain its value. In this section are explained how these fluxes will be calculated in the model.

Soil conduction

The soil conduction, considering it as one-dimensional and with a constant conduction coefficient can be modelled as follows.

$$\boldsymbol{Q_{K,s} = \frac{K_s}{z_s} \cdot (T_s - T_{ds})} \quad \left[\frac{W}{m^2}\right] \tag{4}$$

Where,

K_s → coefficient of conduction for the soil in $\left[\frac{W}{m \cdot K}\right]$
T_{ds} → The soil underground temperature at deep z_s $[K]$.
T_s → Temperature of the soil surface $[K]$.
z_s → Deep of the measure of the underground temperature $[m]$.

Convection exchanges

There are three different convection exchanges. Will be explained below.

- ***Soil-internal air***

The convective exchange between the soil and the internal air is modelled through the following equation:

$$\boldsymbol{Q_{C,s \to ia} = h_{C,s \to ia} \cdot (T_s - T_{ia})} \quad \left[\frac{W}{m^2}\right] \tag{5}$$

Where,

$h_{C,s \to ia}$ → Convective coefficient between the soil and the internal air $\left[\frac{W}{m^2 \cdot K}\right]$.
T_s → Temperature of the soil surface $[K]$.
T_{ia} → Temperature of the internal air $[K]$.

- ***Cover-outside air***

The convective exchange between the soil and the internal air is modelled through the following equation:

$$\boldsymbol{Q_{C,co\rightarrow oa} = h_{C,co\rightarrow oa} \cdot (T_{co} - T_{oa})} \quad \left[\frac{\boldsymbol{W}}{\boldsymbol{m^2}}\right] \tag{6}$$

Where,

$h_{C,co\rightarrow oa} \rightarrow$ Convective coefficient between the cover and the outside air $\left[\frac{W}{m^2 \cdot K}\right]$.
$T_{co} \rightarrow$ Temperature of the cover surface $[K]$.
$T_{oa} \rightarrow$ Temperature of the outside air $[K]$.

- ***Cover-inside air***

The convective exchange between the soil and the internal air is modelled through the following equation:

$$\boldsymbol{Q_{C,co\rightarrow ia} = h_{C,co\rightarrow ia} \cdot (T_{co} - T_{ia})} \quad \left[\frac{\boldsymbol{W}}{\boldsymbol{m^2}}\right] \tag{7}$$

Where,

$h_{C,co\rightarrow ia} \rightarrow$ Convective coefficient between the cover and the internal air $\left[\frac{W}{m^2 \cdot K}\right]$.
$T_{co} \rightarrow$ Temperature of the cover surface $[K]$.
$T_{ia} \rightarrow$ Temperature of the internal air $[K]$.

- ***Ventilation***

The heat variation by ventilation is modeled by the next equation.

$$\boldsymbol{Q_{vent} = \frac{V}{A} \cdot \rho \cdot C_p \cdot (T_{ia} - T_{oa})} \quad \left[\frac{\boldsymbol{W}}{\boldsymbol{m^2}}\right] \tag{8}$$

Where,

$V \rightarrow$ Volume of air interchanged $\left[\frac{m^3}{s}\right]$.
$A \rightarrow$ Area of opened windows $[m^2]$.
$\rho \rightarrow$ Density of the air on internal conditions of temperature an pressure $\left[\frac{Kg}{m^3}\right]$.
$C_p \rightarrow$ Heat capacity of interchange or air in given conditions of pressure and temperature $\left[\frac{J}{Kg \cdot K}\right]$.
$T_{oa} \rightarrow$ Temperature of the outside air $[K]$.

T_{ia} → Temperature of the internal air $[K]$.

Where ventilation is modeled following the Boulard and Baille (1995) suggestion for volume of air. Is a simple approximation for greenhouses with only roof or side openings, assuming that pressure and air speed are constant below and above the neutral plane. In this case the ventilation rate is given *equation 9*.

$$\boldsymbol{V = \frac{A}{2} \cdot C_d \cdot \left(2g \cdot \frac{\Delta T}{T_0} \cdot \frac{H}{4} + C_w \cdot v_w{}^2\right)^{0,5} \quad \left[\frac{m^3}{m^2}\right]} \qquad \textbf{(9)}$$

Where,

A → Area of opened windows $[m^2]$.
C_d → Discharge coefficient (0,6 – 0,8) $[-]$.
g → Aceleration of gravity $\left[\frac{m}{s^2}\right]$.
ΔT → Diference of temperature between inside and outside air $[K]$.
T_0 → Reference of temperature. For our study case internal temperature. $[K]$.
H → Height of neutral axis of pressure in the opened windows $[m]$.
C_w → Pressure coefficient of wind (0,071 – 0,14) $[-]$.
v_w → wind speed $\left[\frac{m}{s}\right]$.

<u>Radiation</u>

In this model is tried to be defined as closely to reality as possible, and for that the radiosities method is implemented, which calculates the radiation exchanges from each surface through the radiosities involved in the radiation problem. Since we consider only two radiating surfaces (soil and cover) the radiation problem is simplified.

More simplifications to the above, would remove rigor a model that aims to simulate the behavior of a problem, such as the greenhouse is, governed mainly by radiation.

- ***Shape factors***

The shape factors, or also view factors, are the proportions of all that radiation which leaves each surface and strikes any others. There are several rules that describe the shape factors calculations, and the final shape factors matrix results as follows.

$$\begin{bmatrix} F_{co\to co} & F_{co\to s} \\ F_{s\to co} & F_{s\to s} \end{bmatrix} = \begin{bmatrix} 0,2 & 0,8 \\ 1 & 0 \end{bmatrix}$$

Where,

$F_{co\to co}$ → Fraction of radiation that leaves the cover that goes to the cover $[-]$.
$F_{co\to s}$ → Fraction of radiation that leaves the cover that goes to the soil $[-]$.
$F_{s\to co}$ → Radiation that leaves the soil and goes to the cover $[-]$.
$F_{s\to s}$ → Radiation that leaves the soil and goes to the soil again $[-]$.

- ***Radiosities***

The radiosity is a convenient quantity in heat transfer that represents the total radiation intensity leaving a surface, accounting for two components: the radiation being emitted by the surface and the radiation being reflected from the surface. In heat transfer, combining these two factors into one radiosity term helps in determining the net energy exchange between surfaces, which will be obtained in the upcoming subsection. Radiosities in this certain heat transfer set out model for cover and soil are obtained with the following expressions.

Cover:

$$J_{co} = \varepsilon_{co} \cdot \sigma \cdot {T_{co}}^4 + (1 - \varepsilon_{co}) \cdot [F_{co\to co} \cdot J_{co} + F_{co\to s} \cdot J_s] \quad \left[\frac{W}{m^2}\right] \qquad \textbf{(10)}$$

The cover radiosity is included in both terms of the equation. This simple fact makes the mathematical solver tool dull, because of the numerical solver algorithms. In order to avoid these problems the expression for the cover radiosity was reset as follows.

$$\boldsymbol{J_{co} = \frac{\varepsilon_{co} \cdot \sigma \cdot {T_{co}}^4 + (1 - \varepsilon_{co}) \cdot [F_{co\to s} \cdot J_s]}{1 - (1 - \varepsilon_{co}) \cdot F_{co\to co}} \quad \left[\frac{W}{m^2}\right]} \qquad \textbf{(11)}$$

Where,

ε_{co} → emissivity of the cover $[-]$.
σ → Stefan-Boltzman constant in $\left[\frac{W}{m^2 \cdot K^4}\right]$.
T_{co} → Temperature of cover $[K]$.
$F_{co\to s}$ → Fraction of radiation that leaves the cover that goes to the soil $[-]$.
$F_{co\to co}$ → Fraction of radiation that leaves the cover that goes to the cover $[-]$.
J_s → Soil Radiosity $\left[\frac{W}{m^2}\right]$.

Soil:

The soil radiosity has an expression similar to the previous one, but it also takes into account the solar radiation that goes inside the greenhouse, which at the same time considers the cover transmissivity. The final expression included in the model to obtain the soil radiosity is as follows.

$$J_s = \varepsilon_s \cdot \sigma \cdot T_s{}^4 + (1 - \varepsilon_s) \cdot [F_{s \to co} \cdot J_{co} + \tau_{SRco} \cdot SR] \quad \left[\frac{W}{m^2}\right] \qquad (12)$$

Where,

$\varepsilon_s \rightarrow$ Emissivity of the soil $[-]$.
$\sigma \rightarrow$ Stefan-Boltzman constant in $\left[\frac{W}{m^2 \cdot K^4}\right]$.
$T_s \rightarrow$ Temperature of the soil $[K]$.
$F_{s \to co} \rightarrow$ Fraction of radiation that leaves the soil that goes to the cover $[-]$.
$\tau_{SRco} \rightarrow$ Transmissivity of the cover for solar radiation wave lengths $[-]$.
$SR \rightarrow$ Solar radiation$[-]$.
$J_{co} \rightarrow$ Cover Radiosity $\left[\frac{W}{m^2}\right]$.

- ***Heat Exchanges***

Three radiation fluxes were drew in the arrows diagram, the radiation that goes from the cover outwards doesn't need to have a previous radiosity calculation. Once the radiosities for the radiative surfaces are obtained, the real radiation heat exchanges can be obtained.

Cover outwards:

The outwards radiation flux from the cover is modelled with the following expression.

$$Q_{R,co \to sky} = \varepsilon_{co} \cdot \sigma \cdot \left(T_{co}{}^4 - T_{oa}{}^4\right) \quad \left[\frac{W}{m^2}\right] \qquad (13)$$

Where,

$\varepsilon_{co} \rightarrow$ Emissivity of cover $[-]$.
$\sigma \rightarrow$ Stefan-Boltzman constant in $\left[\frac{W}{m^2 \cdot K^4}\right]$.
$T_{co} \rightarrow$ Temperature of the cover $[K]$.
$T_{oa} \rightarrow$ Temperature of outside air $[K]$.

Cover inwards:

This flux is determined with this equation:

$$\boldsymbol{Q_{R,co} = \varepsilon_{co} \cdot \sigma \cdot T_{co}{}^4 - \varepsilon_{co} \cdot [F_{co\to co} \cdot J_{co} + F_{co\to s} \cdot J_s]} \quad \left[\frac{W}{m^2}\right] \tag{14}$$

Where,

ε_{co} → Emissivity of cover $[-]$.
σ → Stefan-Boltzman constant in $\left[\frac{W}{m^2 \cdot K^4}\right]$.
T_{co} → Temperature of the cover $[K]$.
$F_{co\to co}$ → Fraction of radiation that leaves the cover that goes to the cover $[-]$.
J_{co} → Cover Radiosity $\left[\frac{W}{m^2}\right]$.
$F_{co\to s}$ → Fraction of radiation that leaves the cover that goes to the soil $[-]$.
J_s → Soil Radiosity $\left[\frac{W}{m^2}\right]$.

Soil upwards

This equation is simpler because the soil can't see itself.

$$\boldsymbol{Q_{R,s} = \varepsilon_s \cdot \sigma \cdot T_s{}^4 - \varepsilon_s \cdot J_{co}} \quad \left[\frac{W}{m^2}\right] \tag{15}$$

Where,

ε_s → Emissivity of soil $[-]$.
σ → Stefan-Boltzman constant in $\left[\frac{W}{m^2 \cdot K^4}\right]$.
T_s → Temperature of the soil $[K]$.
J_{co} → Cover Radiosity $\left[\frac{W}{m^2}\right]$.

3.2.3. Constants.

Several constants have to be set to have numerical resolution of the model.

- $\sigma = 5{,}670373 \cdot 10^{-8}$ $\left[\frac{W}{m^2 \cdot K^4}\right]$ (Stefan-Boltzman constant)
- $K_s = 0{,}11$ $\left[\frac{W}{m \cdot K}\right]$ (Soil conductivity)
- $z_s = 0{,}09$ $[m]$ Soil measured depth
- $\varepsilon_s = 0{,}9$ $[-]$ (Soil emissivity)
- $\varepsilon_{co} = 0{,}3$ $[-]$ (Cover emissivity)
- $\tau_{SRco} = 0{,}8$ $[-]$ (Cover transmisivity for solar radiation)

Transmisivity and emissivities values are typical ones for the materials considered. The Stefan-Boltzman constant is given in the SI units. Soil conductivity is considered independent of the water content and its measured depth is the real one.

3.2.4. Convective coefficients.

The only parameters unknown for the moment are the convective coefficients. In this section is explained the procedure followed to obtain these coefficients. There is data to obtain it by calculation with the previous model but the result is not good, so convective coefficients will be calculated by analytical expressions.

Soil-internal air

This first convective coefficient is obtained through empirical equations approximation. It is considered a free convective exchange from the top of a horizontal surface.

$$h_{C,s\to ia} = Nu_{C,s\to ia} \cdot \frac{K_{ia}}{L_{C,s\to ia}} \quad \left[\frac{W}{m^2 \cdot K}\right] \tag{16}$$

$$Nu_{C,s\to ia} = 0{,}285 \cdot \left(Ra_{C,s\to ia}\right)^{1/4}$$

$$Ra_{C,s\to ia} = Pr \cdot Gr_{C,s\to ia}$$

$$Gr_{C,s\to ia} = \frac{g \cdot \beta_{ia} \cdot (T_s - T_{ia}) \cdot L_{C,s\to ia}{}^3}{\vartheta_{ia}}$$

$$L_{C,s\to ia} = \frac{A}{P}$$

$$\beta_{ia} = \frac{1}{T_{ia}}$$

$$Pr$$

$$K_{ia}$$

$$L_{C,s\to ia} = \frac{A}{P}$$

Where,

$Nu_{C,s\to ia}$ → Nusselt number.

K_{ia} → Air conductivity $\left[\frac{W}{m \cdot K}\right]$.

$L_{C,s\to ia}$ → Characteristic length.

$Ra_{C,s\to ia}$ → Rayleigh number.

$Gr_{C,s\to ia}$ → Grasshoff number.

Pr → Prandtl number.

β_{ia} → volumetric expansion coefficient of the air $\left[\frac{1}{K}\right]$.

T_s → Soil temperature $[K]$.

T_{ia} → Internal air temperature $[K]$.

ϑ_{ia} → Air kinematic viscosity $\left[\frac{m^2}{s}\right]$.

A →Area of soil surface $[m^2]$.

P →Perimeter of soil surface$[m]$.

g →Acceleration of gravity $\left[\frac{m}{s^2}\right]$.

The model was executed for 96 different points from the collected data, obtaining values that go from 0 up to 2 $\left[\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}\right]$, with an average of 1,509 that we smooth to 1,5 $\left[\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}\right]$, including this value for the upcoming models.

Cover-internal air

This parameter will be obtained analogously to the previous coefficient obtain, with a free convection under inclined surface correlation as follows.

$$h_{C,co\rightarrow ia} = Nu_{C,co\rightarrow ia} \cdot \frac{K_{ia}}{L_{C,co\rightarrow ia}} \quad \left[\frac{W}{m^2 \cdot K}\right] \tag{17}$$

$$Nu_{C,co\rightarrow ia} = 0{,}75 \cdot \left(Ra_{C,co\rightarrow ia}\right)^{1/4}$$

$$Ra_{C,co\rightarrow ia} = Gr_{C,co\rightarrow ia} \cdot Pr_{ia} \cdot cos\left(\frac{75+22}{2}\right)$$

$$Gr_{C,co\rightarrow ia} = \frac{g \cdot \beta_{ia} \cdot (T_{co} - T_{ia}) \cdot L_{C,co\rightarrow ia}{}^{3}}{\vartheta_{ia}}$$

$$L_{C,co\rightarrow ia} = \frac{A}{P}$$

$$\beta_{ia} = \frac{1}{T_{ia}}$$

$$Pr_{ia}$$

$$K_{ia}$$

$$L_{C,s\rightarrow ia} = \frac{A}{P}$$

Where,

$Nu_{C,co\rightarrow ia}$ → Nusselt number.

K_{ia} → Air conductivity $\left[\frac{W}{m\cdot K}\right]$.
$L_{C,co\rightarrow ia}$ → Characteristic length.
$Ra_{C,co\rightarrow ia}$ → Rayleigh number.
$Gr_{C,co\rightarrow ia}$ → Grasshoff number.
Pr → Prandtl number.
β_{ia} → Volumetric expansion coefficient of the air $\left[\frac{1}{K}\right]$.
T_{co} → Cover temperature $[K]$.
T_{ia} → Internal air temperature $[K]$.
ϑ_{ia} → Air kinematic viscosity $\left[\frac{m^2}{s}\right]$.
A →Area of cover surface $[m^2]$.
P →Perimeter of cover surface$[m]$.
g →Acceleration of gravity $\left[\frac{m}{s^2}\right]$.

The model was executed for 96 different points from the collected data, obtaining values that go from 0 up to 2,423 $\left[\frac{\mathrm{W}}{\mathrm{m^2\cdot K}}\right]$, with an average of 1,436 that we smooth to 1,5 $\left[\frac{\mathrm{W}}{\mathrm{m^2\cdot K}}\right]$, including this value for the upcoming models.

Cover-outside air

This parameter will be obtained analogously to the previous coefficient obtain, with a mixed convection on top of surface correlation as follows.

$$h_{C,co\rightarrow oa} = Nu_{C,co\rightarrow oa} \cdot \frac{K_{oa}}{L_{C,co\rightarrow oa}} \quad \left[\frac{W}{m^2\cdot K}\right] \tag{18}$$

- $Nu_{C,co\rightarrow oa} = 1{,}38 \cdot \left(Ra_{C,co\rightarrow oa}\right)^{\frac{1}{4}}$
  - $Ra_{C,co\rightarrow ia} = Gr_{C,co\rightarrow oa} \cdot Pr_{oa}$
    - $Gr_{C,co\rightarrow oa} = \frac{g\cdot\beta_{oa}\cdot(T_{co}-T_{oa})\cdot L_{C,co\rightarrow oa}{}^3}{\vartheta_{oa}}$
      - $L_{C,co\rightarrow oa} = \frac{A}{P}$
      - $\beta_{oa} = \frac{1}{T_{oa}}$
    - Pr_{oa}
- K_{oa}
- $L_{C,co\rightarrow oa} = \frac{A}{P}$

Where,

$Nu_{C,co \to oa}$ → Nusselt number.
K_{oa} → Air conductivity $\left[\frac{W}{m \cdot K}\right]$.
$L_{C,co \to oa}$ → Characteristic length.
$Ra_{C,co \to oa}$ → Rayleigh number.
$Gr_{C,co \to oa}$ → Grasshoff number.
Pr → Prandtl number.
β_{oa} → Volumetric expansion coefficient of the air $\left[\frac{1}{K}\right]$.
T_{co} → Cover temperature $[K]$.
T_{oa} → External air temperature $[K]$.
ϑ_{oa} → Air kinematic viscosity $\left[\frac{m^2}{s}\right]$.
A →Area of cover surface $[m^2]$.
P →Perimeter of cover surface$[m]$.
g →Acceleration of gravity $\left[\frac{m}{s^2}\right]$.

The model was now executed for 96 different points from the collected data, obtaining values that go from 0 up to 5,061 $\left[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}\right]$, with an average of 2,966 that we smooth to 3 $\left[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}\right]$, including this value in the upcoming models.

3.2.5. Summary of the model: Inputs-outputs.

Now that all parameters have been defined to decide which variables are inputs and which ones will be outputs from the calculations.

This is a versatile model, so we can choose the input parameters and output as desired. The parameters should be selected depending on the objective of the calculation. Obviously, as the first model should be defined as input parameters the more general boundary conditions, which are: solar radiation, underground soil temperature and outside air temperature.

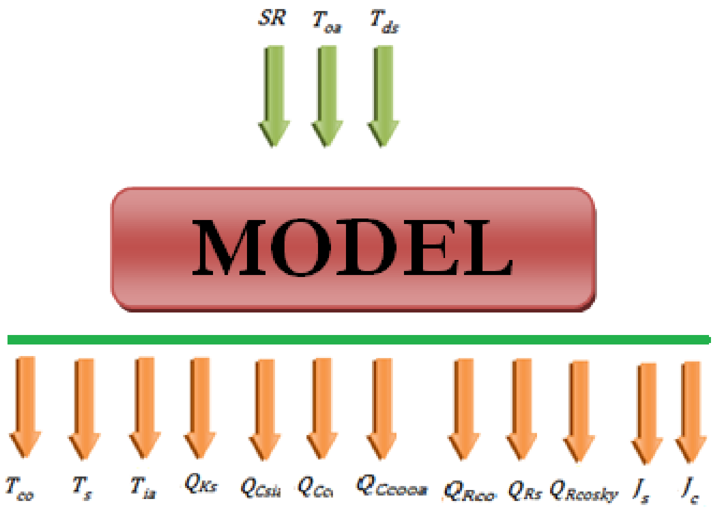

Figure 7. Inputs-Outputs.

3.3. Winter Model.

The winter model follows the same principle as the summer model. The main difference between them is the winter model could be developed to include heating systems to produce the conditions that plants need to grow up like in summer time and there is no ventilation because of the very cold conditions outside. A basic schema of heating flows interchange is shown in the *Figure 8*.

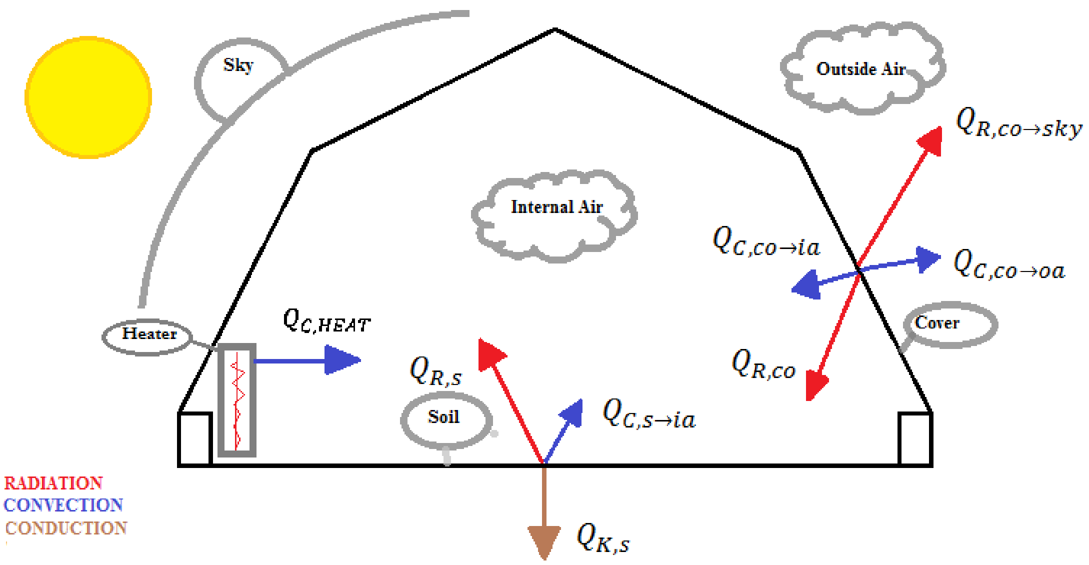

Figure 8. Greenhouse heat winter profile.

The novelty compared with the previous model is an inclusion, in the internal heat convection interchange, a heater. In winter season the ventilation is avoid so is not taking in account.

3.3.1. Heat balances.

The *Figure 8* shown the heat transfer balances for each surface and the inside air. That is, a balance for the cover, one for the soil and finally one for the inside air. These balances will be described below.

Soil surface

There are three heat exchanges, that govern the soil surface balance, go from the soil surface out, which means that summed they might have a value of zero.

$$\boldsymbol{Q_{C,s\rightarrow ia} + Q_{R,s} + Q_{K,s} = 0} \qquad \textbf{(19)}$$

Where,

$Q_{C,s\rightarrow ia}$ → Convection exchange from the soil to the inside air.
$Q_{R,s}$ → Amount of radiation that leaves the soil.
$Q_{K,s}$ → Conduction heat that goes underground

Cover surface

Since we consider that the cover thickness is so low that the conduction through it can be neglected, all four arrows from the cover must be included in only one heat balance.

$$\boldsymbol{Q_{C,co\rightarrow ia} + Q_{C,co\rightarrow oa} + Q_{R,co\rightarrow sky} + Q_{R,co} = 0} \qquad \textbf{(20)}$$

Where,

$Q_{C,co\rightarrow ia}$ → Convection exchange from the cover to the inside air.
$Q_{C,co\rightarrow oa}$ → Convection exchange from the cover to the outside air.
$Q_{R,co\rightarrow sky}$ → Radiation that leaves the cover towards the sky.
$Q_{R,co}$ → Radiation that leaves the cover inwards the greenhouse.

Inside air

As shown in the *Figure 8* is considered that the air is influenced only by convection from both soil and cover surfaces. These two convective exchanges must be complementary, or what is the same, their sum must result zero. It is assumed that no evaporation, condensation or plant respiration.

$$\boldsymbol{Q_{C,co\rightarrow ia} + Q_{C,s\rightarrow ia} + Q_{C,HEAT} = 0} \tag{21}$$

Where,

$Q_{C,co\rightarrow ia}$ → Convection exchange from the cover to the inside air.
$Q_{C,s\rightarrow ia}$ → Convection exchange from the soil to the internal air.
$Q_{C,HEAT}$ → Convection exchange from heater to the internal air.

3.3.2. Heat fluxes.

Each of the heat fluxes introduced above has its own mathematical expression as we explained before in the Summer balance. For that this part is mostly omitted. The only point that is necessary to explain is the convection exchange from heater to the internal air ($Q_{C,HEAT}$).

This convection exchange from heater to the internal air represents the amount of heat necessary to include in the greenhouse to keep inside preset conditions like temperatures of internal air, cover or soil.

The behavior of the Heater is unknown because it depends on the manufacter, but the amount of heat per square meter of interchange will be known by this model. With this value is easy to find any commercial solution with fits perfectly with the characteristics of the greenhouse. Note that there is no heater system installed in the greenhouse.

3.3.3. Summary of the model: Inputs-outputs.

All parameters have been defined and obtained following the same steps as in summer model. Is time to decide which variables are inputs and which ones will be outputs from calculations.

This is a versatile model, so we can choose the input parameters and output as desired. Obviously, is a winter model so the boundary conditions of temperature and solar radiation are known from a meteorological station. The main functionality of this model is to set the internal temperature and decide how much heat is necessary to introduce in the greenhouse to keep it. Then

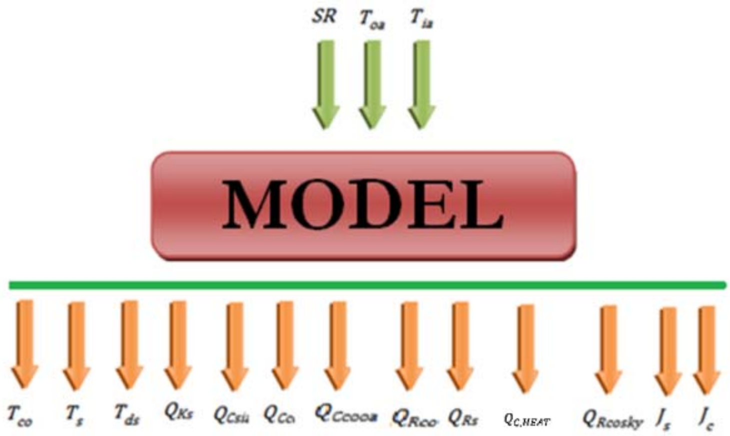

Figure 9. Inputs-Outputs Winter model.

3.4. Model validation.

In this section the validity and reliability of the model will be evaluated.

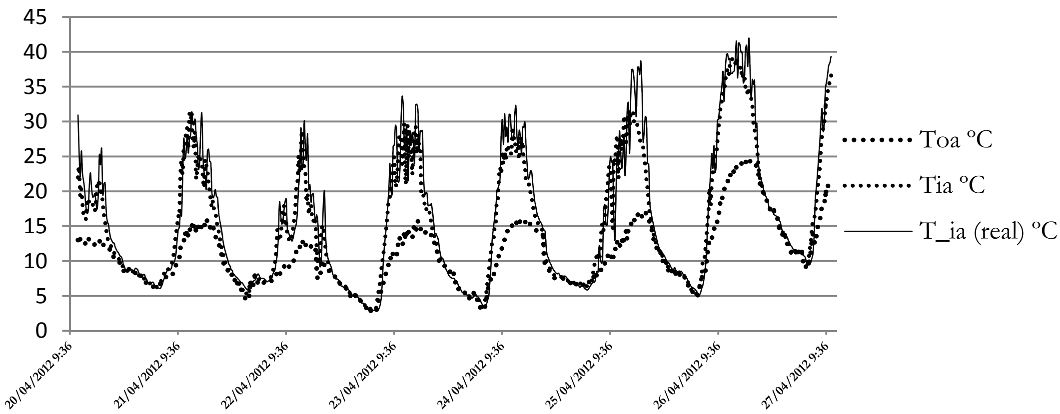

Figure 10. Inside-Outside Temperatures Comparison.

Analyzing the graph above, which represent the actual measured variables directly in the greenhouse such as outside air temperature and actual inside temperature is compared with the inside temperature calculated using the model. It notes that follow the same behavior and simulates very well the reference measurements, which leads us to believe that the behavior of the model is valid.

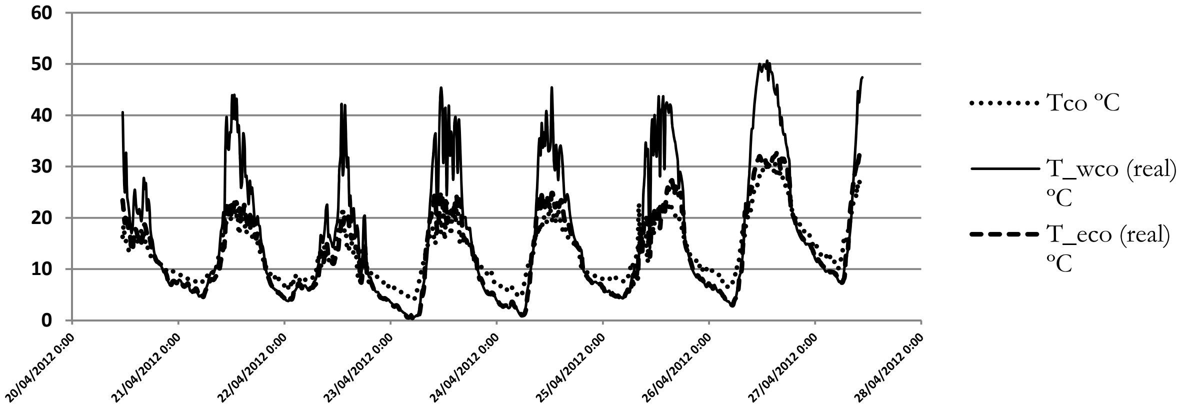

Figure 10. Cover Temperatures Comparison.

Analyzing the last graph, the calculated cover temperature also has closer values to the real east cover temperatures measured, despite the systematic difference during night hours in both models, when the calculated values are over the real ones. This last observation may be fixed if the model is improved in latent heat balances, because as seen previously in almost all the mornings condensation occurred, affecting strongly the cover temperatures.

Considered the previous analysis is possible to determine that the model is valid and is able to copy the reality of the greenhouse very accurate.

4. Experimental measurement.

4.1. Data acquisition process.

Our intention was to record as much data as possible, including temperatures, radiation, humidity and CO_2 emissions before creation a mathematical model, to know the result that our model have to give. For that, the measuring equipment was placed from April the 20th until 27th. We used measuring equipment to get certain values from the greenhouse and we also used data provided by the Agrobiology faculty meteorological station (Agrobiologie MeteoStanice).

Sensitive parts of the installation were protected with plastic bags, to avoid water infiltration or contact when irrigation systems were working to avoid electric risk of short circuit, all over the data logger back side where every sensor is plugged and uncovered wires. The measuring devices were allocated as shown in the *Figure 10*:

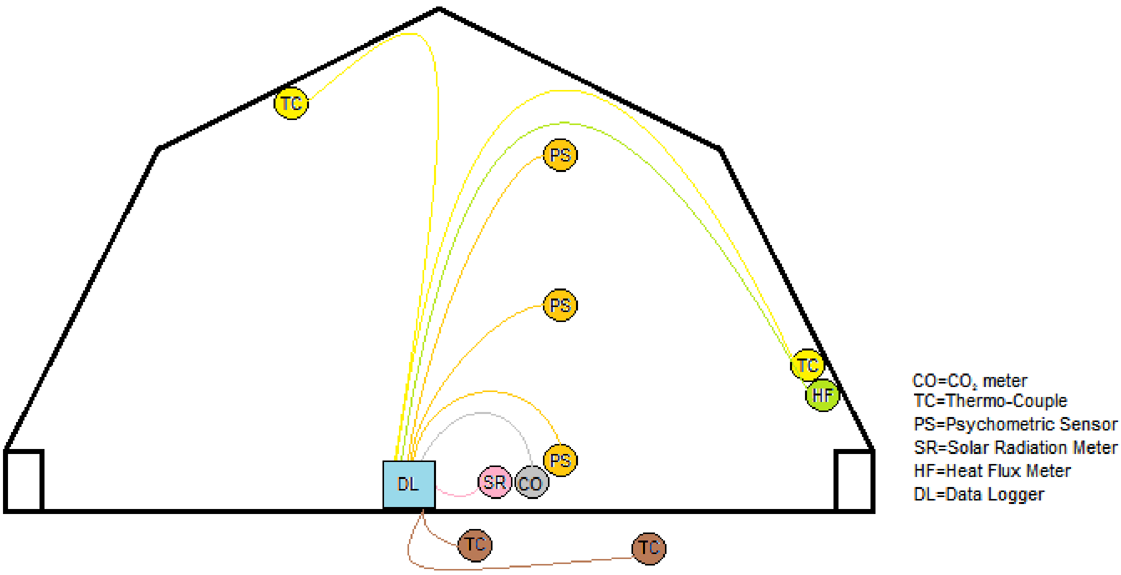

Figure 12. Location sensors and measuring instruments.

4.1.1. Equipment used

<u>Data logger</u>

A data logger is an electronic device that records data over time or in relation to location either with a built in instrument or sensor or via external instruments and sensors. Increasingly, but not entirely, they are based on a digital processor (or computer). They generally are small, battery powered, portable, and equipped with a microprocessor, internal memory for data storage, and sensors. Some data loggers interface with a personal computer

Figure 13.-Ahlborn Almelo 5990.

and utilize software to activate the data logger and view and analyze the collected data, while others have a local interface device (keypad, LCD) and can be used as a stand-alone device.

The data logger model used was Alhborn Almemo 5990, and it was programmed to record all the information each 15 minutes.

Temperature sensors

A number of seven temperature sensors were placed for the measuring. We decided to use soil buried sensors, air sensors and sensors fixed to the glass cover. All of them measure the temperatures in Celsius degrees.

- ***Psychometric sensors***

Psychometric sensors are very useful, since they record not only the temperature but also the dew point and humidity of the surrounding air. We used three psychometric sensors distributed at different heights (15, 105 and 165 cm) placed on the same top-view spot

Figure 14.-Psychometric sensors.

- ***Thermocouples***

A thermocouple is a device consisting of two different conductors (usually metal alloys) that produce a voltage, proportional to a temperature difference, between either ends of the two conductors. Thermocouples are a widely used type of temperature sensor for measurement and control and can also be used to convert a temperature gradient into electricity. They are inexpensive, interchangeable, are supplied with standard connectors, and can measure a wide range of temperatures. In contrast to most other methods of temperature measurement, thermocouples are self powered and require no external form of excitation. The main limitation with thermocouples is accuracy, specifically, system errors of less than one degree Celsius can be difficult to achieve.

Figure 15.-Buriable Thermo-couple.

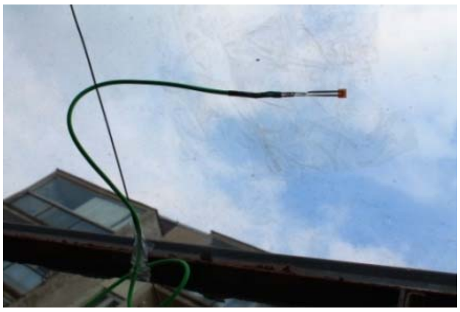

Figure 11.-Fixable Thermo-couple.

Two different types of thermo-couples were used: buriable thermo-couples, to obtain soil temperatures; and fixable thermo-couples, which we placed on the cover surfaces. The buriable sensors were buried one in the walkable corridor ground and another one in the growing medium where plants are planted. The fixable thermo-couples were placed one on the west side cover and another one on the east side cover with the help of cellophane tape.

<u>Radiation sensor</u>

The solar radiation meter seen in the photograph was placed in the greenhouse, with the only purpose of monitoring the radiation levels inside compared with the values from the meteorological station. It provides the measures directly in watts per square meter unit.

Figure 12.-Radiation sensor

<u>Heat flux meter</u>

A heat flux sensor is a transducer that generates an electrical signal proportional to the total heat rate applied to the surface of the sensor. The measured heat rate is divided by the surface area of the sensor to determine the heat flux.

With the aim of contrasting calculations a heat flux meter was placed in the east side of the greenhouse, recording in W/m^2 units the exchange through the glass wall. If the recorded values are positive it means that the flux goes from the cover to the inside part and if negatives the contrarily way.

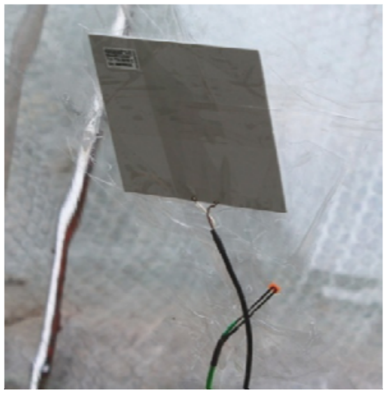

Figure 18.-Heat flux meter.

<u>Air speed meter</u>

Additionally we measured air speeds in many different spots along the greenhouse openings to get some information about the air velocity distribution. We used a thermo-wire air speed meter.

Figure 19.-Air speed meter.

Thermocamera

A thermographic camera or infrared camera is a device that forms an image using infrared radiation, similar to a common camera that forms an image using visible light. Instead of the 450–750 nanometer range of the visible light camera, infrared cameras operate in wavelengths as long as 14,000 nm.

Figure 20.-Thermocamera.

The thermo-camera was used to define a profile of temperature in all greenhouse. Was an estimation of the temperature distribution for a comparison of model and reality. The model used was IR FlexCam.

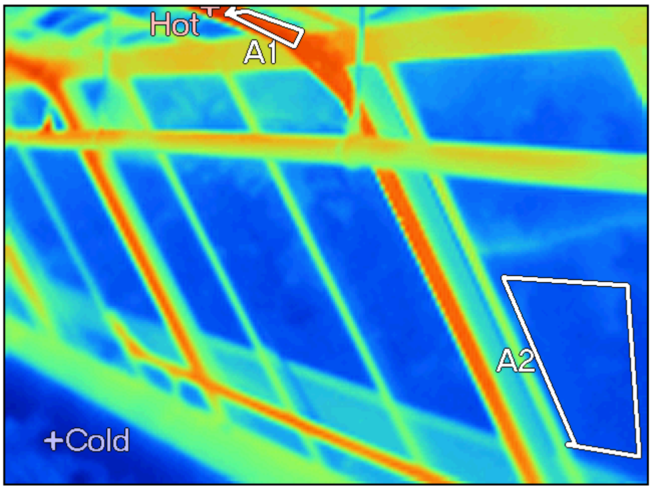

Figure 21. Thermal Image inside Greenhouse.

4.1. 2. Data Handling

Before of data handling and analysis the raw data have to be observed and filtered, trying to find out possible errors in the variables measured. Filtering refers to the process of defining, detecting and correcting errors in given data, in order to minimize the impact of errors in input data on succeeding analyses. In the following sections the filtering changes made are explained.

4.1.3. Data logger times

The data acquisition system (data logger) is scheduled to take measurements every 15 minutes. Therefore, for data manipulation using Excel, we have all the variables referenced to an instant of time. In turn, the Meteo-station data were also taken every 15 minutes, making it possible to include them in the same excel sheet. The only exception is with the solar radiation data as they are taken every 10 minutes. By interpolation of the values we obtain for XX.15 (from xx.10 and XX.20) and the same process for XX.45 values (from XX.30 and XX.50). In this case we have to make a manipulation of the units to have all units W/m^2, the process will be explained later.

4.1.4. Solar radiation negative values

The original solar radiation figures taken from the greenhouse showed several negative radiation values during night hours. This is not possible, so we considered that there were errors in the sensor or in the night compatibility between sensor and logger, so we simply erased these negative values, converting them into zeros.

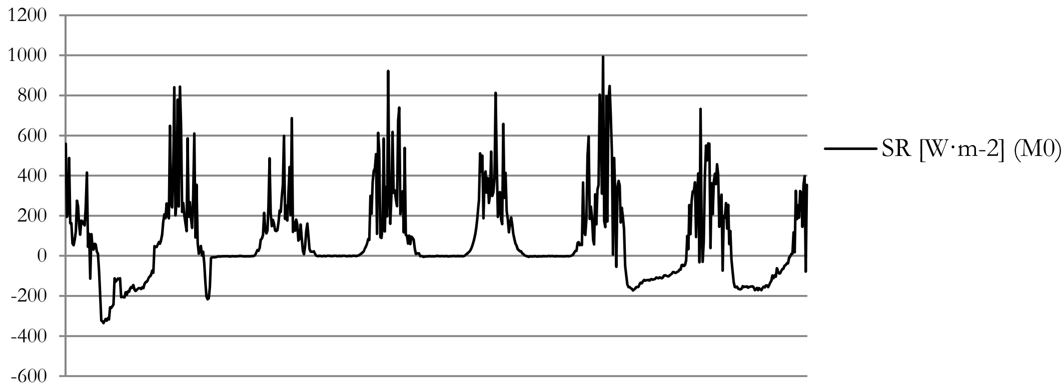

Figure 22. Solar radiation measured inside Greenhouse.

4.1.5. Meteo-station solar radiation units.

The solar radiation data taken from the weather station is provided in $\left[\frac{kJ}{m^2 \cdot 10min}\right]$ units. This needed a conversion into W/m^2.

$$\left[\frac{kJ}{m^2 \cdot 10min}\right] \cdot 1000\frac{J}{KJ} \cdot 600\frac{s}{10\ min} = \left[\frac{W}{m^2}\right]$$

4.1.6. Psychometric sensor

The sensor placed at 105 cm. height third measured parameter (dew point) failed. Temperature and relative humidity were correctly recorded, but an error happened in this measure, so was no possible to make a verification of the dew point from experimental data and from analytic data.

4.2. Analysis of measured data

This section will be analyzed the results of measurements in the greenhouse to understand its behavior, and to propose a model that fits the observed reality.

4.2.1. Solar Radiation.

In the *Figure 23* are plotted the measured solar radiation with our equipment inside the greenhouse and the solar radiation outside the greenhouse, took from the MeteoStanice.

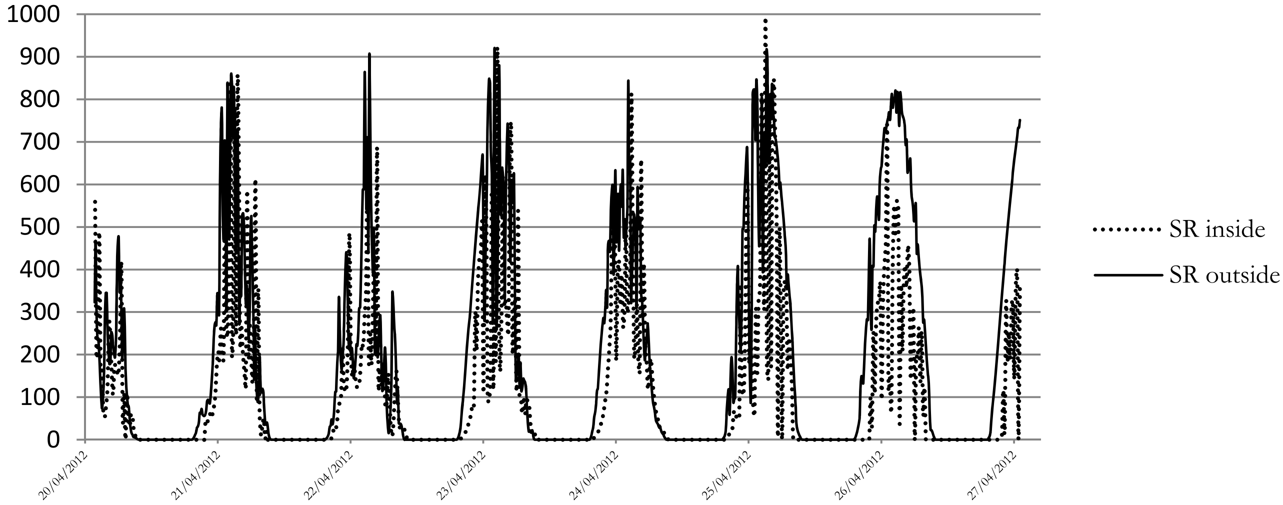

Figure 23. Solar radiation comparion Inside-outside.

In the *Figure 23* we can see that it satisfies the same pattern of solar radiation, leading us to ensure that both measurements are influenced by the same weather conditions while not accurately measured in the same place.

Another remarkable detail is that there are some occasions where the values of radiation inside the greenhouse are higher than measured values at the meteorological station, so it made no sense. This may be due because of a cloud that previously affected the external sensor to the inside of the greenhouse. On the other hand one we can see peaks of radiation inside the greenhouse, this is simply due to measurement errors having no apparent explanation.

4.2.2. Temperatures.

Most of the parameters measured were temperature, are the best indicators of what is happening in the greenhouse. Using graphs, we can interpret the evolution of the parts involved in the exchange of heat or points of contrast of different measures. In this section some assumptions can be chosen to simplify the model are properly justified. Subsequently, in the section of calculations, these parameters are compared again, but with the calculated time.

Inside-Outside air

The outside air values were taken from the MeteoStanice data. The inside air was measured at three different levels. The temperature measured at the medium height (105 cm) is considered as the representative value of the inside air temperature. Taking this into account this inside temperature at medium level (total height of the greenhouse is 2,10 m) is represented with the ambient temperature surrounding the greenhouse.

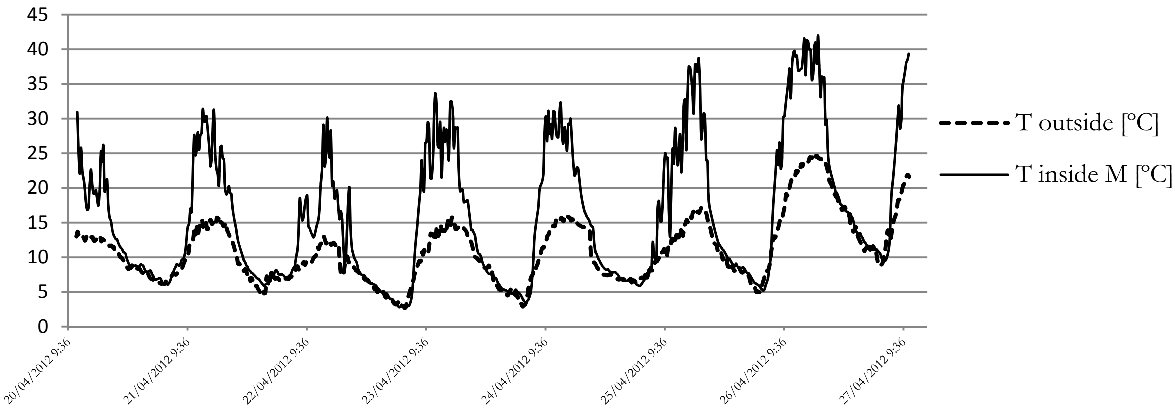

Figure 24. Temperature comparison outside-inside.

These temperatures are influenced of the solar radiation during the day, being then smoothed within no light hours. With the sun shining the area, the inside temperature rises up much more than the outside temperature, simply because of the greenhouse effect (is why greenhouse are used), even though natural ventilation is happening. During the night the inside temperature tends to be closer to the outside temperature because radiation exchanges are very small, so the main relation during night hours are the convective exchanges inside and outside the cover.

Soil-Growing medium

What we can infer from the *Figure 25* is that the soil responds much more smoothly than the growing medium, which is explained by the higher content of water and the influence of the plants. If the growing medium is not properly watered by irrigation system, then it will behaves more like the soil. In other hand, the soil surface is warmer than the growing medium, also because of the humidity difference, so the growing medium is highly affected by its humidity in terms of evaporation, reducing its temperature.

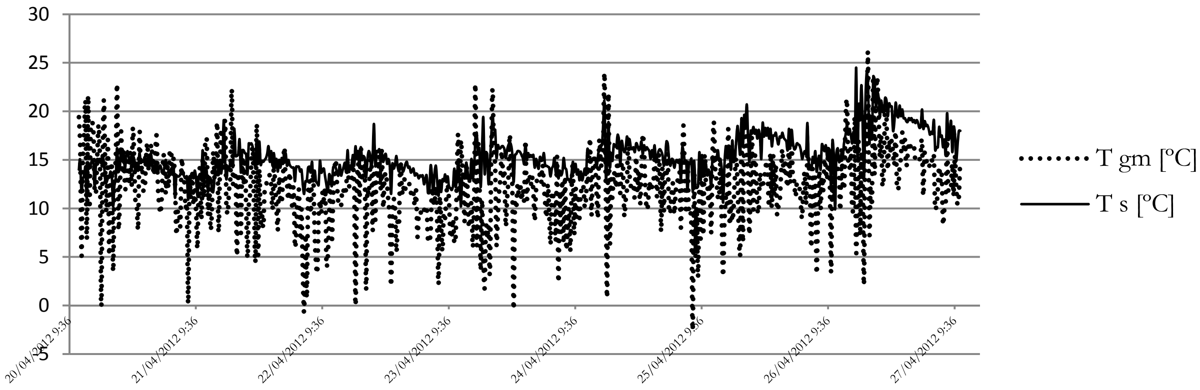

Figure 25. Temperature comparison growing medium-soil.

East-West cover

In this section are displayed the cover temperatures measured at the glass in the east and west side for the whole week.

The thermocouples fixed to the cover in both east and west side showed a very different temperature evolution. A factor that may help to understand this is that the thermocouple fixed to the west cover was placed almost at the top of the glass cover, not only about a meter higher, but also with an inclination that could be directly affected by the sun heat, so it is not a representative parameter as the temperature of the cover.

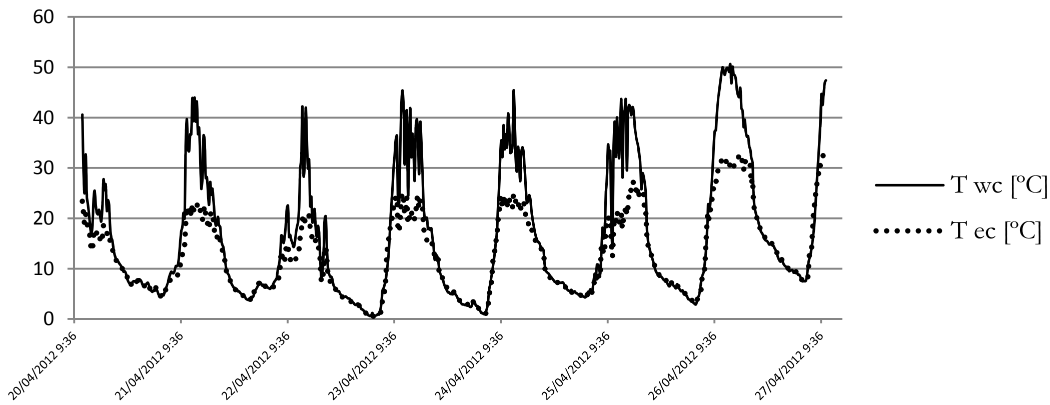

Figure 26. Temperature comparison east-west cover.

4.2.3. Cover-Heat Flux.

This section shows the measured heat flux through the wall with the cover temperatures measured in both east and west sides during the week.

During night hours the heat flux is almost constant from the inside to the outside, affected only by convection. During daytime it presents a pattern, positive values until about midday and from then on negative values, describing a linear negative slope along the day.

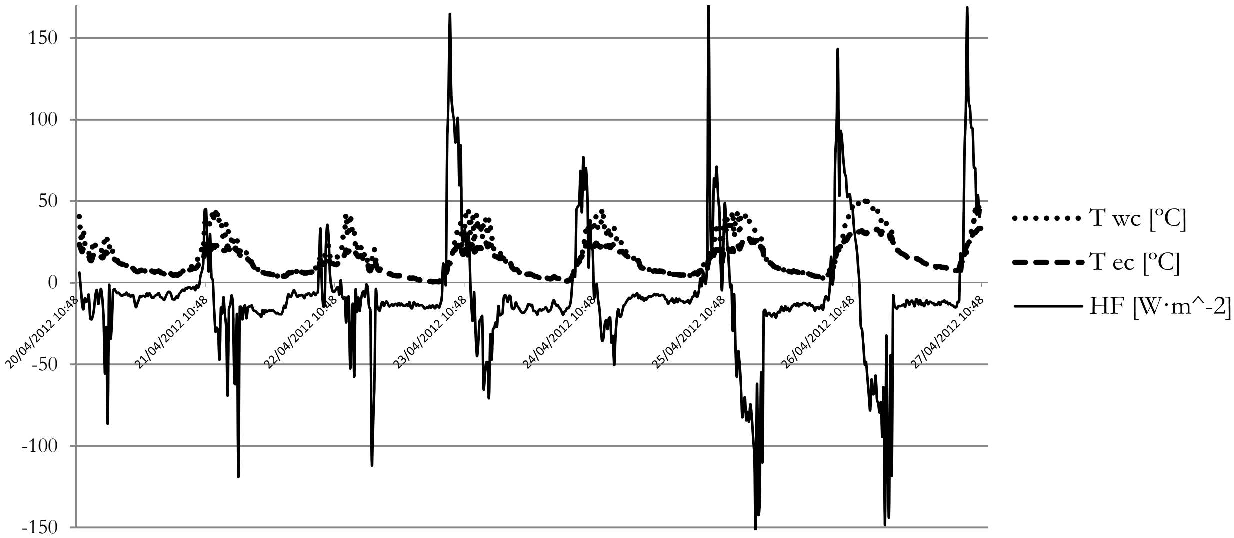

Figure 27. Temperature comparison east-west cover and heat flux.

With a closer view of the behavior for only one day we will understand how this greenhouse works.

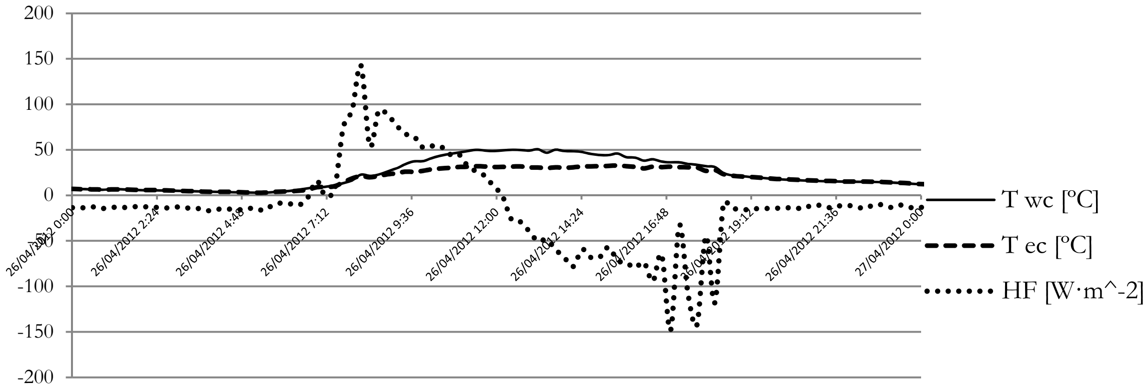

Figure 28. Temperature comparison east-west cover and heat flux for day 26th April 2012.

The heat flux increased very much as the sun starts to shine in the morning, reaching a peak about 8:00, when the cover temperature increase with the time is slowed. Since then on, as the cover temperature is starting to be more stable, the heat flux starts to decrease, describing a linear progression with the pass of time. About midday the heat flux is inverted, meaning that through the walls the greenhouse is being cooled by the outside air. Despite this cooling flux the internal air is still being heated in these hours, but because of the radiation exchanges not only by the cover but also by the soil, while convection reduce this heats.

4.2.4. Relative Humidity.

Some relative humidities are available from the data collection: the three internal relative humidities at different levels plus the relative humidity measured by the MeteoStanice, which we named outside relative humidity. In this section the humidity behaviours will be analysed.

The psychometric sensors recorded the data shown in the *Figure 29* for the measurement week.

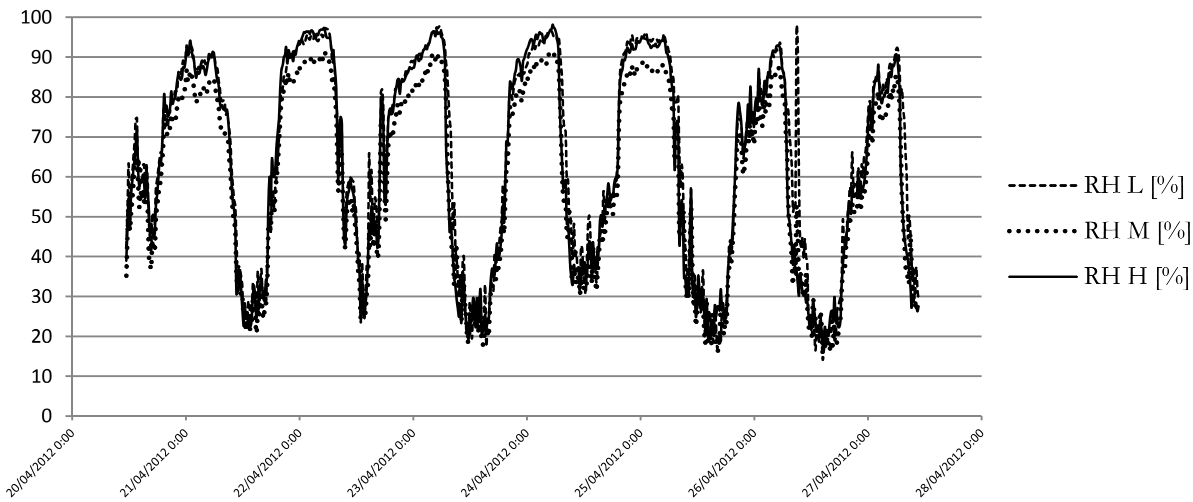

Figure 29. Inside Relative Humidity comparison at different levels.

Humidities fluctuate from 15% up to 95% or more. Such big differences clearly come from the drying process during daytime, when high internal temperatures promote high evaporation rates from the ground. During the night relative humidity rises up drastically due to the condensation inside the greenhouse and the low temperatures. The top and bottom humidities (in dark blue and light blue, respectively) generally have very close values. This happens because the bottom air is more influenced by the ground water content, hence the evaporation, and the top air is more affected by the outside air and the cover, therefore the condensation on the glass. Meanwhile the medium level relative humidity during the night does not reach such high humidities as the others do, so the middle humidity is more likely to be the inside air representative humidity, if we consider that it follows an homogeneous behavior.

With the previous consideration that the middle level psychometric sensor is more representative than the others now we focus on the internal-external humidities comparison.

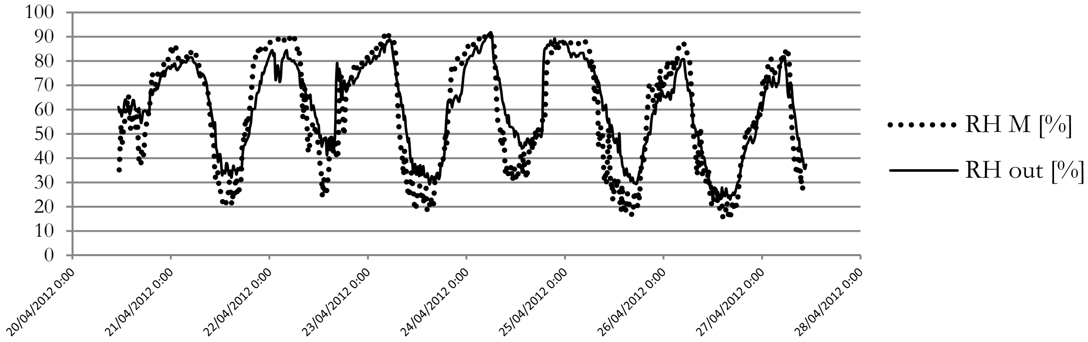

Figure 30. Relative Humidity outside-inside comparison.

The outside relative humidity is plotted in blue and the internal air relative humidity in violet. During the day hours the inside humidity is lower than the outside relative humidity, something obvious because of the much higher internal temperatures. As the psychometric diagrams show, with the same or similar water content in the air, expressed in grams of water per kilogram of dry air $\left[\frac{g\,H_2O}{kg\,dry\,Air}\right]$, if the temperature rises the relative humidity decreases, or from other point of view, the higher the temperature is, more water capacity the air has. During the night hours the behaviour is just the opposite, but adding a certain increase due to small evaporation rate from the ground.

4.2.5. Condensation.

Condensation can occur on the internal surface of the glass cover, when the cover temperature is below the dew point of the internal air. With high relative humidities the internal air temperature might be more close to the dew point, so the condensation is more likely to happen in these conditions.

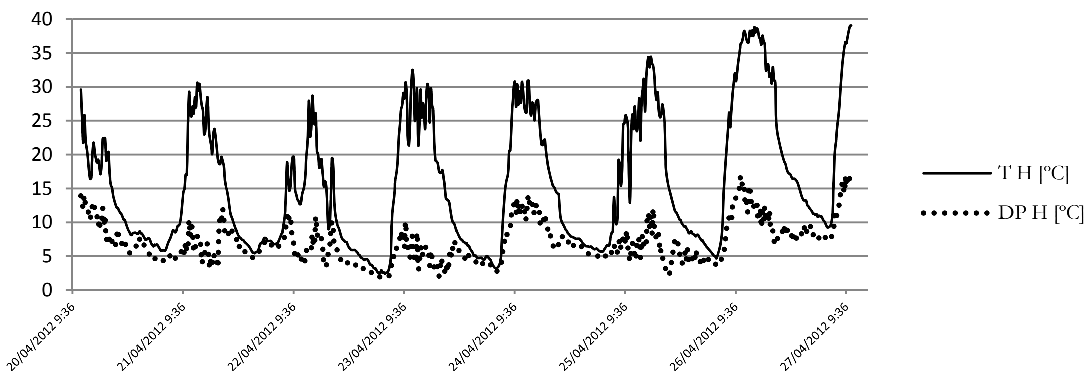

Figure 31. Dew Point verification (165 cm high)(1).

If the air reaches temperatures close to the dew point the condensation probability is increased. In the *Figure 31* it is noticeable that during the nights these two temperatures are much more similar than during the day, which is also an effect of the humidity increase during night hours. Specifically in the nights of the 21st, 22nd and 23rd the temperature of the air goes really close to the dew point, both measured with the top psychometric sensor.

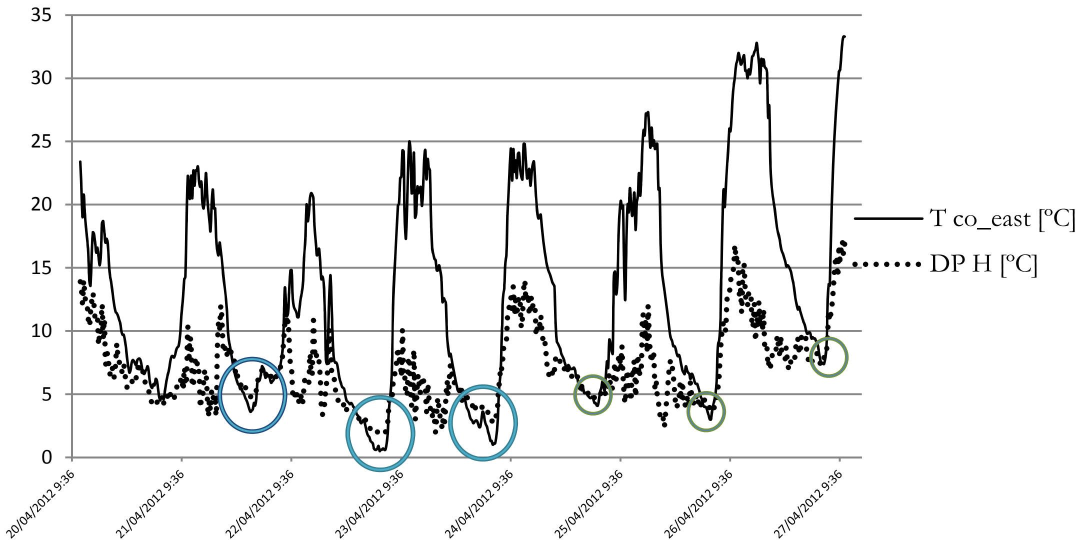

Figure 32. Dew Point verification (165 cm high)(2).

Comparing the dew point at the top sensor with the cover temperature we can figure out whether condensation took place. As explained previously, the thermo-couple placed at the east cover is more representative for the cover temperature, though during night hours both east and west have similar values. As predictable from the *Figure 32* during the early mornings of the 22nd, 23rd and 24th strong condensation on the internal surface of the cover took place, highlighted with big blue circles. Moreover condensation also appeared in the mornings of the 25th, 26th and 27th, highlighted with small green circles.

4.2.6. Statistical analysis of variables: regressions.

This section tries to find any correlation between variables that could be fixed, done by linear regressions. Internal and external variables are the objectives, referred to temperatures and humidities, in order to find out any relation.

<u>Temperatures.</u>

Previously was justified that the middle inside air temperature is the most representative value for the internal temperature of the air enclosed in the greenhouse, so this is the variable brought face to face versus the outside temperature.

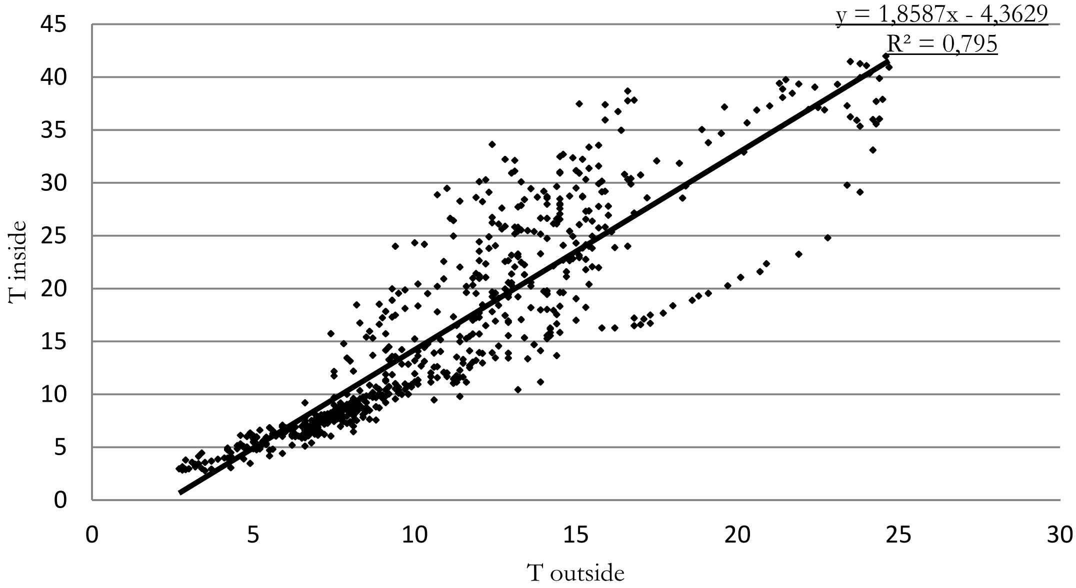

Figure 33. Regresion Tinside-Toutside all data.

A correlation factor of 0,795 shows that inside and outside temperatures don't have a linear relation, which is also visible with the distance of the points to the green linear trend line.

Now we try to differ day hours from night hours in order to find out if there is any difference.

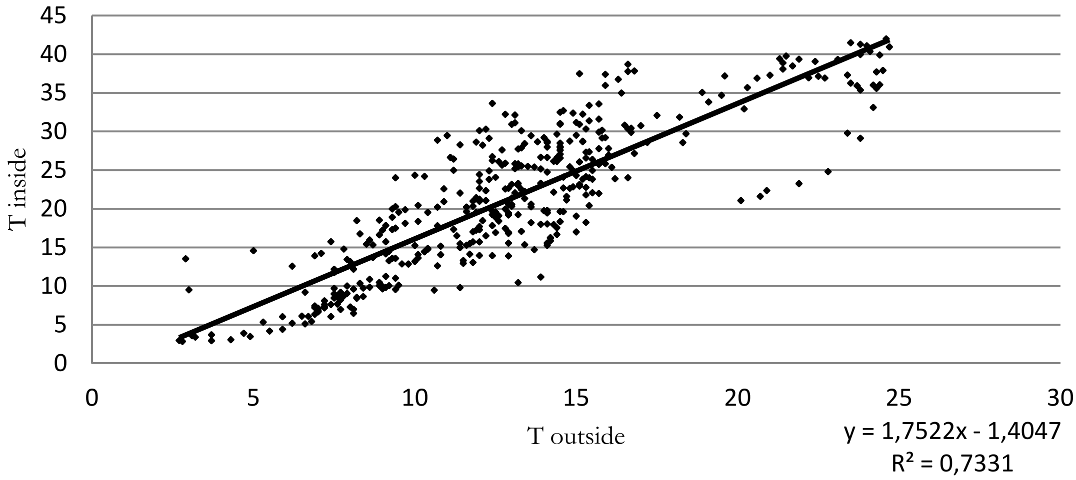

Figure 13. Regresion Tinside-Toutside day hours.

The correlation during day hours is even worse than the overall, as the regression factor shows decreasing to 0,7331. This worsening comes from radiation effects, which depend on temperatures to the power of 4 and are the main influence during the day.

However during night hours the inside and outside temperatures clearly show a linear relation, with the regression coefficient increased to 0,9669. This is possible because during the night radiation effects are null and the exchanges are mainly by convective exchanges. Taking this into account is helpful to obtain convective coefficients, knowing that during the night might be simpler to obtain.

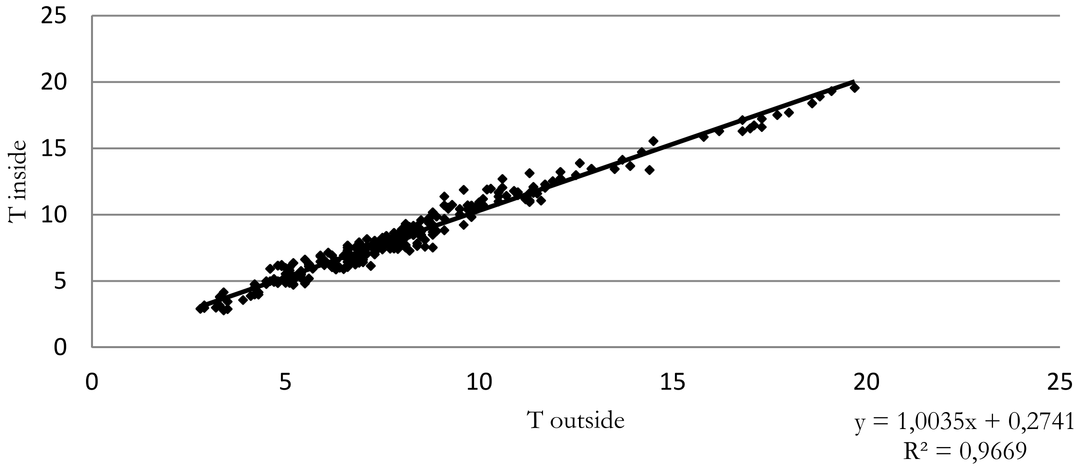

Figure 35. Regresion Tinside-Toutside night hours.

Relative humidity.

Analogously to the temperatures analysis, here the relative humidities will be statistically analysed.

With all the points plotted it doesn't seem to be a close linear relation between inside and outside humidities, although regression is 83,96% accurate. Latent heat processes (evaporation, plan transpiration and condensation) may have an indirect linear influence in the relative humidity, expressed by the vapour pressures.

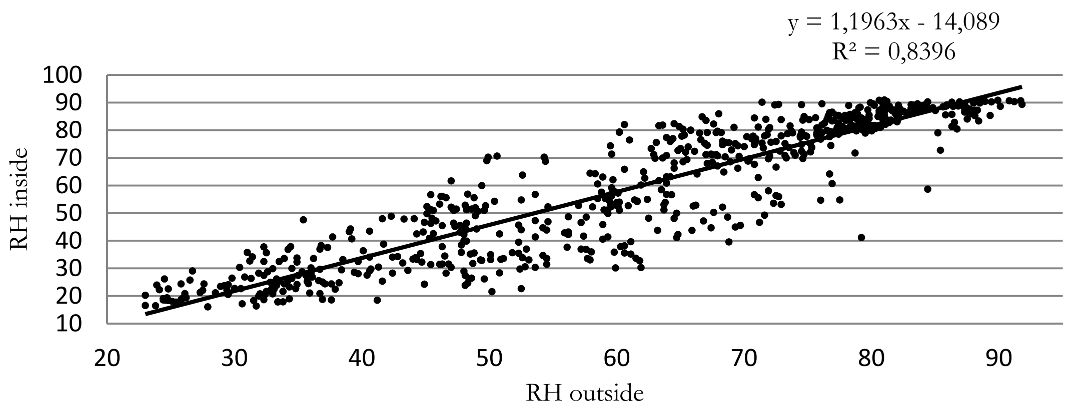

Figure 36. Comparison Relative Humidity inside-outside.

The differentiation between day and night hours doesn't improve the inside-outside humidity relation, indeed it is worse in both cases than in the overall. No direct influence of the outside humidity can be drawn on the inside relative humidity.

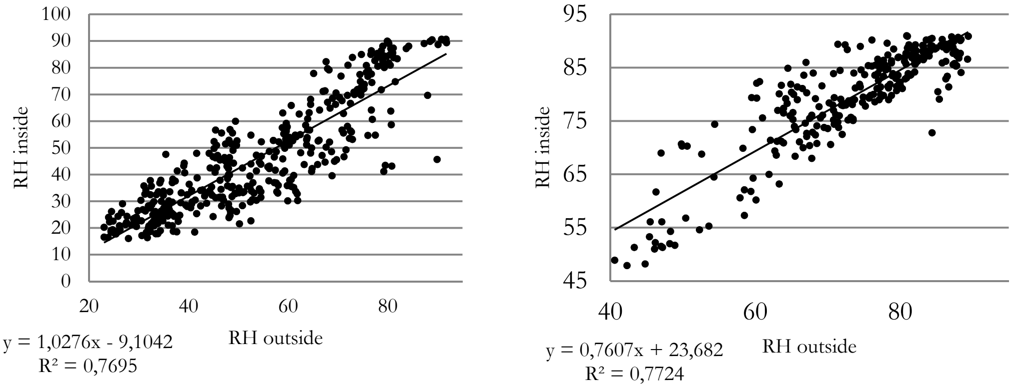

Figure 37. Relative Humidity comparison between inside-outside and day-night.

5. Use and economy of greenhouses in different climatic conditions.

The main use of greenhouses allow for greater control over the growing environment of plants. Depending upon the technical specification of a greenhouse, key factors which may be controlled include temperature, levels of light and shade, irrigation, fertilizer application, and atmospheric humidity. Greenhouses may be used to overcome shortcomings in the growing qualities of a piece of land, such as a short growing season or poor light levels, and they can thereby improve food production in marginal environments.

As they may enable certain crops to be grown throughout the year, greenhouses are increasingly important in the food supply of high-latitude countries. One of the largest complexes in the world is in Almeria, Spain, where greenhouses cover almost 200 km^2.

Figure 38. Greenhouses in Spain. View from the space.

Greenhouses are often used for growing flowers, vegetables, fruits and transplants. Special greenhouse varieties of certain crops, such as tomatoes, are generally used for commercial production. Many vegetables and flowers can be grown in greenhouses in late winter and early spring, and then transplanted outside as the weather warms. Bumblebees are the pollinators of choice for most pollinitation although other types of bees have been used, as well as artificial pollination. Hydroponics can be used to make the most use of the interior space.

The relatively closed environment of a greenhouse has its own unique management requirements, compared with outdoor production. Pest and diseases, and extremes of heat and humidity, have to be controlled, and irrigation is necessary to provide water. Most greenhouses use sprinklers or drip lines. Significant inputs of heat and light may be required, particularly with winter production of warm-weather vegetables.

Another important point in a greenhouse is the ventilation. Ventilation is one of the most important components in a successful greenhouse. If there is no proper ventilation, greenhouses and their plants can become prone to problems. The main purposes of ventilation are to regulate the temperature to the optimal level, and to ensure movement of air and thus prevent build-up of plant pathogens (such as Botrytis cinerea) that prefer still air conditions. Ventilation also ensures a supply of fresh air for photosynthesis and plant respiration, and may enable important pollinators to access the greenhouse crop.

Ventilation can be achieved via use of vents - often controlled automatically - and recirculation fans. In our case of study, ventilation was only natural ventilation setting by hand (opening windows) when the internal temperature rose to a reference value.

The economy of a greenhouse is related with the conditions of the location. For cold areas, as Prague, is necessary heating systems for 7 month per year. It means an investment is necessary to buy the equipment and also the maintenance, such electricity, biofuel or another type or source of energy. On the other hands, the materials for the construction may be different for each climatic condition. In cold latitudes, as for example in the north of Europe glass covers are necessary to give less heat losses to the greenhouse. In Spain, the greenhouse covers are made by plastic materials. Attending to this is easy to think that a greenhouse could be profitable depending on the climate conditions, for that is necessary to make a long period economical balance. This model shown in this thesis is a powerful tool for this purpoise; can be evaluated different materials and shapes for the greenhouse and predict the conditions for any crop.

6. Conclusions and recommendations for practical applications.

After months of work and research during spring time in the greenhouses modelling two proper models have been set, one for the obtaining of the inside air temperature and ventilation (summer model) and another one for calculation of quantity of heat needed by a heating system to keep a preset temperature inside the greenhouse (winter model). Also other models were developed for small calculations and verifications such convective coefficient of heat for different fluxes and cover temperature. Their behaviours have been duly compared with real data from the measurement period carried in April of 2012 in the CULS facilities, helping to validate the mathematical models at the time that a deep analysis of the processes happening in the greenhouse led to better understanding the greenhouse climate and assumptions taken into account. Several deductions presented throughout this work may also help understanding the nature of the physical processes happening in a typical non-heated greenhouse.

An important part of the greenhouses work has not been included in the models due to the simplifications assumed as for example the interchange of heat between plants and greenhouse, in the analyzed greenhouse were no plants, or heat latent exchanges, to take into account condensation on the inside cover, which affects the cover temperature but doesn't significantly affect the air temperature in the greenhouse. Future work on the same direction could probably add latent heat exchanges in the greenhouse, which have been totally neglected in this study and also add equations to describe the heat equations for future plants. Facts like the wind shear difference between different heights or geographic locations, if data are considered in different places, may be taken into account.

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