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Simulation Model of Energy Fluxes in Passive Solar Greenhouses with a Concrete North-Wall

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Simulation Model of Energy Fluxes in Passive Solar Greenhouses with a Concrete North-Wall

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ABSTRACT

Solar energy which is an abundant, clean and safe source of radiation is an attractive substitute for conventional fuels for a passive and active heating of greenhouses. Passive solar systems are used to provide space and water heating for greenhouses or buildings relying on the natural heat transfer forces of conduction, convection and radiation to distribute the collected heat to the surrounding area.

The overall objective of this study was to develop a simulation model for the passive solar greenhouses. Therefor, a solar greenhouse model was designed by using Simulink (MATLAB (PALM, 1999)), which is an interactive tool for modeling, simulating and analysing dynamic systems. The essence of this method is the assumption that the heat capacities of the greenhouse are lumped in certain nodes, which are greenhouse cover, soil, plants, north wall and greenhouse air. The temperature of each node is spatially uniform. For such a model, the energy balance was simulated. The thermal radiative, sensible, latent, and conductive heat fluxes were modeled by mathematical equations in terms of unknown temperatures and vapour pressures.

To evaluate the solar greenhouse model, an east-west-orientated plastic-covered greenhouse with a concrete north wall was built.

In the present work, the predicted and measured air-, soil surface-, wall layers-temperatures and relative humidity values for four typical periods of five consecutive days chosen from the measuring period from April to 31 August 2001 were compared. As a whole, a good agreement between the predicted and measured values was obtained during the entire modeling period. This means that the model can be used to predict a thermal performance of the greenhouse elements in a wide range of solar radiation and temperatures.

A case study to prove the applicability of the model was conducted at **Shebin El-Kom, Egypt 30 54`-N**, where a model to calculate and optimize the inclination of the lighting surface and the wall thickness was developed.

Finally, it can be emphasised that a model which can be used as a research tool for providing information, such as: expected inside temperature, soil layer-, wall layer-, cover-, and leaf-temperatures in the greenhouse was developed. Furthermore, the model can also be

used as a design tool for passive solar systems to investigate the impact of design parameters and as a tool for identifying design problems.

Zusammenfassung

Solarenergie, die reichlich vorhanden ist und eine saubere und sichere Energiequelle darstellt, ist ein attraktiver Ersatz für herkömmliche Kraftstoffe bei der passiven und aktiven Beheizung von Gewächshäusern. Passive Solarsysteme werden als Raum- und Wasserheizung für Gewächshäuser oder Gebäude verwendet. Die Verteilung der gespeicherten Wärme beruht auf den natürlichen Wärmeübertragungskräften wie Konvektion, Leitung oder Strahlung.

Zielsetzung dieser Arbeit ist die Entwicklung eines Simulationsmodells für passive Solargewächshäuser. Zunächst wurde ein Solargewächshausmodell mit dem Software Tool *Simulink* (bzw. MATLAB (PALM, 1999)) entworfen, welches ein interaktives Werkzeug zum Modellieren, Simulieren und Analysieren dynamischer Systeme ist.

Zur Erstellung des Modells wurde angenommen, dass die Wärmekapazität des Gewächshauses in fünf Knotenpunkten konzentriert ist, nämlich in der Gewächshausbedachung, dem Boden, den Pflanzen, der Nordwand und der Gewächshausluft. Für das Modell wurden Energiebilanzen erstellt und Auswertealgorithmen implementiert.

Um die Rechenergebnisse des Gewächshausmodells zu evaluieren, wurde ein ost-west-orientiertes Foliengewächshaus mit Beton-Nordwand errichtet. Der Vergleich von Messwerten mit Rechenergebnissen für 20 Tage im Zeitraum von 01. April bis 31. August 2001 zeigten eine gute Übereinstimmung. Es konnte gezeigt werden, dass das Modell zur Voraussage der thermischen Leistung eines Gewächshauselements für eine Vielfalt an Solarstrahlungen und Temperaturen verwendet werden kann. Mit diesem Modell können Temperaturen der Wandschicht, der Luft, der Bodenschicht, der Gewächshausbedachung sowie die Blattemperaturen der Pflanzen und die relative Feuchte im Gewächshaus berechnet werden.

Um die Anwendbarkeit des Modells nachweisen zu können, wurde es am Beispiel von Shebin El-Kom, Ägypten durchgeführt. Dafür wurden die Wandstärken und der Dachneigungswinkel ermittelt, die für das Gewächshaus optimale thermische Speichereigenschaften erzeugen.

Mit dem entwickelten System lassen sich die erwarteten Innentemperatur des Gewächshauses, sowie die Temperaturen der Bodenschicht, der Wandschicht, die der Abdeckung und die Blattemperaturen ermitteln. Außerdem kann das Modell auch als Designwerkzeug für passive

Solarsysteme benutzt werden, um die Auswirkung der Designparameter für Designproblemen nachzuforschen.

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List of Symbols (units as given in the text)

α	heat transfer coefficient	[$Wm^{-2}K^{-1}$]
α_{ins}	heat transfer coefficient inside the greenhouse	[$Wm^{-2}K^{-1}$]
α_{out}	heat transfer coefficient outside the greenhouse	[$Wm^{-2}K^{-1}$]
λ	thermal conductivity of the material	[$Wm^{-1}K^{-1}$]
$\lambda_{(So)}$	Thermal conductivity of the soil	[$Wm^{-1}K^{-1}$]
$\lambda_{(Wa)}$	Thermal conductivity of the wall	[$Wm^{-1}K^{-1}$]
ϕ	Constant factor depends on the angle between the surfaces	[-]
ϕ_{Cm-sk}	A constant depends on the tilt angle of the greenhouse cover	[-]
ϕ_{So-Cm}	A constant depends on the angle between the soil and cover material	[-]
ϕ_{So-Wa}	A constant factor depends on the angle between the soil and the wall	[-]
ϕ_{Wa-Cm}	A constant depends on the angle between the wall and cover material	[-]
δ	Thickness of the element	[m]
φ_{So}	the soil surface absorption	[-]
Ψ_1	Constant factor	[m^{-1}]
Ψ_2	Constant factor	[m^{-1}]
σ	the STEFAN-BOLTZMANN constant, $= 5.67\ 10^{-8}$	[$Wm^{-2}K^{-4}$]
ζ	Water covering ratio	[-]
ξ	surface reflectance value	[-]
γ	Surface-solar azimuth angle	[°]
β	Title angle of the surface	[°]
θ	Incidence angle	[°]
θ_z	Zenith angle	[°]
ν	Kinematic viscosity	[m^2s^{-1}]
υ	Hour from midnight	[h]
ρ	Air density	[kgm^{-3}]
ε	Emissivity of the material	[-]
ε_{Cm}	The emissivity of the greenhouse cover material	[-]
ε_{er}	The emissivity of the surrounding	[-]
ε_{sk}	The emissivity of the sky	[-]
ε_{So}	The emissivity of the greenhouse soil	[-]
ε_{Wa}	The emissivity of the greenhouse north wall	[-]
ε_{Pl}	The emissivity of the greenhouse plants	[-]
ϖ	period of the sine wave oscillation	[h]
τ	Simulation time	[h]
A	Surface area	[m^2]
Al	Leaf area	[m^2]
ASo	Greenhouse soil surface area	[m^2]
A_{Cm}	Greenhouse cover area	[m^2]
A_{Wa}	Greenhouse north wall surface area	[m^2]
b	Cloudiness factor	[-]

c_p	Specific heat of the air	[$Whkg^{-1}K^{-1}$]
Cr	soil covering ratio without plants	[-]
h	Wall height	[m]
c_{pm}	Specific heat of the material	[$Whkg^{-1}K^{-1}$]
L	Thickness of the element	[m]
l	Optimum thickness of the wall	[m]
M	A modulating function constant	[-]
m_w	Mass of water	[kg]
m_d	Mass of dry air	[kg]
n	Selected simulation time	[h]
P_a	Atmospheric (air) pressure	[kPa]
P_d	Partial air pressure	[hPa]
p_s	Saturation vapour pressure at the dry-bulb temperature	[kPa]
p_s^*	Saturation vapour pressure at the wet-bulb temperature	[kPa]
P_{wv}	Water vapour pressure	[kPa]
P_{wvs}	Saturated vapour pressure	[kPa]
PSG	Passive solar greenhouse	-
Q_{cd}	heat transfer by conduction	[W]
$Q_{cd(So)}$	heat transfer by conduction for the soil	[W]
$Q_{cd(Wa)}$	heat transfer by conduction for the wall	[W]
Q_{cv}	heat transfer by convection	[W]
$Q_{cv(ins)}$	heat transfer by convection at the cover inside	[W]
$Q_{cv(So)}$	heat transfer by convection at the soil surface	[W]
$Q_{cv(Wa)}$	heat transfer by convection at the wall surface	[W]
$Q_{cv(iout)}$	heat transfer by convection at the cover outside	[W]
Q_{rd}	heat transfer by radiation	[W]
$Q_{rd(So-Cm)}$	Thermal radiation exchange between the soil and the cover	[Wm^{-2}]
$Q_{rd(Wa-Cm)}$	Thermal radiation exchange between the wall and the cover	[Wm^{-2}]
$Q_{rd(Cm-sk)}$	Thermal radiation loss from the cover to the sky	[Wm^{-2}]
$Q_{rd(Cm-er)}$	Thermal radiation loss from the cover to the surrounding	[Wm^{-2}]
$Q_{rd(So-Wa)}$	Thermal radiation exchange between the wall and the soil	[Wm^{-2}]
$Q_{rd(He)}$	Thermal radiation from heating system	[Wm^{-2}]
$Q_{rd(So)}$	Thermal radiation exchange with the soil	[Wm^{-2}]
$Q_{rd(Cm)}$	Thermal radiation exchange with the cover	[Wm^{-2}]
Q_{evap}	Latent heat loss from soil surface due to evaporation	[Wm^{-2}]
Q_{cond}	Latent heat of condensation	[Wm^{-2}]
Q_{vent}	Thermal heat loss from greenhouse air due to ventilation	[Wm^{-2}]
Q_{lat}	Latent heat loss from greenhouse air due to ventilation	[Wm^{-2}]
Q_G	Total solar radiation for the horizontal surface	[Wm^{-2}]
$Q_{G(Wa)}$	Total solar radiation at the wall surface	[Wm^{-2}]
$Q_{G(So)}$	Total solar radiation at the soil surface	[Wm^{-2}]
$Q_{G(Pl)}$	Total solar radiation at the leaf surface	[Wm^{-2}]
Q_{Gt}	Total solar radiation for the inclined surface	[Wm^{-2}]
Q_D	Direct or beam radiation for the horizontal surface	[Wm^{-2}]
Q_{Dt}	Direct or beam radiation for the inclined surface	[Wm^{-2}]
Q_d	Diffuse radiation for the horizontal surface	[Wm^{-2}]
Q_{dt}	Diffuse radiation for the inclined surface	[Wm^{-2}]
Q_{rt}	Reflected radiation for the inclined surface	[Wm^{-2}]
Q_{sup}	Heat supplied to the greenhouse element	[Wm^{-2}]

Q_{los}	Heat lost from the greenhouse element	[Wm^{-2}]
Q_{nrd}	Radiative heat flux at the leaf area	[Wm^{-2}]
ΔQ	the magnitude of the heat flow	[$Wm^{-2}h^{-1}$]
r	Latent heat of vaporisation	[Whg^{-1}]
rH	Relative humidity inside the greenhouse	[%]
t	Temperature	[°C]
te	Outside air temperature	[°C]
t_{dry}	Dry-bulb temperature	[°C]
tsk	Sky temperature	[°C]
t_{wet}	Wet-bulb temperature	[°C]
T	Surface temperature	[K]
T_e	Outside air temperature	[K]
T_{er}	Surrounding temperature	[K]
T_{dp}	Dew point temperature	[°C]
Tr	the transmission coefficient of the plants	[-]
T_{sk}	Sky temperature	[K]
T_{Cm}	Cover temperature	[K]
T_{So}	Soil surface temperature	[K]
T_{Wa}	Wall surface temperature	[K]
T_{ins}	Inside air temperature	[K]
T_l	leaf temperature	[K]
ΔT	temperature difference	[K]
ΔTs	the magnitude of the average storage surface temperature	[°C]
v_w	Wind velocity	[ms^{-1}]
x_{air}	Water content of the air	[$kgkg^{-1}$]
x_{ins}	Water content of the greenhouse air	[$kgkg^{-1}$]
x_{out}	Water content of the outside air	[$kgkg^{-1}$]
x_{sat}	Water content of the saturated air at the same temperature	[$kgkg^{-1}$]
$x_{sat(l)}$	Water content of the air at the given leaf surface temperature	[$kgkg^{-1}$]
$x_{sat(So)}$	Water content of the air at the given soil surface temperature	[$kgkg^{-1}$]
$x_{sat(Cm)}$	Water content of the air at the given cover temperature	[$kgkg^{-1}$]
Z	Air exchange number	[h^{-1}]

1 Introduction

Mankind has a future only if the way for a sustainable development is found. Sustainable development is commonly agreed to mean that every generation has to meet its needs in such a way that the existence of the next generations is not endangered. What can be done to direct mankind towards the sustainability is then best anticipated by planing for what can be reached some day to attain the end aim of almost a sustainable condition. This world will be characterized by the following boundary conditions:

(1) There will be no fossil energy resources. They will either be depleted or their use will be prohibited because of their environmental impact.

(2) Almost the easily accessible sources of raw materials are depleted.

(3) The world population will be stabilized at a level compatible with an adequate, equitable and sustainable standards of living.

This last point is very important because if this condition cannot be met, then no technological or political progress can save the world.

There is no denying of the fact that the equation: input = output also applies to man and his existence on the planet earth, where solar energy comes to. The only input that this planet receives is solar radiation. It is generally known that solar energy is the only source of energy for plant and animal life on earth (GOETZBERGER 1995).

The solar radiation in winter time is weak because the sun's rays strike the earth more obliquely with the result that less radiation falls on a given area and the path of rays through the atmosphere is longer, so that the atmosphere absorbs more radiation and consequently less radiation reaches the earth (GRAFIADELLIS 1990).

The power from the sun intercepted by the earth is approximately 1.8 x 10^{11} MW, which is many thousand times than the present consumption rate on the earth of all commercial energy sources. Additionally, solar energy has two other unique features. Firstly, unlike fossil fuels and nuclear power, it is an environmentally friendly source of energy. Secondly it is free and available in adequate quantities in almost all parts of the world where people live (SUKHATME 1984).

The successful operation of any greenhouse depends on maintaining the inside temperature within a specific desired range; for example , 16-28 °C for roses and 12-35 °C for melons. In climates having clear mild winter days, air temperatures in a closed greenhouse can reach a peak of over 40 °C during the day and drop rapidly to the ambient level at night. Thus, on most of winter days, heat has to be removed away during the day by natural or forced ventilation, while at night heat is needed to keep the temperature at the minimum desired temperature level (KORIN et al. 1996).

To be able to utilize greenhouses to produce agricultural products outside the normal cultivation season, it is necessary to heat them, particularly during the cold seasons. Applying heating in the greenhouses have an important effect on the yield as well as on the quality and on the cultivation time of the products as well.

Because of the relatively high cost and uncertain availability of fossil fuels, considerable attention has been given to a new and renewable energy sources as an alternative means of heating greenhouses. Additionally, developing efficient and economical heat storage systems with related devices are as important as developing new energy sources from the point of view of energy conservation. Solar energy which is an abundant, clean and safe source, is an attractive substitute for conventional fuels for passive and active heating of greenhouses. During the day, excess solar heat is collected for short- or long-term storage and it is recovered at night in order to meet the heating needs of the greenhouses.

Thermal energy can be stored as sensible heat, latent heat, heat of reaction, or as a combination of them. In most storage systems, it is stored as sensible heat in materials such as water and rocks. In latent heat storage, the latent heat accompanying a phase change of a material is used for thermal energy storage (BASÇETINÇELIK et al. 1998 and JOHNSON 1992).

In Egypt crops grown in greenhouses are mainly vegetables and ornamentals. The total greenhouses area in Egypt in 1998 was 526 ha, of which about 10 % is glass house, and the rest is plastic ones, including low and high plastic tunnels. A small proportion of the greenhouse owners use auxiliary heating systems only in the coldest winter nights. The sunshine period of Egypt is 3375 - 3800 [h $year^{-1}$]with a maximum of [384.4 h $month^{-1}$] in July and a minimum of 201.5 [h $month^{-1}$] in December. The mean solar radiation intensity is about 3.2 - 4.9 [kWh m^{-2} day^{-1}] in winter and [7.8 - 8.8 kWh m^{-2} day^{-1}] in summer (MOSTAFA et al. 1995).

In the following pages, a Ph.D. research work done at the institute for Horticultural Engineering University of Hannover in the period between 1998 – 2002 on simulation model for a passive solar greenhouse with north-wall is described.

2 Literature Review

2.1 Solar energy systems

2.1.1 General

Ever since the early history of man, sun is utilized to prepare and dry agricultural products. In recent times, a vas improvements have been realized in the production and processing of food and fiber through increased use of non-human energy. In the 1970's and 80's, an increased ratio of CO_2 deposition in the atmosphere was observed which scientists believe that such increment is already increasing the temperature of the earth. If this is really the situation, it is then for sure that the increase rate of earth temperature will be accelerated. The use of solar energy can contribute to the improvement of man's standards of living and help to decrease the potential for disastrous earth warming. Furthermore, this volume of solar energy can play a considerable role in the development of facilities necessary for economic production and preservation of food and fiber (PARKER 1991).

Since 1973, a great attention has been paid to the renewable energy sources because of the effect of sudden rise in the fossil fuels on the global market. Therefore, a world-wide research program to use solar energy has been started (ZAKARIA 1993). One field of the use of solar energy is the greenhouse utilization. For heating of greenhouses with sun energy, two problems according to DAMRATH and von ZABELTITZ (1981) must be solved:

(a) Changing solar radiation into heat energy

(b) Storing heat energy for greenhouse heating.

Systems of greenhouse solar heating were constructed and tested in several countries. The main advantages of solar energy use are:

1. It is undepleted and continuously renewable resource.
2. It is not subject to political or international control.
3. Of all energy sources, it is the least encumbered by environmental and safety hazards,

4. It is cost-free,

5. Most significantly, it is possible to collect, convert and store solar energy with exist technology which can be used or applied in the developing countries too,

6. It can be used through different systems: direct, passive, concentrated or unconcentrated systems (after SAYIGH 1977 and GAMEA 1998).

2.1.2 Thermal systems

In general, solar energy systems can be categorized as one of two types: Thermal systems, which use the sun's energy in the form of heat, and light-utilizing systems (photovoltaics), which use the sun-light directly to provide electricity.

2.1.2.1 Active systems

Active systems are the systems that use some kind of mechanical means to collect and transfer heat. It consists of collectors that collect and absorb solar radiation and electric fans or pumps to transfer and distribute the solar heat into fluids (liquid or air) from the collectors. The active system may has a storage system to provide heat when the sun is also not shining. Active solar energy systems are used to provide heat for thermal comfort in buildings or greenhouses and water heating.

However, the disadvantages of these systems can be summarized as follows:

(1) Large collector area is needed,

(2) Their operation depend on the other energy resources,

(3) They must be maintained regularly. Most systems require 8 to 16 hours of maintenance annually (EREN 2002),

(4) They should be controlled regularly. Controlling of active solar heating systems are usually more complicated than those of the conventional heating systems, because more signals and more control devices (including the conventional, backup heating system) have to be analyzed.

(5) It is costly compared to other systems such as passive system as an example (EREN 2002).

(6) They are less efficient in winter.

2.1.2.2 Passive systems

2.1.2.2.1 Introduction

Like active systems, passive solar systems are used to provide space and water heating for greenhouses or buildings. But unlikely, they do not use pumps or fans to store or distribute heat. Insteadly, they rely on the natural heat transfer forces of conduction, convection and radiation to distribute the collected heat. Passive space heating systems consist of south-facing glass or plastic film to collect heat, and massive building materials within the structure (such as brick, concrete or containers of water) to store the heat. These massive materials have the ability to absorb heat, and then release it slowly to the surrounding cooler areas. Thermal storage in passive designs is usually part of the architecture and acts as a finish material since the space itself is considered as a collector and storage device (SHORT and KUTSCHER 1985, BALCOMB 1992, MIHALAKAKOU 2002, ULGEN 2002). Although some energy is saved by properly applying thermal mass, thermal storage affects comfort most directly because it determines the temperature swings of the occupied space. The area of the house thus heated tends to get very hot in the day unless storage mass is provided in the room. The oscillations in the temperature of the air are large. These oscillations are reduced by providing a thermal storage media either under the floor or in the north wall (SINGH and BANSAL 1984).

Passive systems are usually simpler and operate quieter than active systems. They have a number of tremendous advantages which can be summarized as follows:

1. their operation is natural and normally maintenance-free,
2. the principles are simple and easily understood,
3. the cost of the system may be lower than that of the active system and
4. the system continues to operate even in case of failure in the utility system (BALCOMB 1979).

5. The passive storage device is typically a slab floor, wall, or ceiling and does not take up the extra space associated with active storage.

6. It also operates at a lower temperature (due to the large surface area for heat transfer) and thus does not require the higher collector outlet temperatures of normal active systems (SHORT and KUTSCHER 1985).

Thermal energy can be stored as a sensible heat, a latent heat or a combination of them. In most storage systems, it is stored as a sensible heat. In latent heat storage systems, the latent heat accompanying a phase change of a material is used for thermal energy storage (JOHNSON 1992).

Sensible heat storage is so far considered to be the most common and the least expensive way of storing heat in passive solar heating systems. The heat is stored in massive elements of the building, such as: concrete, brick, or tile floor and masonry walls, partitions, or roof. The greenhouse is a solar-collector/ thermal-storage unit (GARZOLI and BLACKWELL 1981).

2.1.2.2.2 Thermal storage wall systems

Thermal storage walls are used in passive systems such as buildings or windows. The fundamental physical principle which is used in these applications is the wave length shift between the solar radiation absorbed by a dark surface, which may be an absorber or aperture to a room, and the thermal radiation which is emitted by the heated absorber or a room (GOETZBERGER 1995).

Thermophysical properties, such as specific heat, thermal conductivity and density of materials used in passive systems have a strong effect on the energy consumption (JOKISALO et al. 2001). To meet the requirements of the thermal properties and energy conservation, temperature distributions in the wall must be calculated. The temperature distributions in the external wall can be seen as cyclic variation in 24 hours. When the radiation enters through the cover materials (glass or plastic film) and distributed on the soil and walls of the heating space, it is absorbed so that it heats their surface layers. One part of the absorbed heat is transferred to the inner layer of elements, and another part is transferred by convection to the air and also by radiation between the surfaces. This illustrate that the wall stores heat sometimes and releases it at other times throughout the changing period of temperature, the storage and release of heat change according to time and place (BALCOMB 1979; JING 1988; TODOROVIĆ and MILANOVIĆ 1989).

The thermal-storage wall concept has been popularized by the Trombe-Michel houses (Trombe-wall) in the south of France. The wall was constructed from concrete with thickness of 60 cm. The wall may have no vents or have vents only at the top and bottom of the wall (Fig. 2.1). These vents provide for thermocirculation of air from the floor of the building up through the space between the glazing, the wall and out through vents at the top of the wall, returning the heated air to the ceiling space (BALCOMB 1979).

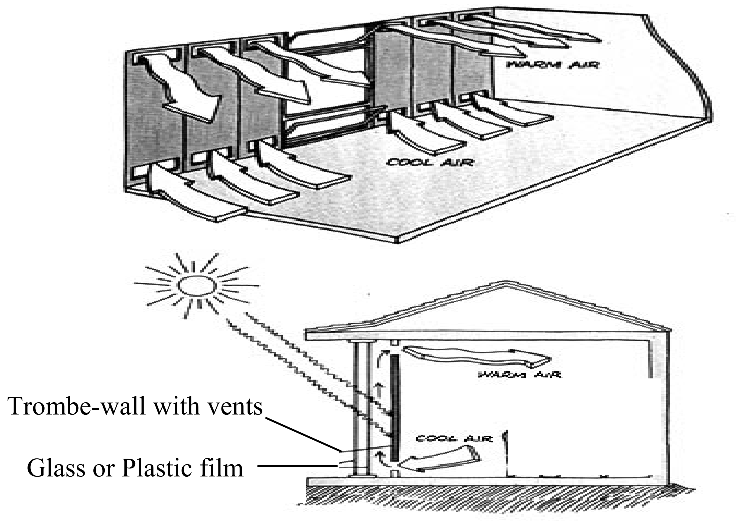

Fig. 2. 1. Illustration of a Trombe-wall.

Many questions arisen when considering the design of interior heat storage walls. What materials are the best? How thick should the walls be? How should they be constructed? Several studies have been conducted in order to answer these questions.

Energy-conscious buildings conserve energy because they are designed well (JOHNSON 1992). The designer’s choice of components and materials also affects occupant comfort and building operating costs. Most of the building’s thermal loads can be suitably controlled at or near the outside wall by using the new glazing and thermal storage materials. The specific heat, thermal conductivity and mass of most building materials are about the same. Since materials which have a high density also usually have high thermal conductivity, it concludes that wall materials which are good insulators are also poor for thermal storage. The properties which make a wall perform well as an interior thermal storage element make it also perform poorly as an exterior insulating element (BALCOMB 1979).

DUANSHENG et al. (1991) studied experimentally the thermal efficiency of the walls of two different types of the greenhouses. The first type wall of the greenhouse was built by rammed earth with 0.50 m thickness and that of the second type of greenhouse held the vacancy interlayer brick wall, i.e. from inside room to outside room with brick of 0.12 m, vacancy interlayer 0.12 m and 0.24 m brick respectively. The results showed that the earth wall usually is an endothermic body but the brick wall is different. During the daytime, the wall is considered as an endothermic body and during the night when the room air temperature drops, the wall body is considered as an exothermic body. They proposed the ideal wall structure to be as follows:

- its inside heat preservation layer consists of materials with strong endothermic and heat preservation capability ,
- its outside heat preservation layer consists of materials with poor heat-conducting and exothermic capability and
- between the two layers there is a thermal-protective coating.

The authors studied the thermal efficiency of the wall of the heat conservation composed of different thermal-conservation materials by the same method. There were four treatments in the heat conservation material: vacancy in the middle (without infilling materials), sawdust, coal cinder and perlite. Their results showed that during the stage of the exothermic of the wall body, the temperature of the wall with the perlite as the heat conservation material was the greatest followed by coal cinder, sawdust and vacancy in the middle respectively. It indicated also that its exothermic efficiency was the most obvious. Moreover, the exothermic duration of the wall with perlite was 4 hours longer than that with the vacancy in the middle.

The authors also studied the thermal efficiency of the following two different wall structures:

- the first wall structure from inside to outside was: brick – perlite with 0.12 m thickness each and 0.24 m brick and
- the second was: 0.24 m brick and perlite – brick of 0.12 m each.

The results showed that the difference of both room air temperature was little, but during day time, the air temperature inside the greenhouse with the first structure was higher than that of the second structure.

Some researchers have tried to improve the thermophysical properties of the materials used to store energy as specific heat by embedding foreign materials, such as magnesium (MAZRIA 1979), but the high cost of this approach prohibited development. While the others have tried to improve the construction of the wall by developing a new type of solar wall, defined as a lattice passive solar heating wall ,LPSHW, (FANG and LI 2000). The LPSHW, which is usually used as the southern wall of the passive solar building, consists of a lattice wall and a glazing cover. A typical lattice wall has rectangular vents which are equal in size and are distributed uniformly (Fig. 2.2). The comparison between the LPSHW and the Trombe wall is carried out under their optimum wall structural parameters with the other parameters held unvariable. The results show that the LPSHW has more advantages over the Trombe wall (FANG 1984).

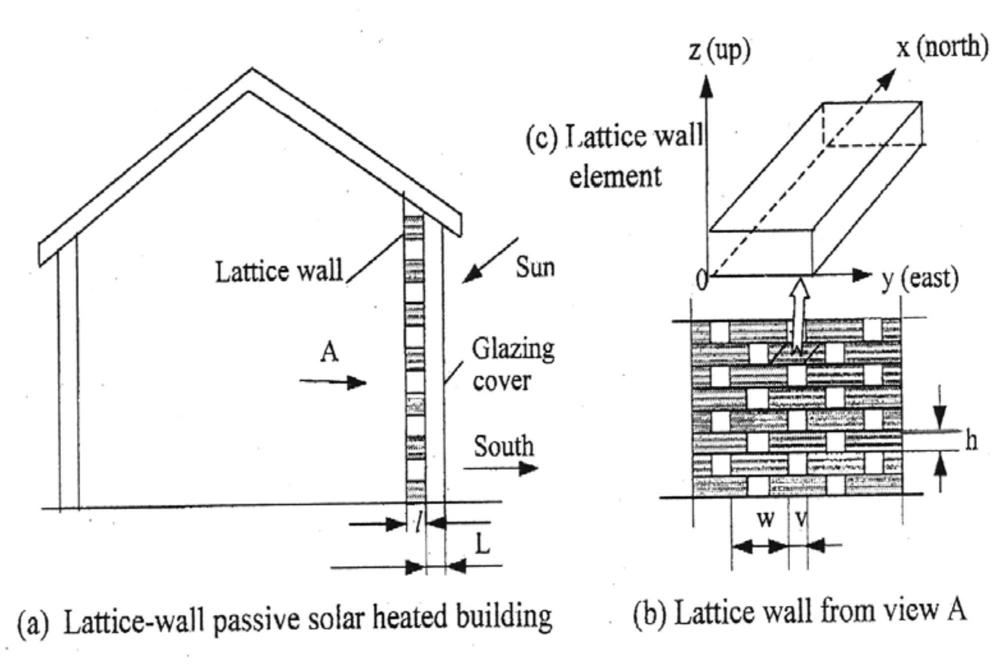

Fig. 2. 2. Lattice wall and lattice-wall passive solar heated building

Looking for a high energy efficiency of a thermal systems, there are two critical characteristics:

1. the fraction of the solar input which can be absorbed by the system – depending on the solar transmittance of the cover and the absorptance of the absorber – and

2. the heat produced in the system which can be stored and used – depending mainly on the thermal insulation of the system, U-value which is assumed to include long-wave radiation transfers as well as conductive and convective transfers (GOETZBERGER et al. 1995). In order to reduce heat losses by convection and infra-red radiation from the warm wall to the environment, a glazing system is employed or a transparent insulation material (TIM) like structure may be integrated to the wall (GOETZBERGER et al. 1995, BILGEN 2000, RADON and BIEDA 2001). The benefits of transparent insulation (TI) can be described as a mechanism which allows solar gains to be harnessed through controlled use but which prevents most thermal losses in a manner similar to conventional (opaque) insulation (Fig. 2-3). TI materials can be characterised by the following:

- high optical transmissivity achieved through the use of transparent/translucent construction materials such as low iron glass, thin wall polycarbonates or clear gels.
- low thermal radiation transmissivity achieved through the use of coated glazing by low emissivity component
- low thermal conductivity achieved through the use of light weight construction materials incorporating significant volume proportions of low conductivity gases or a vacuum
- good convection suppression achieved by compartmentalisation to avoid bulk movement of gaseous components

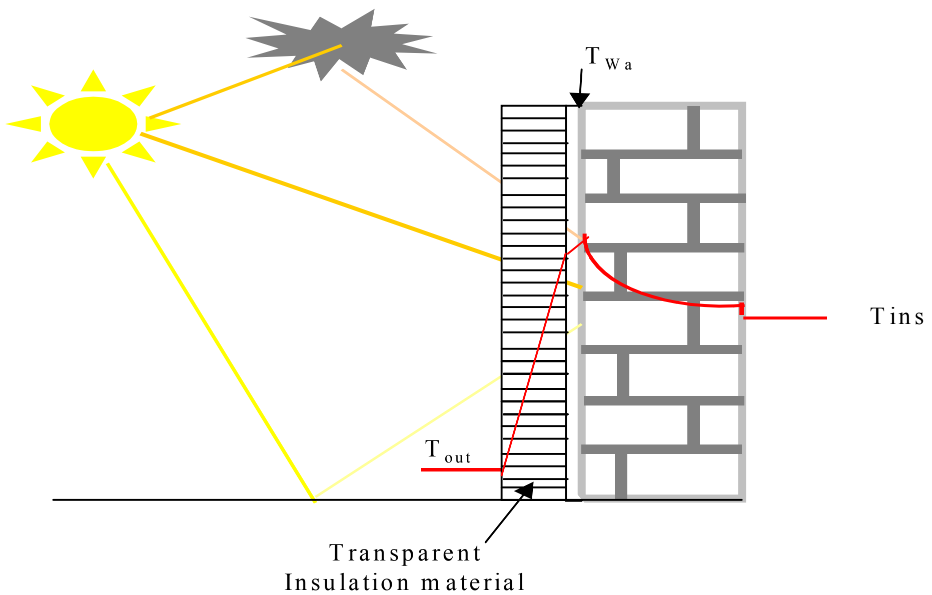

Fig. 2. 3. Layout of Trombe wall with TI glazing

The structure and material type of transparent insulation sets it apart from conventional insulation and other building materials. Plastic is an example material type, while several common structures for transparent insulation include: honeycombs, capillaries, small bubbles and, beads.

The experimental, theoretical and practical work during the last few years has led to an essential understanding of transparent insulation materials. Materials available now reach heat loss coefficients of 0.8 $Wm^{-2}K^{-1}$ with diffuse transmission values of more than 0.7.

The initial applications have shown that well-known solar systems can be significantly improved by the use of TIM's (e.g., process heat collector) and completely new concepts are made possible (e.g., space heating with TI-walls).

According to GOETZBERGER et al. (1995) and MATUSKA (2001), further research is needed to improve and optimize the following characteristics:

- Cost reduction through technical development: One objective for development of insulation in existing buildings is the cost reduction of external wall insulation techniques
- Development of new materials: New insulation materials or techniques with lower U-values including: aerogels, vacuum insulation, substitute foaming agents.etc. are required in order to improve insulation techniques.
- Developing new skills: An objective to reduce heat losses through building envelopes is the development of technical solutions for preventing uncontrolled air flows in rockwool insulation.
- Thermal exchanges: Development of radiation and convection barriers within structures is needed to complement conduction barriers already available.

A design parameter of interest is the ratio of the volume of thermal storage material to the projected glazing area, or the number of cubic meter of thermal storage material per square meter of projected area. In the thermal-wall cases, the thermal storage ratio is just the wall thickness. The wall thickness is the usual design parameter (BALCOMB et al. 1984, JOHNSON 1992). The thermal behavior and storage capacity of the storage materials under the influence of a driving thermal source, such as the sun, can be accurately determined by analytical or simulation methods (NILES 1992). The most common analytical method for thin sections is the admittance, or harmonic method which is a measurement of the wall ability to absorb and store heat during one part of a cycle and then release the absorbed heat back through the same surface during the second part of the cycle. The thermal admittance a, is simply the ratio seen below:

$$a = \Delta Q / \Delta T_s \qquad 2\text{-}1$$

where:

a : thermal admittance [$Wm^{-2}K^{-1}$]

ΔQ : the magnitude of the heat flow [Wm^{-2}]

ΔT_s : the magnitude of the average storage surface temperature [K]

For a thick wall it is given by the formula:

$$\Delta Q / \Delta T_s = \sqrt{\frac{2\pi\lambda\rho c_{pm}}{\varpi}} \quad [Wm^{-2}K^{-1}] \qquad 2\text{-}2$$

Where:

λ : thermal conductivity of the material [$Wm^{-1}K^{-1}$]

ρ : density of the material [kgm^{-3}]

c_{pm} : specific heat of the material [$Whkg^{-1}K^{-1}$]

ϖ : period of the sine wave oscillation, = 24 [h]

There is an optimum wall thickness for which the thermal admittance is in its greatest value. This optimum thickness (*l)*, is given by the BALCOMB equation (1979) as follows:

$$l_{optimum} = 1.18\sqrt{\frac{\varpi\lambda}{\pi\rho c_{pm}}} \quad [m] \qquad 2\text{-}3$$

Thick section of 20-30 cm are used when the sun shines directly on the material, and thinner larger-area sections of 10-15 cm are used when the sunlight is diffused within a space where storage, and release occurs from the same surface (JOHNSON 1992). Based on the sensitivity analysis, the optimum thickness (*l)* of the lattice passive solar heating wall (LPSHW) used in dwelling passive solar heated buildings is according to FANG and LI (2000) as follows: 37 cm, 35-40 cm and 40-45 cm for the brick walls; low concrete walls and the high concrete walls respectively.

2.1.2.2.3 Water systems

In several thermal-storage wall installations, the wall material used for thermal storage is water contained in drums, cans, bottles, tubes, or tanks. Water has been used for sensible storage because of its high specific heat and because in most cases, the entire mass will participate due to the fact that natural convection overcomes any temperature distribution within the liquid (JOHNSON 1992). Therefore, many interesting studies have been carried out on the solar energy storage for greenhouse heating using water such as water in underground tanks (KOZAI et al. 1986), water in stainless steel tanks in the greenhouse (KÜRKLÜ 1998), water drums in the greenhouse (SORENSON 1989), and water-filled PE tubes in the greenhouse (GRAFIADILLES 1987, THOMAS 1994). Most of these applications involved active parts such as pumps or fans. From these applications, water drums, working as a passive system, was reported to delay the frost considerably (SORENSON1989, and KÜRKLÜ 1998). The use of such built-in (water in stainless steel tanks) stores in which energy storage material is heated directly by the sun, has been investigated further by HAMDAN and JURBAN (1992) for the purpose of studying solar energy storage. They found that the efficiency of this type of storage was higher than that of the conventional flat-plate solar collectors. Therefore, with the built-in storage, the overall cost of the energy storage system is minimized (KÜRKLÜ 1998).

Within the last few years water-filled transparent PE tubes have been increasingly introduced into practice as a passive solar heating system in greenhouses (von ZABELTITZ 1989). During the day, global radiation is absorbed by the tubes and when irradiation and temperature decrease, heat energy is released by radiation and convection. Several experiments have been carried out at different experimental and research stations in Mediterranean and Central European regions. The experiments were aimed at using water-filled transparent PE tubes as a passive heating system in greenhouses. In most cases, an insulating layer under a black absorbing film is placed between the PE tubes and the soil. Table 2.1 shows the structure of the experiments done on water-tube used to heat greenhouses. The results of these experiments can be summarized as follow:

(1) There was a higher temperature difference between heated and non-heated greenhouses, which resulted from the heat-storing effect of the plastic film tube,

(2) Yields were compared between air-heated tunnel and tunnel with PE tubes. The final yield in those both tunnels was nearly the same. However, the first yield was earlier in the air-heated tunnel.

(3) The heated crop was still about two weeks earlier than the non-heated and showed better and faster vegetative growth in the beginning, but later on in the season, there was no significant difference.

Table 2. 1: Experimental studies done on water-tube used to heat greenhouse

Author, year	Tube			Plantation	Note
	Diameter cm	Filling ratio L/m	Covering ratio $m^3/1000\ m^2$		
BAILLE 1989	--	30 $l/(m^2.h)$	23.2	---	Radiant mulch
BAYTORUN 1989	35	--	20-40	**Tomato**	
ESQUIRA et al.1989	23	--	20-40	**Melon**	
FARAH 1989	31.8	--	89	**Tomato**	
GRAFIADELLES et al. 1989	31.8	--	--	**Tomato**	
JELINKOVÀ 1989	32	--	--	**Tomato, Cucumber**	
MAVROYANOPOULOS and KYRITSIS 1989	30	--	34	**Tomato**	
MONTERO et al. 1989	21	--	10-20% of Soil surface	**Strawberries**	
MOUGOU 1989	32	--	4-8 tubes	**Muskmelon**	
PACHECO et al. 1989	32	--	80	**Melon**	
PHOTIADES 1989	35	60-70	33, 40, 48.7	**Tomato, Cucumber, beans**	
SALLANBAS et al. 1989	32	--	66-77	**Pepper, Tomato and cucumber**	
THOMAS 1994	70 - 120	25-75	200	**Tomato**	
v. ZABILTITZ and ROSOCHA 1989	31	--	46	**Tree nurseries**	

2.1.2.2.4 Greenhouse soil as a passive solar storage element

The greenhouse soil can be considered as a heat storage affecting on the energy balance of a greenhouse by absorbing and emitting heat. The supply of energy to the soil at day time depends mainly on the global radiation absorbed by the soil surface and the thermal properties of the soil which determine the heat conduction to deeper soil horizon (HÖLSCHER 1988). During the day, the heat emission due to conduction into the soil means a loss in the energy balance of the greenhouse. During the night time, however, the direction of heat transfer changes and energy is emitted into the greenhouse by convection and radiation. The heat flux in the soil has an effect on the heat demand of a greenhouse which must not be neglected. When taking into consideration the heat flux into the soil, to decreasing the calculated amount of heat demand needed annually by 21.7 % in case of a heating set point of 18 °C (HÖLSCHER 1988).

To predict the time evolution of the conditions in a certain greenhouse as a function of the climate conditions existing at a hypothetical location, a model based solely on primary boundary conditions including the heat storage capacity of the soil is needed (KINDELAN 1980).

Previous examples of steady models based on primary boundary conditions are those of SELCUK (1971), KIMBALL (1973), TAKAMI and UCHIJIMA (1977), and DAMRATH (1980, 1981). However, these models did not take properly into consideration the storage of heat in the soil and therefore they used some of ad hoc approximation to compute the heat transfer from the floor.

Probably the most sophisticated models available are that of TAKAKURA et al. (1971), KINDELAN (1980), von ELSNER (1982), HÖLSCHER (1988) and RATH (1994), whose analysis include heat storage in the soil using mainly primary conditions.

RATH (1994) has studied theoretically and experimentally the model correcting unheated greenhouse model which integrates the influence of thermal storage into the conventional U-value-model-calculation. The greenhouse temperature during the night time was simulated considering the temperature increase by the storage. This causes a reduction of heat consumption of 30-40 % in case of heating set point of 2 °C. The results showed that the influence of the correction-model is maximal by heating set point values between 16 and 18 °C, while it decreases to values less than 10 % at set point of 18 °C. Von ELSNER (1982) pointed out to similar results where the influence of heat storage in the soil is affected by selected heating set point and a reduction of 15 % of heat consumption in case of heating set point of 18 °C was observed.

2.2 Simulation models carried out on passive solar systems

2.2.1 Models for house building

A significant part of the rapid development of the field of passive solar buildings has been due to the feasibility and optimization results provided by simulation-based research studies (NILES 1992).

A goal of 70 % reduction in energy cost was established early and maintained throughout the design process. Using the microclimatic phenomena of the canyon as a model, an integrated set of solutions for architectural design and energy efficiency was determined, including extensive daylighting, natural ventilation, evaporative cooling, and passive solar radiant heating using Trombe wall (HAYTER et al. 2001).

A new type of solar wall, defined as a lattice passive solar heating wall (LPSHW), has been yielded (FANG and LI 2000). A lattice passive solar heating wall can remarkably improve the heating performance of passive solar heated buildings. The authors have developed a mathematical model of lattice-wall passive solar-heated buildings considering three-dimensional heat conduction in lattice wall. The model can be used to simulate and evaluate the transient thermal performance, to analyze the sensitivity and the effect of climate and to optimize the LPSHW configuration.

Thermal-network models have become widely accepted as an accurate technique for simulating the dynamic performance of passive solar buildings (PERRY 1977, ABRASH et al. 1978, ARUMI-NOE 1978, MCFARLAND 1978, CLINTON 1979, JUDKOFF et al. 1980, WRAY 1980, SEBALD 1981, and MOORE 1992). In the thermal-network approach, the thermal components of a building are represented by lumped parameters, which are analogous to lumped electrical circuit elements and frequently use the same symbols. In practice, each element of a building thermal system can be represented by a lumped thermal conductance or a lumped thermal capacitance or a combination of them, interconnected to represent the energy pathways, which are usually idealized to be one-dimensional.

Energy performance of external building elements demands consideration of all parameters which contribute towards the overall energy balance of a building. Nowadays, it is more usual to define the overall heat loss coefficient (*U*), solar gain factor (*g*) and transmittance (ε) as energy parameters playing a role in overall energy balance (BANSAL et al. 1996). The authors studied four climate zones where winter heating is required and the required area of passive heating concepts were calculated by a steady-state analysis applied to a single zone building. For a building with capacity effects in walls and roof, the dynamic simulation confirms the values of room temperature at a comfortable level which is assumed to be 18.3 °C in the steady-state analysis. BHANDARI and BANSAL (1994) found that the solar gain (*g*) and the corresponding (*U*) values for various passive heating concepts, namely, direct gain, mass wall, water wall and solarium. Numerical calculations were performed to determine the values of solar heat gains and losses through these passive heating elements for different values of solar radiation and ambient temperatures for the following conditions: cold and sunny, cold and cloudy, composite and hot and finally for the dry climatic conditions.

A major barrier to using energy simulation tools during the design process of a building has been the difficulty of using available programs. BALCOMB (2001) developed a simulation program, *ENERGY-10*, which is a PC-based building energy simulation program for smaller buildings that focuses on the early stages of the architectural design process and the integration of day-lighting, passive solar design, low-energy cooling, and energy-efficient equipment into high-performance buildings. *ENERGY-10* is fast, easy to use and accurate. It allows the user to quickly identify cost-effective energy-efficient strategies based on detailed hourly simulation analysis that accounts for interactive effects.

In passive-solar-heated buildings, because the energy storage is often thermally coupled to the living space, the discharge from storage is determined by governing heat transfer equations and cannot be switched on or off (BAKOS 2002). The sun space, the storage wall, the enclosure and the storage floor are modeled using a single node for each (i.e. lumped capacitance) (BAKOS 2000). The collector-storage wall operates as a passive component by transmitting portion of the absorbed solar energy into the building via either of the two paths. Along the first path, energy is conducted through the wall and subsequently convected and radiated from the inside wall surface into the building. The second path is convection of energy from the outer wall surface to air in the gap between the wall and the innermost glazing. This air is circulated through the gap, heated and returned to the building (UTZINGER et al. 1980). This model can be used to develop and analyse the minimum cost control strategy (BAKOS 2002).

2.2.2 Models for greenhouse

Several studies have been performed in order to understand the relationship between the outdoor and indoor microclimates of greenhouses. A number of dynamic models have been developed (TAKAKURA et al. 1971, TAKAKURA 1989, KIMBALL 1973, AVISSAR and MAHRER 1982, and van BAVEL et al. 1985).

In many countries such as Netherlands and other northern countries, modern greenhouse horticulture is an energy-intensive activity (SAYE et al. 2000). The solar greenhouse researches are aimed at the development of a greenhouse concept with zero-fossil energy consumption. The solar greenhouse is formulated as a combination of a low-energy-demanding greenhouse, an energy recovery installation and an energy storage facility. Energy saving options such as new building materials, a dehumidifier, a heat pump and long-term storage have been studied. The authors have developed a simplified model in MATLAB to describe the total system. The calculation results indicated that implementing the properties of the new building materials with high insulation, the installation of a dehumidifier, a heat pump and a storage system provides a significant reduction in the fossil energy use and an increase in the relative solar energy contribution to the total energy use.

Various models have been developed to predict internal environmental conditions based on external climatic characteristics, crop and greenhouse characteristics. However, most of these models were developed and validated for northern European countries (BOT 1983; CHALABI and BAILEY 1989). In other regions, like Mediterranean countries, most greenhouses are of very simple constructions, covered with polyethylene films and without heating systems (solar greenhouse). Characteristics of these greenhouses are very different from those found in northern countries (BAPTISTA et al. 2000). NAVAS (1998) has developed a one-dimensional and single layer dynamic model for a Mediterranean greenhouse in Spain. In that model, the greenhouse is divided in process and boundary components. The dynamic characteristics of the model are due to the consideration of heat storage in the growing medium and soil, which requires these components to be sub-divided into layers in order to describe correctly their thermal capacities. The model can be used to predict the internal conditions in a greenhouse, mainly the air temperature, relative humidity and cover temperature.

2.2.3 Overview

Ensuing the literatures reveal many investigations studying the passive solar systems. Some of these studies are presented in the following table (table 2.1).

Table 2. 2. Reviews the studies done on the passive solar systems.

Author	Year	Model objective	Method
von ELSNER	1982	Conventional greenhouse system	Finite element
MOORE	1992	Dynamic performance of passive solar buildings	Thermal-network models
NAVAS	1998	Heat storage in greenhouse soil and plants	differential equation
THOMAS	1994	Passive solar heated greenhouse with water tubes	Regression equations
FANG and LI	2000	Passive solar heated building with new type of solar wall (LPSHW)	Tow dimensional differential equation
BALCOMB	2001	Passive solar heated building	Differential equation
ELSHEIKH	2001	Greenhouse soil heating	Finite element and differential equation
HAYTER et al.	2001	Passive solar heated building with Trombe wall	Microclimatic model
BAKOS	2002	Passive solar heated building	Governing heat transfer equations

3 Research objectives

Perusing previous related literature indicates that all previous research done on the simulation on walls were specific only in buildings but not in the greenhouses. The only research done using wall as a solar collector and energy store was practically done in a specific area in China. Therefore, it seemed to be of utmost importance to develop a method using the wall system within a greenhouse so that it can be applied in any area with different environmental conditions.

Thus, the overall objective of this study was to develop a simulation model for passive solar greenhouses with a thermal storage system.

Hence, to achieve this goal, the main objectives of this study were aimed at: working out a mathematical model with numerical solution to:

- simulate the heat and relative humidity of the air inside the solar greenhouse and
- optimize the wall thickness according to changeable location.

4 Basics

4.1 Introduction

The design and analysis of all solar thermal systems requires familiarity with the fundamentals of heat transfer. In discussion of modeling in the present study, it has been assumed that the various heat transfer coefficients involved have different values. For example, the coefficients α_{ins} , α_{out} and λ all unincorporated knowledge about the magnitude of convection and radiation coefficients used to represent the heat transfer between the interior and exterior surfaces of the greenhouse and the environment.

In this chapter the resources available to determine the values of the convection, conduction and radiation will be explored. Related radiation simplifications of the greenhouse inside and outside will be discussed. In addition, evaporation, transpiration and condensation are also discussed for their application to the modeling of a greenhouse.

4.2 Convection

Heat exchange by convection occurs at five different locations of any greenhouse : on the inward and outward sides of the walls, on a soil, on the vegetation and on heating pipes. The convective heat flux between a couple of inward sides , called Q_{cv} , is proportional to the temperature difference ΔT , between the inward side and the medium. Consequently , the Q_{cv} is given by the following equation:

$$Q_{cv} = \alpha \ A \ \Delta T \qquad [W] \qquad 4\text{-}1$$

Where :

Q_{cv}	: heat flux due to convection	[W]
α	: coefficient of convective thermal transmission	[$Wm^{-2}K^{-1}$]
A	: surface of thermal transmission	[m^2]
ΔT	: temperature difference	[K]

Essentially, all the current state-of-the-art greenhouse analysis programs assume that convection occurs between greenhouse surfaces that are at uniform temperature over their surface to inside air at a single temperature with only a few exceptions (ANDERSSON 1980). The convection coefficients between the surfaces and the air are assumed to be constant and independent of temperature difference (ALTMAYER et al. 1982), but at most, it is dependent on the surface orientation and direct of heat flow. Probably the most widely used values for convection coefficients are the constant values recommended by TANTAU 1983. Table 4-1 gives the average convection coefficient values for the greenhouse.

Table 4. 1. Average heat thermal coefficient values for the greenhouse (TANTAU 1983).

Greenhouse Location	Convection coefficient, α [$Wm^{-2}K^{-1}$]	Notes
Greenhouse inside	2-5	depending on heating system and roof temperature
Greenhouse outside	4-30	depending on velocity of wind
Heating pipe (in)	400 - 4380	depending on flow rate and diameter of the tube
Heating pipe (out)	4-9	depending on both temperature and diameter of the tube

4.3 Conduction

The flux of conductive heat (Q_{cd}) through an element of a wall or soil measured in W depends upon the cross – sectional area of the element, the temperature gradient and thermal conductivity of the wall material or soil. This can be expressed as follows:

$$Q_{cd} = \lambda A \Delta T / L \quad [W] \qquad 4\text{-}2$$

Where:

Q_{cd} : heat flux due to conduction [W]

λ : thermal conductivity [$W\,m^{-1}\,K^{-1}$]

A : surface area [m^2]

ΔT : temperature difference [K]

L : thickness [m]

Table 4-2 shows the values of thermal conductivity of some materials used in horticultural shelters.

Table 4. 2. Thermal conductivity of some materials (TANTAU 1983)

Materials	Thermal conductivity, λ [$Wm^{-1}K^{-1}$]
Glass	0.76
Polyethylene(PE)	0.45
Polypropylene(PP)	0.22
Polyvinyl chloride(PVC)	0.19
Air	0.026
Water	0.596
Steel	58.2
Aluminium	211
Copper	385
Concrete	0.81-1.4
Soil (dry)	0.17-0.58
Soil (30% humidity)	0.93
Wood	0.08-0.21

4.4 Radiation

4.4.1 Solar radiation

The important features of the solar radiation at the earth's surface are its directional distribution, spectral distribution, and intensity (BALCOMB 1992). The directional distribution is of paramount importance because it allows the calculation of the incident energy on the surfaces. The spectral distribution is important in cases where the radiative properties (transmittance, absorptance and reflectance) depend on the wave length. The total solar radiation can be divided into the following:

- direct radiation(Q_D) which comes in a beam directly from the sun and

- diffuse radiation(Q_d) which is reflected in the atmosphere and comes from every direction of the sky. Most of this incoming solar radiation at earth level is within the wave length region between 290 and 3000 nm.

The amount of solar radiation incident in a greenhouse is affected by:

(a) Geographic location,

(b) Site location of the greenhouse,

(c) The greenhouse orientation,

(d) Time of the day,

(e) Time season of the year,

(f) Atmosphere conditions,

(g) Covering material.

To calculate the radiation for any surface, the solar incidence angle θ, which is the angle between the normal to the vertical surface and the vector to the earth-sun line, as shown in fig. 4-1 should be known. This angle of incidence determines the key radiative properties (transmittance and reflectance) for the beam radiation of the collecting surface. It is also important because the intensity of the direct beam of solar radiation on the surface is proportional to cosθ, thus, values of θ approaching 90° imply greatly reduced intensity of solar radiation available for collection. This angle is calculated from sun angle equations using the location of the greenhouse, the orientation of the wall and the time of day and year as input data. Therefore, the total radiation can be calculated as follows:

(a) For inside greenhouse surface

Solar radiation is the only and main energy source of the solar greenhouse. The amount of solar radiant energy into the greenhouse not only depends on the transparency of the cover material and the pollution degree of the material, but also has a direct correlation with the inclination of the lighting surface. It is known that in the same location and at the same time, after the cover material is selected, the solar radiant energy into the greenhouse is only considered as a function of the angle of the incidence. The roof angle plays an important role in the energy system of the solar greenhouse. Therefore, the direct solar radiant energy into the greenhouse through the cover material is calculated with different roof angles as follows:

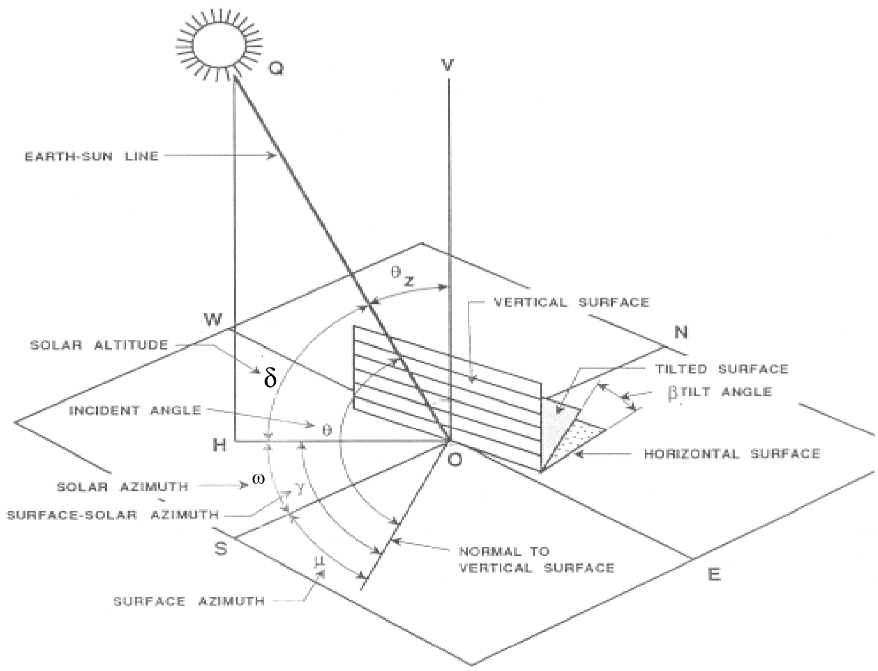

Fig. 4. 1. Solar angles (Parker 1991, modified).

$$Q_{G(ins)} = Q_{G(out)} \tau_{Cm} \qquad [Wm^{-2}] \qquad 4\text{-}3$$

Where:

$Q_{G(ins)}$: solar radiant energy into the greenhouse [Wm^{-2}]

$Q_{G(out)}$: solar radiant energy reached at the outside lighting surface [Wm^{-2}]

τ_{Cm} : transmissivity of the cover material [-]

where τ has a correlation with the angle of incidence θ. These correlation can be seen in figure 4.2. However, the following points should be noted:

- The orientation of the greenhouse in the location of the experiment is east-west and the wall was fixed in the north (its azimuth angle $\gamma = 0$),
- The influence of the atmosphere was neglected.

When the incidence angle is below 45 °, the transmissivity of the cover material can be above 80 % (KARLSSON et al. 2001). To be most efficient, solar radiation should strike the light surface at a right angle.

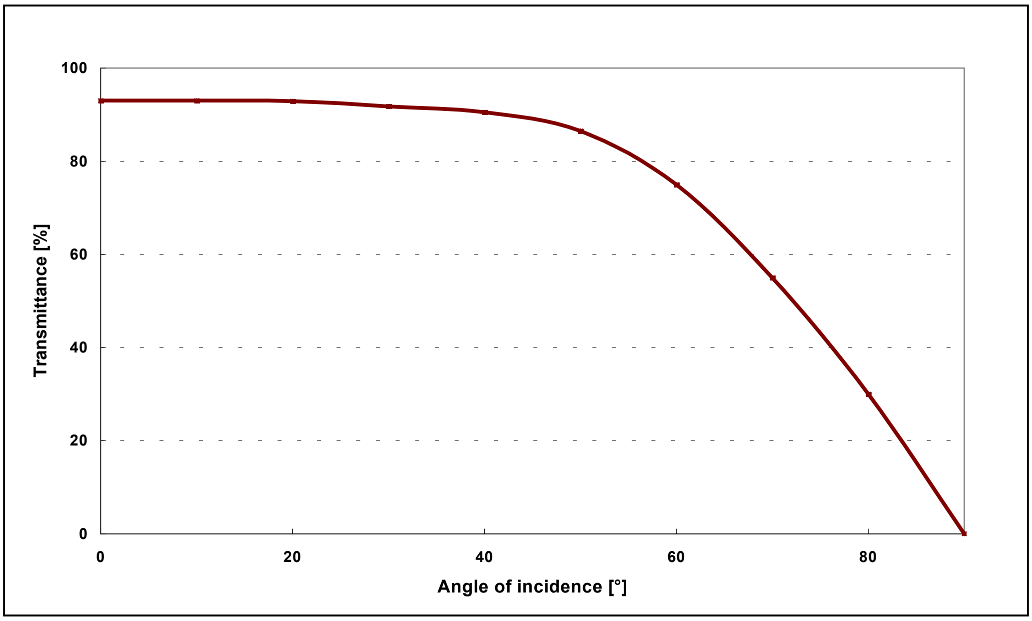

Fig. 4. 2. The angular profile of the direct total solar energy transmittance (KARLSSON et al. 2001, modified).

(b) For the horizontal surface :

$$Q_{G(ins)} = Q_D + Q_d \qquad [Wm^{-2}] \qquad 4\text{-}4$$

where:

$Q_{G(ins)}$: solar radiant energy into the greenhouse [Wm^{-2}]

Q_D : direct or beam radiation [Wm^{-2}]

Q_d : diffuse radiation [Wm^{-2}]

- ***soil surface*:**

The solar radiation at the soil surface is calculated in the model as follows:

$$Q_{G(So)} = (Cr + Tr) Q_{G(ins)} \varphi_{So} \cos\theta \qquad [Wm^{-2}] \qquad 4\text{-}5$$

Where:

$Q_{G(So)}$: solar radiation absorbed at soil surface [Wm^{-2}]

Cr : soil covering ratio without plants [-]

Tr : transmission coefficient of the plants [-]

$Q_{G(ins)}$: solar radiant energy into the greenhouse [Wm^{-2}]

φ_{So} : soil surface absorption, was assumed 0.70 [-]

θ : incident angle of the radiation at the surface. [°]

- ***plant surface*:**

The solar radiation at the plants is calculated in the model as follows:

$$Q_{G(Pl)} = Q_{G(ins)} \varphi_{Pl} \cos\theta \qquad [Wm^{-2}] \quad 4\text{-}6$$

where:

$Q_{G(Pl)}$: solar radiation absorbed at leaf surface [Wm^{-2}]

$Q_{G(ins)}$: solar radiant energy into the greenhouse [Wm^{-2}]

φ_{Pl} : leaf surface absorption [-]

(c) **For the inclined surface**:

$$Q_{Gt} = Q_{Dt} + Q_{dt} + Q_{rt} \qquad [Wm^{-2}] \quad 4\text{-}7$$

Where:

Q_{Gt} : solar radiation absorbed at wall surface [Wm^{-2}]

Q_{Dt} : direct solar radiation absorbed at wall surface [Wm^{-2}]

Q_{dt} : diffuse solar radiation absorbed at wall surface [Wm^{-2}]

Q_{rt} : reflected radiation from the surroundings (will be explained in the next section)

Direct solar radiation

According to HINZEPETER (1974), HEINDL and KOCH (1976), PARKER (1991), REHMAN and HALAWANI (1997) and TAYATI and WATANA (2002), the direct or beam radiation can be calculated using the Lambert's law with the described geometric terms as follows:

$$Q_{Dt} = \left(Q_{Gt} - Q_{dt}\right)\cos\theta$$ [Wm^{-2}] 4-8

Where:

Q_{Dt} : direct solar radiation absorbed at wall surface [Wm^{-2}]

Q_{Gt} : solar radiation absorbed at wall surface [Wm^{-2}]

Q_{dt} : diffuse solar radiation absorbed at wall surface [Wm^{-2}]

θ : incidence angle [°]

Diffuse solar radiation

The next step in the process is to estimate the amount of sky diffuse radiation incident on a collecting surface. The diffuse radiation is mainly influenced by the atmosphere conditions. Various methods have been developed for estimating the diffuse radiation.

LIU and JORDAN (1960) used a simplified assumption that the diffuse radiation on the tilted surface, Q_{dt}, was isotropic and could be calculated as follows:

$$Q_{dt} = Q_d\left(\left(1+\cos\beta\right)/2\right)$$ [Wm^{-2}] 4-9

Where:

Q_{dt} : diffuse solar radiation absorbed at wall surface [Wm^{-2}]

Q_d : diffuse radiation [Wm^{-2}]

β : tilt angle of the surface [°]

The tilt angle of the north wall is 90°.

TEMPS and COULSON (1977) showed that the intensity of the clear sky skylight is about 40% greater near the horizon than at the zenith and that the gradient is strongest at low elevation angles. They added two terms to the isotropic model to represent the anisotropic condition, the formula is expressed as follows:

$$Q_{dt} = Q_d\left(\left(1+\cos\beta\right)/2\right)\left(1+\sin^3\left(\beta/2\right)\right)\left(1+\cos^2\theta\sin^3\theta_z\right)$$ [Wm^{-2}] 4-10

Where:

Q_{dt} : diffuse solar radiation absorbed at wall surface [Wm^{-2}]

Q_d : diffuse radiation [Wm^{-2}]

β : tilt angle of the surface [°]

The tilt angle of the north wall is 90°.

θ_z : zenith angle of the sun which is the incidence angle of the horizontal surface [°]

Finally, a modulating function M was added by KLUCHER (1979) to account for the variations from clear to overcast skies

$$Q_{dt} = Q_d\left((1+\cos\beta)/2\right)\left(1+M\sin^3(\beta/2)\right)\left(1+M\cos^2\theta\sin^3\theta_z\right) \quad [Wm^{-2}] \quad 4\text{-}11$$

Where :

Q_{dt} : diffuse solar radiation absorbed at wall surface [Wm^{-2}]

Q_d : diffuse radiation [Wm^{-2}]

β : tilt angle of the surface [°]

θ_z : zenith angle of the sun which is the incidence angle of the horizontal surface [°]

M : is a constant, $M = 1 - \left(Q_d / Q_{G(ins)}\right)^2$ [-]

Reflected solar radiation

The final component of solar radiation incident on a collecting surface is the ground-reflected component. The amount of radiation that is reflected onto a tilted surface is a function of the amount of beam or direct radiation , diffuse radiation and the reflectivity of the horizontal surface. According to TEMPS and COULSON (1977), the formula is expressed as follows:

$$Q_{rt} = Q_d\,\xi\left((1-\cos\beta)/2\right) + Q_d\,\xi\left(1-\cos(\beta/2)\right)\left(1+\sin^2(\theta_z/2)\right)(\cos\gamma) \quad [Wm^{-2}] \quad 4\text{-}12$$

Where:

Q_{rt} : reflected solar radiation absorbed at wall surface [Wm^{-2}]

Q_d : diffuse radiation [Wm^{-2}]

ξ : surface reflectance value [-]

γ : surface–solar azimuth angle (fig. 4.1). [°]

4.4.2 Long-wave radiation

Longwave radiation is an important mode of heat transfer between surfaces inside the greenhouse and the environment. Inside, the elements of the greenhouse (cover material, soil, plants and walls), heat is transferred directly to each element by radiation, and some heat is radiantly exchanged with the air. It is possible to calculate the radiant energy exchanges of the greenhouse. The surface of any part of the greenhouse at a given temperature T emits electromagnetic radiation, the flux measured in W, is subjected to the Stefan-Boltzmann law seen below :

$$Q_{rd} = \varepsilon \sigma A T^4 \qquad [W] \quad 4\text{-}13$$

Where :

Q_{rd} : heat transfer by radiation [W]

ε : surface emissivity is < 1 [-]

σ : STEFAN-BOLTZMANN constant, = 5.67 10^{-8} [$Wm^{-2}K^{-4}$]

A : surface area [m^2]

T : surface temperature [K]

The radiant heat transfer process is very complicated , and the geometry's of the greenhouse parts have a significant effect. The equations describing the radiant exchange between two surfaces, A_1, A_2, [roof(inside)-soil , roof(inside)-wall , roof(inside)-plants, soil-wall, soil-plants, wall-plants and roof(outside)-sky] with emittances ε_1 and ε_2 respectively ,are expressed as follows:

<u>Roof radiative exchange (inside)</u>

According to STRAUCH (1985) the heat radiative exchange between the soil surface, wall surface, leaf surface and roof material is calculated according to the following equation:

$$Q_{rd(So-Cm)} = \varepsilon_{So} \varepsilon_{Cm} \phi_{So-Cm} \left(\frac{A_{So}}{A_{Cm}} \right) \sigma \left(T_{So}^4 - T_{Cm}^4 \right) \qquad [Wm^{-2}] \quad 4\text{-}14$$

Where:

$Q_{rd(So-Cm)}$: radiation exchange between the soil and the cover [W]

ε_{So} : the emissivity of the soil [-]

ε_{Cm} : the emissivity of the cover material [-]

$\phi_{So\text{-}Cm}$: constant factor depends on the angle between soil and cover material

$\phi_{So-Cm} = (1-\cos(\beta))/2$ from the soil to the cover BALKOMB (1992)

β : tilt angle of the surface [°]

A_{So} : soil surface area [m^2]

A_{Cm} : cover or roof material area [m^2]

σ : STEFAN-BOLTZMANN constant, $= 5.67\ 10^{-8}$ [$Wm^{-2}K^{-4}$]

T_{So} : soil surface temperature [K]

T_{Cm} : cover material temperature [K]

$$Q_{rd(Wa-Cm)} = \varepsilon_{Wa}\varepsilon_{Cm}\phi_{Wa-Cm}\left(\frac{A_{Wa}}{A_{Cm}}\right)\sigma\left(T_{Wa}^4 - T_{Cm}^4\right) \quad [Wm^{-2}] \quad 4\text{-}15$$

Where:

$Q_{rd(Wa-Cm)}$: radiation exchange between the wall and the cover [W]

ε_{Wa} : the emissivity of the wall [-]

ε_{Cm} : the emissivity of the cover material [-]

$\phi_{Wa\text{-}Cm}$: constant factor depends on the angle between wall and the cover [-]

A_{Wa} : wall surface area [m^2]

A_{Cm} : cover or roof material area [m^2]

σ : STEFAN-BOLTZMANN constant, $= 5.67\ 10^{-8}$ [$Wm^{-2}K^{-4}$]

T_{Wa} : wall surface temperature [K]

T_{Cm} : cover material temperature [K]

$$Q_{rd(l-Cm)} = \varepsilon_{l}\varepsilon_{Cm}\phi_{l-Cm}\left(\frac{A_{l}}{A_{Cm}}\right)\sigma\left(T_{l}^4 - T_{Cm}^4\right) \quad [W] \quad 4\text{-}16$$

Where:

$Q_{rd(l-Cm)}$: radiation exchange between the plants and the cover [W]

ε_{l} : the emissivity of the plants [-]

ε_{Cm} : the emissivity of the cover material [-]

$\phi_{l\text{-}Cm}$: constant factor depends on the angle between the plants and the cover [-]

A_l : leaf surface area [m^2]

A_{Cm} : cover or roof material area [m^2]

σ : STEFAN-BOLTZMANN constant, = 5.67 10^{-8} [Wm^{-2}K^{-4}]

T_l : leaf surface temperature [K]

T_{Cm} : cover material temperature [K]

Roof radiative exchange (outside)

For the radiative exchange at the outside of the roof, it was assumed that the mean temperature of the surroundings T_{er} is related to the outside air temperature T_e. The radiation heat transfer from the greenhouse cover to sky accounts for radiation exchange with the sky at sky temperature T_{sk} rather than the ambient temperature T_e. The sky can be considered as a blackbody at some equivalent sky temperature T_{sk} to account for the facts that the atmosphere is not a uniform temperature and that the atmosphere radiates only in certain wavelength band (Duffie and Beckman 1991). It can be calculated as follows:

(1) According to TANTAU (1975) equation:

$$T_{sk} = T_e \sqrt[4]{0.82 - 0.25 \cdot 10^{-0.095 \cdot P_d}} \quad \text{[K]} \quad 4\text{-}17$$

where :

P_d : partial water vapour pressure [hPa]

T_{sk} : temperature of the sky [K]

T_e : temperature of the outside air [K]

(2) According to von ELSNER (1983) equation:

$$t_{sk} = 1.2 t_e - 21.4 \quad \text{when the sky is clear} \quad [°C] \quad 4\text{-}18$$

$$t_{sk} = 1.2\, t_e - 21.4 + b\left(20.6 - 0.26\, t_e\right) \quad \text{when the sky is overcast} \quad [°C] \quad 4\text{-}19$$

Where :

t_{sk} : temperature of the sky [°C]

t_e : temperature of the outside air [°C]

b : cloudiness factor , (0-1) [-]

(3) According to NIJSKENS et al.(1984) equation:

$$T_{sk} = 0.0552\, T_e^{1.5} \qquad [\text{K}] \quad 4\text{-}20$$

$T_{er} = T_e$ when the sky is overcast [K]

$T_{er} = \left(2T_{sk} + T_e\right)/3$ when the sky is clear, vertical surface [K]

$T_{er} = T_e$ when the sky is clear, horizontal surface [K]

T_{er} : Surrounding temperature [K]

(4) According to DUFFIE and BECKMAN (1991):

$$T_{sk} = T_e\left[0.711 + 0.0056T_{dp} + 0.000073T_{dp}^2 + 0.013\cos(15\upsilon)\right]^{1/4} \qquad 4\text{-}21$$

where:

T_{sk} : temperature of the sky [K]

T_e : temperature of the outside air [K]

T_{dp} : dew point temperature [°C]

υ : hour from midnight [h]

(5) According to VOLLEBREGT and VANDE BRAAK (1995) equation:

The mean temperature of the surrounding is equal to the outside air temperature

$$T_{er} = T_e \qquad [\text{K}] \quad 4\text{-}22$$

The sky radiant temperature is a few Kelvin degrees below the outside air temperature. The radiative exchange of the roof with the sky and surroundings of the greenhouse are then given by the following equations:

$$Q_{rd(Cm-sk)} = \varepsilon_{Cm}\, \varepsilon_{sk}\, \phi_{(Cm-sk)}\, \sigma\left(T_{Cm}^4 - T_{sk}^4\right) \qquad [\text{Wm}^{-2}] \quad 4\text{-}23$$

$$Q_{rd(Cm-er)} = \varepsilon_{Cm}\,\varepsilon_{er}\,\sigma\left(T_{Cm}^{4} - T_{er}^{4}\right)$$ [Wm^{-2}] 4-24

Where :

$Q_{rd(lCm-sk)}$: radiation exchange between the cover and the sky [W]

$Q_{rd(lCm-er)}$: radiation exchange between the cover and the surrounding [W]

ε_{sk} : the emissivity of the sky , = 1.0 (von ELSNER 1982) [-]

ε_{Cm} : the emissivity of the cover material [-]

ε_{er} : the emissivity of the surroundings, = 0.9 (STRAUCH 1985) [-]

ϕ_{Cm-sk} : constant factor depends on the tilt angle of the cover material [-]

$\phi_{Cm-sk} = (1+\cos(\beta))/2$ from the cover to the sky (BALCOMB 1992)

σ : STEFAN-BOLTZMANN constant, = 5.67 10^{-8} [Wm^{-2}K^{-4}]

T_{Cm} : temperature of the cover material [K]

T_{sk} : temperature of the sky [K]

T_{er} : temperature of the surrounding [K]

Radiative exchange of the soil surface and the plants

The radiant exchange between the soil surface, wall surface, leaf surface and the roof surface is calculated as follows:

$$Q_{rd(So-Wa)} = \varepsilon_{So}\,\varepsilon_{Wa}\,\phi_{(So-Wa)}\left(\frac{A_{Wa}}{A_{So}}\right)\sigma\left(T_{So}^{4} - T_{Wa}^{4}\right)$$ [Wm^{-2}] 4-25

$$Q_{rd(So-l)} = \varepsilon_{So}\,\varepsilon_{l}\left(\frac{A_{l}}{A_{So}}\right)\sigma\left(T_{So}^{4} - T_{l}^{4}\right)$$ [Wm^{-2}] 4-26

$$Q_{rd(l-Wa)} = \varepsilon_{l}\,\varepsilon_{Wa}\,\phi_{(l-Wa)}\left(\frac{A_{Wa}}{A_{l}}\right)\sigma\left(T_{l}^{4} - T_{Wa}^{4}\right)$$ [Wm^{-2}] 4-27

Where:

$Q_{rd(So-Wa)}$: radiation exchange between the soil and the wall [W]

$Q_{rd(So-l)}$: radiation exchange between the soil and the plants [W]

$Q_{rd(l\text{-}Wa)}$	: radiation exchange between the plants and the wall	[W]
$\phi_{So\text{-}Wa}$	: constant factor depends on the angle between the soil and the wall	[-]
$\phi_{l\text{-}Wa}$	: constant factor depends on the angle between the plants and the wall	[-]
ε_{So}	: the emissivity of the soil surface	[-]
ε_{Wa}	: the emissivity of the wall surface	[-]
ε_{l}	: the emissivity of the leaf surface	[-]
σ	: STEFAN-BOLTZMANN constant, $= 5.67\ 10^{-8}$	[$Wm^{-2}K^{-4}$]
A_l	: leaf surface area	[m^2]
A_{Cm}	: cover or roof material area	[m^2]
A_{So}	: cover or roof material area	[m^2]
A_{Wa}	: wall surface area	[m^2]
T_{So}	: temperature of the soil surface	[K]
T_{Wa}	: temperature of the wall surface	[K]
T_l	: temperature of the leaf surface	[K]

4.5 Evaporation and Transpiration

During the day time, the soil surface and the leaf surface are heated by solar radiation. The surfaces also free heat to the greenhouse air, north wall and roof by convection and long-wave radiation. At the surface, not only sensible but also latent heat transfer occurs.

Latent heat transfer is based on vapour flow due to the vapour gradient between the surface and the air. The vapour potential is expressed in the actual content of vapour in the air on either a weight or a volume basis. Here, the weight basis will be used. Therefore, the vapour content of the unit weight of dry air is expressed as vapour weight mixed with unit weight of dry air (which does not include vapour) and is expressed as x ($kgkg^{-1}$dry air). The equation expressing the latent heat flow is then:

$$Q_{evap} = \frac{\alpha_{ins}}{c_p} r \zeta_{So} \left(x_{sat(So)} - x_{ins} \right) \qquad [Wm^{-2}] \quad 4\text{-}28$$

$$Q_{trans} = \frac{\alpha_{ins}}{c_p} r \zeta_{l} \left(x_{sat(l)} - x_{ins} \right) \qquad [Wm^{-2}] \quad 4\text{-}29$$

Where :

Q_{evap}	: heat flow due to evaporation	[Wm^{-2}]
Q_{trans}	:heat flow due to transpiration	[Wm^{-2}]
α_{ins}	: heat transfer coefficient	[Wm^{-2} K^{-1}]
c_p	: specific heat of the air	[Wkg^{-1} K^{-1}]
r	: latent heat of vaporisation = 0.682 (TANTAU 1983)	[Whg^{-1}]
ζ_{So}	: water covering ratio of the soil surface	[-]
ζ_l	:water covering ratio of the leaf surface	[-]
$x_{sat(So)}$	: saturation water content at the soil surface temperature	[kg kg^{-1}]
$x_{sat(l)}$	: saturation water content at the leaf surface temperature	[kg kg^{-1}]
x_{ins}	: water content of the greenhouse air	[kg kg^{-1}]

According to TANTAU (1987), water covering ratio can be estimated as follows:

$$\zeta = \frac{c_p}{r\left(x_{ins} - x_{sat(l)}\right)}\left(\left(T_{ins} - T_l\right) + \frac{Q_{nrd}\,\mathrm{A}_{So}}{\alpha_{ins}\,\mathrm{A}_l}\right) \quad [-] \qquad 4\text{-}30$$

$$Q_{nrd} = Q_{G(Pl)} + Q_{rd(He\text{-}l)} + Q_{rd(So\text{-}l)} + Q_{rd(Cm\text{-}l)} \quad [\mathrm{Wm^{-2}}] \qquad 4\text{-}31$$

Where:

ζ	: water covering ratio	[-]
A_{So}	: soil surface area	[m^2]
A_l	: leaf surface area	[m^2]
c_p	: specific heat of the air	[Whkg^{-1}K^{-1}]
α_{ins}	: heat transfer coefficient inside the greenhouse	[Wm^{-2}K^{-1}]
r	: latent heat of vaporisation	[Whg^{-1}]
x_{ins}	: water content of the greenhouse air	[kg kg^{-1}]
$x_{sat(l)}$	: saturation water content at leaf temperature	[kg kg^{-1}]
T_l	: leaf temperature	[K]
T_{ins}	: greenhouse air temperature	[K]

Q_{nrd} : radiative heat flux [Wm^{-2}]

$Q_{G(Pl)}$: solar radiation at the leaf surface [Wm^{-2}]

$Q_{rd(He-l)}$: long wave radiation from heating system [Wm^{-2}]

$Q_{rd(So-l)}$: long wave radiation exchange with the soil [Wm^{-2}]

$Q_{rd(Cm-l)}$: long wave radiation exchange with the roof [Wm^{-2}]

Absolute humidity x_{air} is defined as the mass of water divided by the mass of dry air (LEWIS 1990).

$$x_{air} = \frac{m_w}{m_d} \quad [kg\ kg^{-1}]$$

$$x_{air} = \frac{18\,P_{wv}}{29\left(P_a - P_{wv}\right)} \quad [kg\ kg^{-1}] \qquad 4\text{-}32$$

Where:

x_{air} : water content of the air [$kg\ kg^{-1}$]

m_w : mass of water [kg]

m_d : mass of dry air [kg]

P_{wv} : water vapour pressure [kPa]

P_a : atmospheric (air) pressure [kPa]

Air becomes saturated when the water vapour pressure P_{wv} is equal to the saturated vapour pressure, at given temperature. Therefor, the absolute humidity x_{sat} of saturated air is given by the following equation:

$$x_{sat} = \frac{18\,P_{wvs}}{29\left(P_a - P_{wvs}\right)} \quad [kg\ kg^{-1}] \qquad 4\text{-}33$$

Where

x_{sat} : water content of the saturated air [$kg\ kg^{-1}$]

P_{wvs} : saturated vapour pressure. [kPa]

The following algorithm used for calculating saturation vapour pressure is limited to the range of temperatures from 0 to 100 °C (WEISS 1977). The determination of the saturation vapour pressure is the most important calculation in specifying moist air properties since all such properties are considered as a function of the vapour pressure. This equation is expressed as follows:

$$P_{wvs} = 0.61078 \exp\left(\frac{17.2693882\, t}{t + 237.3}\right) \qquad \text{[kPa]} \qquad 4\text{-}34$$

Where:

P_{wvs} : saturation vapour pressure [kPa]

t : temperature [°C]

It should be noted that the equation 4-34 can be extended down to –50°C for super cooled water.

4.6 Condensation

Due to the high evapotranspiration rates in the greenhouses combined with low insulation levels and low (leakage) ventilation rates, condensation often occurs on the inner surface of the greenhouse covers. This effect is well known to growers who fear the wetting of plants by dripping, since it can induce plant diseases. Another consequence of condensation is related to the transmission of solar radiation and particularly where plastic cladding materials are not treated with surfactants, condensation drops can cause a considerable decrease in the amount of incoming solar radiation.

The equation to express the latent heat flow can be written similar to the equation 4-26 as follows:

$$Q_{cond} = \frac{\alpha_{ins}}{c_p}\, r\, \zeta \left(x_{ins} - x_{sat(Cm)}\right) \qquad [\mathrm{Wm^{-2}}] \qquad 4\text{-}35$$

Where

Q_{cond} : latent heat of condensation [Wm^{-2}]

α_{ins} : heat transfer coefficient inside the greenhouse [$Wm^{-2}K^{-1}$]

c_p : specific heat of the air [$Whkg^{-1}K^{-1}$]

r : latent heat of vaporisation [Whg^{-1}]

ζ : water covering ratio, for water film condensation $\zeta = 1.0$ [-]

x_{ins} : water content of the greenhouse air [kg kg^{-1}]

$x_{sat(Cm)}$: saturation water content at roof surface temperature [kg kg^{-1}]

4.7 Ventilation

The greenhouse cover prevents mixing the internal air with the external air. Air exchange through openings in the cover (leaks and ventilation windows) is called ventilation which is one of the most important tools for controlling greenhouse climate and which also can greatly influence on the environmental conditions such as temperature, humidity and carbon dioxide concentration that all affect on the development and production of the crop (BAKKER et al. 1995).

Ventilation and leakage rates are influenced by environmental factors such as wind speed, temperature difference between inside and outside as well as ventilator aperture (BAPTISTA et al. 1999). One important component of the energy balance that indirectly influences the ventilation rate is the solar radiation. When the intensity of the solar radiation is high, the temperature inside the greenhouse increases and the ventilation rate rises as a result of the stronger thermal buoyancy effect. Thus, in the areas where the wind is not so strong (less than 2 ms^{-1}), the difference in temperature is more important in the natural ventilation (BOT 1983 and OCA et al. 1999).

The net energy flux Q_{vent} from inside to outside due to ventilation through a ventilation openings can be easily calculated according to TANTAU formula (1975) as follows:

$$Q_{vent} = Z\, V_g\, \rho\, c_p \left(T_{ins} - T_e\right) \quad \text{[W]} \qquad 4\text{-}36$$

Where:

Q_{vent} : thermal heat loss from greenhouse air due to ventilation [W]

Z : air exchange number [h^{-1}]

V_g : greenhouse volume [m^3]

ρ : density of the air [kgm^{-3}]

c_p : specific heat of the air [Whkg^{-1}K^{-1}]

T_{ins} : inside temperature [K]

T_e : outside temperature [K]

In respect of mass flux Q_{lat} by ventilation, the same kind of relation can be set up:

$$Q_{lat} = Z V_g \rho \, r \, (x_{ins} - x_{out}) \qquad [W] \qquad 4\text{-}37$$

Where:

Q_{lat} : latent heat loss from greenhouse air due to ventilation [W]

Z : air exchange number [h^{-1}]

V_g : greenhouse volume [m^3]

ρ : the air density [kgm^{-3}]

r : latent heat of vaporisation [Whg^{-1}]

x_{ins} : water content of the inside air [$kg\,kg^{-1}$]

x_{out} : water content of the outside air [$kg\,kg^{-1}$]

Concerning the air change number (Z), various phenomenological formula have been proposed in the literature.

- TANTAU (1975) used for the heat consumption calculations the following relationship:

$$Z \approx \psi_1 v_w \qquad [h^{-1}] \qquad 4\text{-}38$$

Where

v_w : the wind velocity [$m\,s^{-1}$]

Ψ_1 : constant factor = 0.25 m^{-1}

- Von ELSNER (1982) used after KANTHAK the following equation:

$$Z = \psi_2 v_w + 0.25 \qquad [h^{-1}] \qquad 4\text{-}39$$

Where:

Ψ_2 : constant factor = 0.13 m^{-1}

- According to the recommendations of the USA (ASAE 1981) for calculation of air change numbers Z, the following values are used:

- for the glasshouse (new construction), $Z = 0.75$ to 1.5

- for the double folied greenhouse, $Z = 0.5$ to 1.0

- for the old construction glasshouse, $Z = 1$ to 2.

4.8 Greenhouse Energy Balance

The state of the important greenhouse variables are determined by energy and mass balances. The energy balance of this greenhouse was simulated. In this chapter, the various terms of the energy balance will be described. Before going into details, it is necessary to determine which parts of the greenhouse are considered in one balance. Although, a balance could be formulated for every single part of the greenhouse, the energy balance of the following parts should be considered:

1. the greenhouse cover,
2. the greenhouse air,
3. the greenhouse soil,
4. the greenhouse north wall, and
5. the greenhouse plants

Figure (4.3) illustrates all the greenhouse parts considered by this model.

Concerning the greenhouse cover, the energy balance is composed of radiative exchange with the sky, radiative exchange with the interior of the greenhouse, convective exchange between the cover and both the greenhouse air and outside air, and latent heat released by condensation of water vapour inside the greenhouse.

In respect to the greenhouse air, it includes the convective exchange with the cover, soil, leaf and north wall as well as exchange with the outside air (ventilation).

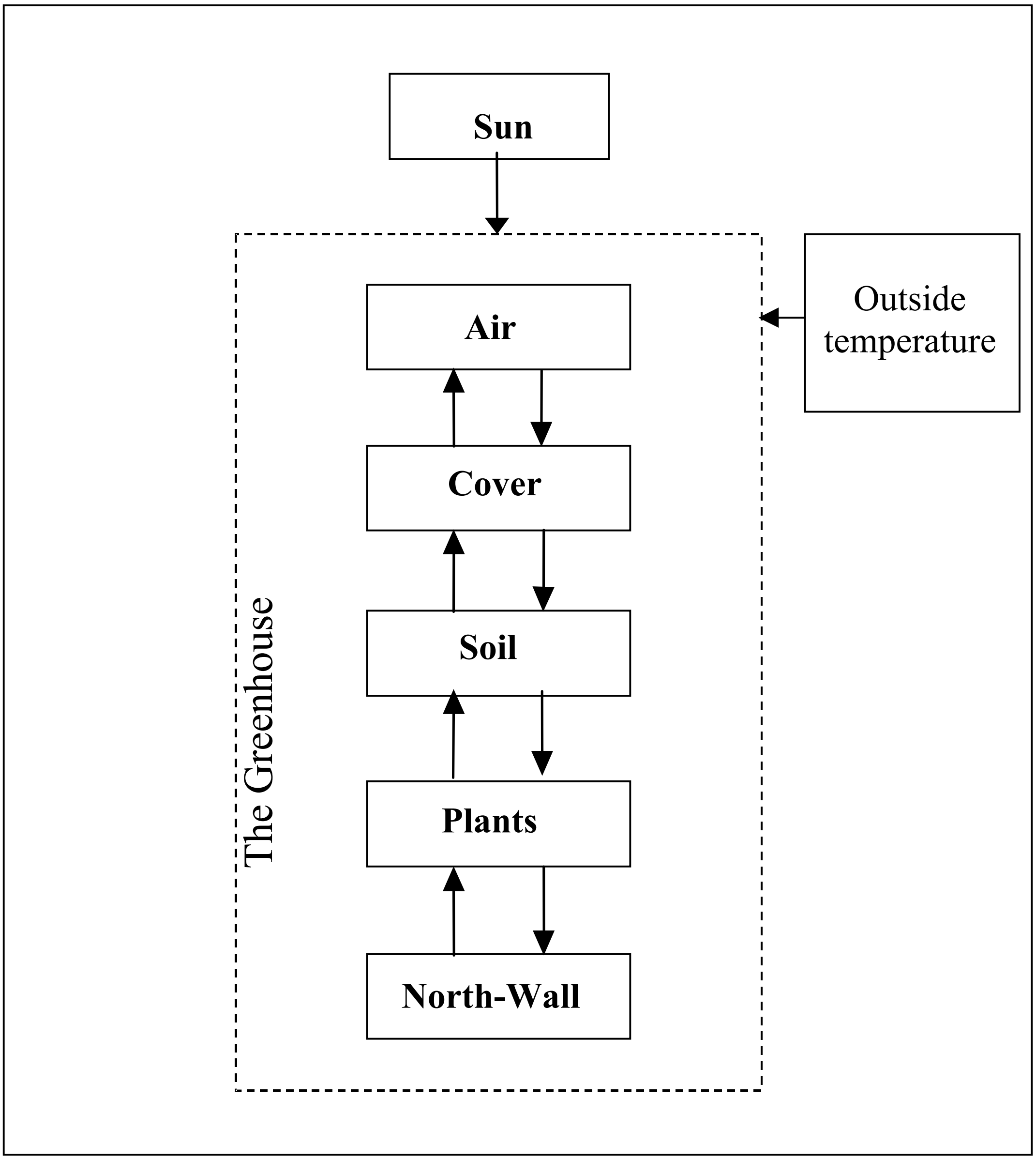

Fig. 4. 3. Schematic illustration of all parts of the greenhouse considered by this model

Soil part includes absorption of solar radiation, convective exchange with the greenhouse air, radiative exchange with the cover, the leaf and the north wall, conductive exchange with the underlying soil layers and latent heat linked to evaporation.

Whereas, greenhouse north wall is composed of absorption of solar radiation, convective exchange with the greenhouse air, radiative exchange with the cover, the leaf and the soil, conductive exchange with the wall back layers and latent heat released by condensation of water vapour inside the greenhouse.

Finally, greenhouse plants include absorption of solar radiation, convective exchange with the greenhouse air, radiative exchange with the cover, the soil and the north wall, and latent heat linked to transpiration.

The balance for the different parts are:

For the cover:

$$Q_{rd(Cm-Wa)} + Q_{rd(Cm-So)} + Q_{cv(ins)} + Q_{cv(out)} + Q_{cond} = 0 \qquad 4\text{-}40$$

For the soil:

$$Q_{G(So)} + Q_{rd(So-Wa)} + Q_{rd(So-Cm)} + Q_{cv(So)} + Q_{cd(So)} + Q_{evap} = 0 \qquad 4\text{-}41$$

For the wall:

$$Q_{Gt(Wa)} + Q_{rd(So-Wa)} + Q_{rd(Wa-Cm)} + Q_{rd(Wa-Pl)} + Q_{cv(Wa)} + Q_{cd(Wa)} + Q_{cond} = 0 \qquad 4\text{-}42$$

For the greenhouse air:

$$Q_{cv(Wa)} + Q_{cv(So)} + Q_{cv(Cm)} + Q_{cv(Pl)} + Q_{vent} = 0 \qquad 4\text{-}43$$

For the greenhouse plants

$$Q_{G(Pl)} + Q_{rd(Pl-Wa)} + Q_{rd(Pl-Cm)} + Q_{rd(Pl-So)} + Q_{cv(Pl)} + Q_{trans} = 0 \qquad 4\text{-}44$$

For the mass balance of the greenhouse

$$Q_{cond(Wa)} + Q_{cond(Cm)} + Q_{evap(So)} + Q_{trans(Pl)} + Q_{vent} = 0 \qquad 4\text{-}45$$

- Differential equation:

To calculate the temperature of the greenhouse elements (air, soil, wall, plants and covering material) the following differential equation was used:

$$t = \frac{1}{\rho c_p \delta} \int_{\tau=0}^{\tau=n} \left(Q_{\sup} - Q_{los} \right) d\tau \qquad 4\text{-}46$$

where:

t	: temperature	[K]
c_p	: specific heat	[Wh $kg^{-1}K^{-1}$]
ρ	: density of the air	[kgm^{-3}]
δ	: thickness of the element	[m]
Q_{sup}	: heat supplied to the greenhouse element	[W m^{-2}]
Q_{los}	: heat loss from greenhouse element	[W m^{-2}]
τ	: simulation time	[h]
n	: selected simulation time	[h]

5 Materials and Methods

5.1 Experimental set-up

5.1.1 Preliminary studies on roof inclination

Hannover is situated at 52° 28' degrees latitude where the sun at noon is usually at a higher angle (67°) in summer (June) and at a lower angle(15°) in winter (December). This is important to be taken into consideration because, the optimal inclination angle depends on the geographical latitude of a given site and also on which time of the year the solar energy system is used for the aim to be most efficient. In order to increase the solar radiant energy through the plastic film, the slope of the lighting surface should be considered carefully. Therefore, the month average value of the direct solar radiant energy into the greenhouse during sunshine to sunset with different angles (10-60°) of the lighting surface from January to December is simulated (Fig. 5.1). It can be seen that the slope angle varies over time and the optimum value of the angle depends on which time of the year the solar energy system is used. In this case, the slope of plastic film of the greenhouse was constructed according to the desired design as follows: The top part is at 35°, the part against front wall of the greenhouse is at 30°.

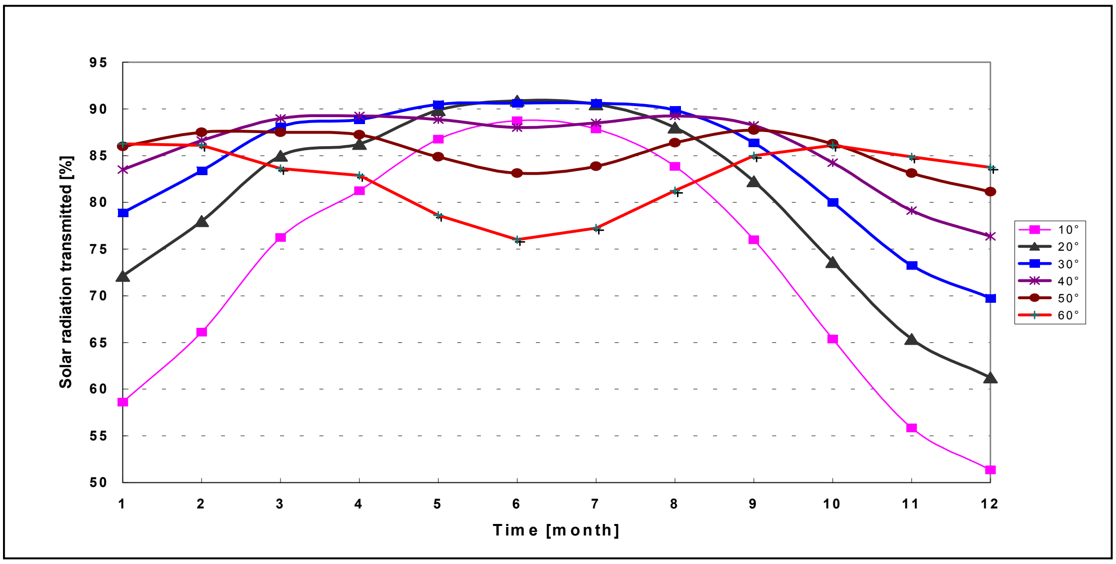

Fig. 5. 1. The relation between the month average value of the direct solar radiant energy through the cover material and the time of the year with different slope angles ranging between 10 - 60°.

5.1.2 Greenhouse construction and roof material

To evaluate the solar greenhouse model, an east-west-orientated plastic covered greenhouse with concrete north wall with dimensions of 3 x 5 m ground and 55 m^2 surface area was built. The greenhouse construction is presented in figure 5.2.

Fig. 5. 2. Greenhouse construction (1) concrete north wall and east-west gable, (2) construction material, (3) roof covering material and (4) greenhouse door.

The most important function of the greenhouse cover is the protection of the crop from unfavourable weather conditions (low temperature and wind), diseases, pests and to conserve the energy in the greenhouse.

To determine which material to be used, the following properties should be taken into consideration:

- light transmittance,
- thermal transmittance (infrared above 3000 nm),
- UV transmittance (ultraviolet up to 400 nm) ,
- withstanding to unfavourable environmental conditions as well as soil chemicals and especially pesticides,
- condensation behaviour ,
- insulation value,

- resistance to hail load and
- sizes available.

The greenhouse was covered with PE plastic film. Table 5-1 shows the characteristics of these material used in the experimental.

Table 5. 1. Characteristics of the PE plastic film used

Heat capacity [$Whkg^{-1}K^{-1}$]	Conductivity [$Wm^{-1}K^{-1}$]	Density [kgm^{-3}]	Light transmission	
			Direct radiation [%]	Diffuse radiation [%]
0.014	0.064	920	84	79

5.1.3 Concrete north wall

Interior walls which are irradiated by direct or indirect sun can store heat. In order to make this heat to be stored in the wall of the greenhouse, it must first be transferred to the surface of the wall and then conducted into the wall. The process at night is the reverse-conduction out of the wall to the surface and then transmission back into the greenhouse by convection and radiation.

To be an effective heat storage element, a wall should have:

- a high thermal heat capacity c_p and
- a high thermal conductivity λ too.

Since materials which have a high density also usually have high thermal conductivity, which mean that wall materials which are good insulators are poor for thermal storage. Materials such as concrete, brick and rock are relatively suitable sources for thermal storage (BALKOMB 1979). Table 5-2 shows the thermal properties of some materials which are commonly used for thermal heat storage.

Table 5. 2. Thermophysical properties of various materials (INCROPERA 1990)

Materials	Density,ρ [kgm^{-3}]	Specific heat, c_{pm} [Whkg^{-1}K^{-1}]	Specific heat, c_{pv} [Whm^{-3}K^{-1}]	Thermal conductivity, λ [Wm^{-1}K^{-1}]
Water	1000	1.163	1163.0	0.625
Concrete	2300	0.249	572.70	1.400
Sand	1515	0.220	333.30	o.270
Clay	1460	0.304	443.84	1.300
Coal	1350	0.350	472.50	0.260
Iron	7870	0.124	975.88	80.20

The wall of the greenhouse in the experimental was made of concrete where the dimensions of the wall were chosen based on the results of the theoretical solution (solar greenhouse model) suitable for this system as follows: wall width = 5.0 m , height, h = 1.80 m and thickness, l = 0.20 m. The wall surface was coated with a dark colour (black) in order to increase the wall surface absorption, which absorbs almost all the radiation in the visible portion of the solar spectrum and emits only very little in the infrared range. High absorbence turns the light into heat at the wall's surface, and low emittance prevents the heat from radiating back towards the cover material.

To prevent the heat losses by convection and radiation to the surrounding the back surface of the wall should be insulated. The function of the heat insulation of a north wall is to keep the heat inside the storage unit and to minimize heat losses. This function has to be guaranteed during the whole lifetime of the storage unit. The most important requirements of the insulators heat are summarized below:

- high durability for storage temperatures of up to 95 °C (PFEIL and KOCH 2000)
- long-term stability of the mechanical and thermodynamic properties
- small level of water absorption

- insensitivity to humidity and weather condition
- ecological safety

In the experimental greenhouse, the wall was insulated by 0.10 m polystyrene insulation substrate.

5.1.4 Soil and plants

The experimental greenhouse soil was a clay soil which has the physical properties as shown in table 5-3.

Table 5. 3. Physical properties of the experimental greenhouse soil

Heat capacity $[Whkg^{-1}K^{-1}]$	Conductivity $[Wm^{-1}K^{-1}]$	Density $[kgm^{-3}]$	Absorption [%]
0.24	0.84	1460	70

The experiment was divided into two periods, with plants from April to July and without plants on August. During the first period, the soil was covered with grass because grasses are usually tolerate the variable and fluctuating environmental conditions and also oft used as a standard for transpiration balances. Furthermore, since the greenhouse is not heated and the plants which are grown usually are much susceptible to the environmental conditions, while grasses can be a better alternative choice. The properties of the grass used in the model are shown in the following table (table 5.4).

Table 5. 4. Properties of the grass used in the model

Covering ratio [%]	Transmission [%]	Emissivity [%]	Absorption [%]
80	20	90	40

5.2 Measurements and Devices

5.2.1 Solar radiation

Global and diffuse solar irradiance are measured by ground-based pyranometers. Basically, the pyranometer consists of a black painted ceramic disk which absorbs radiant energy and acts as a sensing element. The thermocouples are imprinted on this disk. Only the border of the disk is in good thermal contact with the pyranometer body, which acts as a heat sink. The cold junctions are located near this border. The hot junctions are located near the center of the disk in a rotationally symmetric arrangement. When the pyranometer absorbs radiation, the absorbed energy results in a heat flow from the center to the edge of the disk. The temperature difference across the thermal resistance of the disk creates an electromotive force which is then read by a datalogger. The rise of temperature is easily affected by wind, rain and thermal radiation losses to the environment ('cold' sky). Therefore, two glass domes shielded the detector. Glass domes allow isotropic transmission of the solar component from every position of the sun in the sky. The spectral range of the pyranometer is limited by the transmission of the glass. The sensing element of the pyranometer is coated with highly absorbent black paint. This element absorbs well all wavelengths equally, but the absorbance will vary according to the angle of incidence. For most pyranometers the absorbance remains constant until the incident angle reaches about 70°. Beyond this point, the absorbance drops rapidly as the angle of incidence approaches 90°. Fortunately, at low solar elevations, the energy contained in the solar beam is very small and a small percentage change in the measurement is not-critical, since reflections from the dome compensate for loss of absorbance.

Five pyranometers CM 6 (Kipp and Zonen 1998) were used to measure the solar irradiation outside the greenhouse (one pyranometer was fixed on a top stand to the east which has a height of 2.5 m) and inside the greenhouse (two pyranometers were placed above the soil at a height of 1.0 m and the other two were suspended at the wall at a height of 0.75 m and 1.30 m). The solar radiation, temperature and the relative humidity were measured every 15 seconds and their average were recorded at 10-minute intervals during the experiments with a data logger (MCU-ITG 1996, TANTAU 2000).

5.2.2 Temperature and humidity

Thermocouples JK (Ni-CrNi) was used to measure the temperatures of the air (inside and outside), the wall layers and the soil layers. For the measurement of wall layers temperature, 36 thermocouples were used. Their positions are shown in figure 5.3.

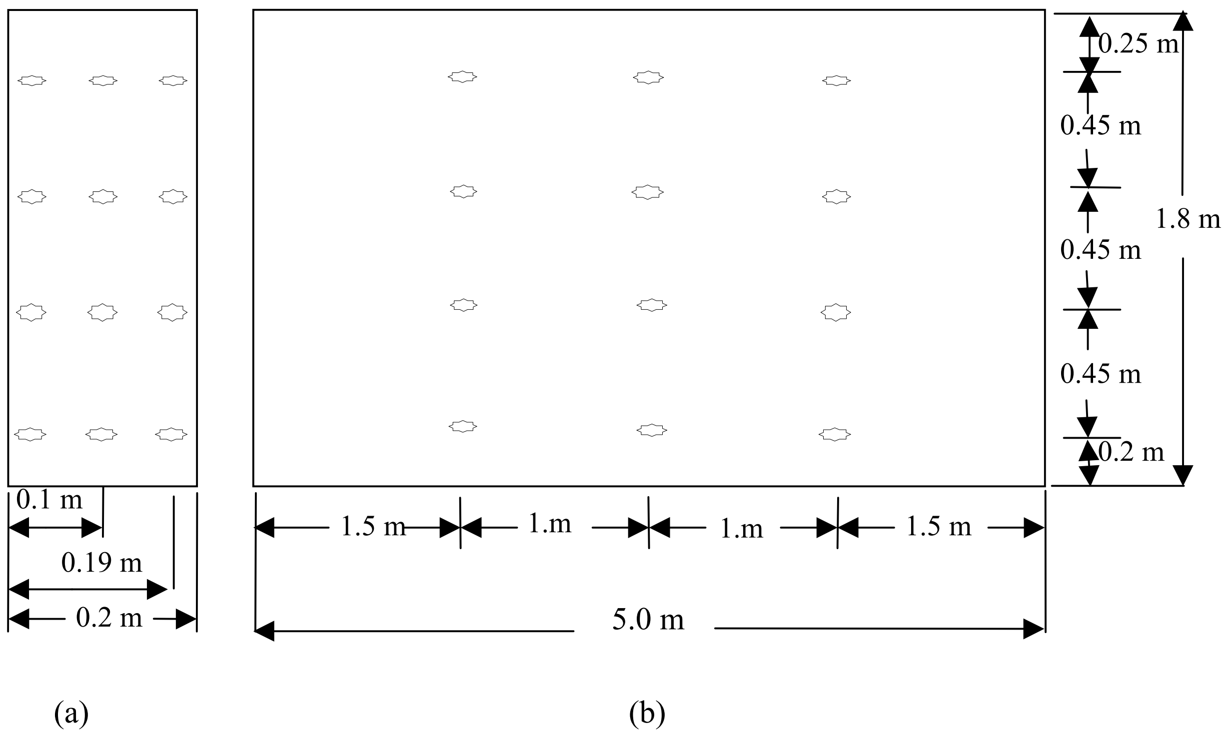

Fig. 5. 3. Thermocouple positions in the wall

(a) side view

(b) front view

The soil temperature was measured at three different depths 1.0, 10 and 35 cm from the soil surface, their thermocouples were placed in the middle of the greenhouse soil.

The amount of water vapour in the air can be described at least in 5 ways, in terms of:

(1) water-vapour pressure;

(2) relative humidity;

(3) absolute humidity;

(4) mixing ratio and

(5) dewpoint.

To measure the inside and the outside humidity, three aspirated psychrometers which have been developed at the institute of Horticulture and Agricultural Engineering, Hannover University, were used. The outside psychrometer was suspended at a height of 2.5 m and the other two inside the greenhouse were suspended at a height of 1.5 m. A psychrometer measures the wet-bulb temperature in a moving air stream, preferably above 2 ms^{-1}. The instrument has two thermometers. One of these thermometers is covered with muslin sleeve which is kept moist with distilled and clean water. This thermometer measures the wet-bulb temperature and the other one measures the dry-bulb temperature. The relative humidity can then be calculated according to the following formula (WEISS 1977):

$$rH = \left(\left(\frac{p^*_{wvs}}{p_{wvs}} - \frac{\left(63.2 + \frac{72.3\, p^*_{wvs}}{101.3 - p^*_{wvs}} \right) * \left(t_{dry} - t_{wet} \right)}{p_{wvs} \left(0.62 + \frac{0.62 * p^*_{wvs}}{101.3 - p^*_{wvs}} \right)^2 * \left(2500.8 - 2.3668 * t_{wet} \right)} \right) * 100 \right)$$

Where

rH	: Relative humidity inside the greenhouse	[%]
p_{wvs}^*	: saturation vapour pressure at the wet-bulb temperature	[kPa]
p_{wvs}	: saturation vapour pressure at the dry-bulb temperature	[kPa]
	being defined in Chapter 4, equation 4-32.	
t_{dry}	: dry-bulb temperature	[°C]
t_{wet}	: wet-bulb temperature in	[°C].

5.2.3 Data collection

To collect data (air-, soil- and wall-temperature, relative humidity and solar irradiation) which were measured in the experiments, a MCU-ITG 1996 datalogger was used. The MCU-

ITG 1996 datalogger has been developed at the Institute of Horticulture and Agricultural Engineering, Hannover University. Figure 5.4 illustrates the parts of this datalogger.

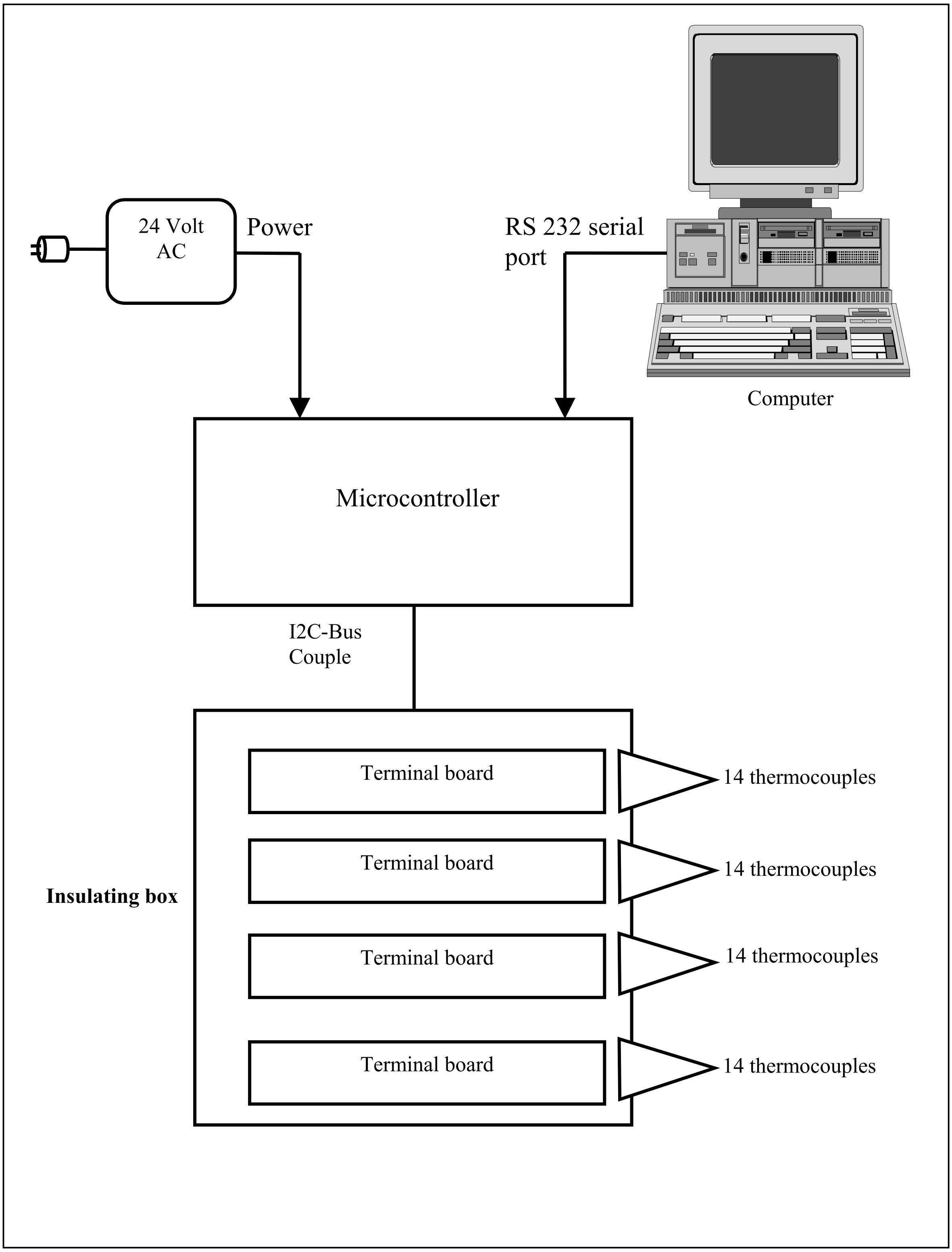

Fig. 5. 4. Datalogger with personal computer

It consists of the following parts:

(1) ITG70: It expands the number of channels that can be read by the Micro datalogger. The system consists of a terminal board, for making gage connections and a multiplexer board, which switches the gage connections. A multiplexer is supported by 16 channels of 4 conductors.

(2) Micro datalogger: especially designed to meet all data collection requirements. It is housed in a rugged, weather-resistant galvanized steel and designed for use in field conditions. The micro datalogger serves as a microcomputer, multimeter, calibrator, scanner, frequency counter and controller.

(3) IBM computer with the special software program which has been developed at the same Institute (TANTAU 2000). The program which operates the datalogging system is created based on the options selected. These options include interval types and channel configuration and weather instruments are connected through ITG70 multiplexer. Each measurement channel can be configured for instrument type and programmed to output temperature corrected data in engineering units. The software provides two-way communication between computer and datalogger. The program has a graph mode which allows real-time graphical display of datalogger measurements. Collected data can be stored in an ASCII file or Exel compatible worksheet.

(4) Power resource, the micro-datalogger can be powered by an external 24 Volt battery.

5.3 Experimental realization

The research was carried out during summer 2001 between April and August at the institute of Horticulture and Agricultural Engineering, Hannover university. The greenhouse was built without irrigation system therefore the grass was irrigated by hand during the experimental period every 15 days. This irrigation treatment was not considered in the studied model. The greenhouse doors were closed during the measurements period.

5.4 Software tools

The solar greenhouse model was designed by using Simulink, which is an interactive tool for modeling, simulating and analysing dynamic systems. Simulink provides a complete set of modeling tools that can be used to quickly develop detailed block diagrams of the systems. It integrates seamlessly with MATLAB, providing the user with immediate access to an extensive range of analysis. Simulink enables the building of graphical block diagrams, simulate dynamic systems, evaluate system performance and refine the designs (PALM 1999).

MATLAB is both a computer programming language and a software environment for using that language effectively (PALM 1999). The MATLAB interactive environment enables the managing variables, importing and exporting data, performing calculations, generating plots, as well as developing and managing files for use with MATLAB. The language was developed for applications involving matrix, linear algebra and numerical analysis (the name MATLAB stands for "Matrix Laboratory"). MATLAB has a number of add-on software modules, called tool-boxes, that perform more specialised computations. More than 16 tool-boxes such as image and signal processing, financial analysis, control systems design and fuzzy logic are available (PALM 1999).

6 Modelling

6.1 General

In general the aim of a simulation model is to simplify the problem. The use of the simulation model allows researchers to build and operate systems in the computer, where weather and other parameters can be varied much more easily and generally as well as economically than to do it experimentally. To perform a thermal simulation of a greenhouse system, the greenhouse model should be made in the following processes (AAS 2002):

(1) Get a clear picture of the problem to deal with **which in the present study is how night temperature could be risen with the use of passive solar energy.**

(2) the greenhouse could be translated into mathematical form which is usually a system of equations, where each equation can be described by a discrete thermal process in the system.

(3) solve the mathematical problem, by equations to demonstrate the greenhouse response over time.

(4) utilize the answer (the output of the simulation model) back into the language of the original problem and

(5) finally evaluate the model output which has been produced (BALCOMB 1995, AAS 2002).

6.1.1 Model developed

Heat transfer is energy in transit due to a temperature difference between two nodes with different temperatures. Considering the whole greenhouse, it is a tedious task to calculate the heat diffusion equation for heat conduction in all parts of the greenhouse and simultaneously calculate the heat transfer between the air and all the surfaces of cover (glass or plastic film), ground, plants and walls, using the equations for convection and radiation. Furthermore, in practice, such a detailed calculation seems to be meaningless due to the uncertain specification of the heat capacities and conductivities. Therefore, the heat dynamics in the greenhouse have to be simplified (NIELSEN and MADSEN 1995). A simple, yet common, simplification is the lumped capacitance method (INCROPERA 1990). The essence of this method is the assumption that the heat capacities of the greenhouse are lumped in certain nodes, which are greenhouse cover, soil, plants, north wall and greenhouse air. The temperature of each node is spatially uniform. For such a model, the energy balance was simulated. The thermal radiative, sensible, latent, and conductive heat fluxes were modeled by mathematical equations in terms of unknown temperatures and vapour pressures. The energy balance equations were then developed for each node in the experimental greenhouse, where the sum of the fluxes at that node should be zero. The equations were solved by an iterative procedure to obtain the unknown temperatures and vapour pressures. Figure 6.1 shows the model of the heat dynamics in the greenhouse. Also, the greenhouse was then designed so that the cover-, soil-, plants-, wall-, and air-temperature can be calculated. The energy balance which was assumed for each node in the greenhouse model is described in the next paragraph.

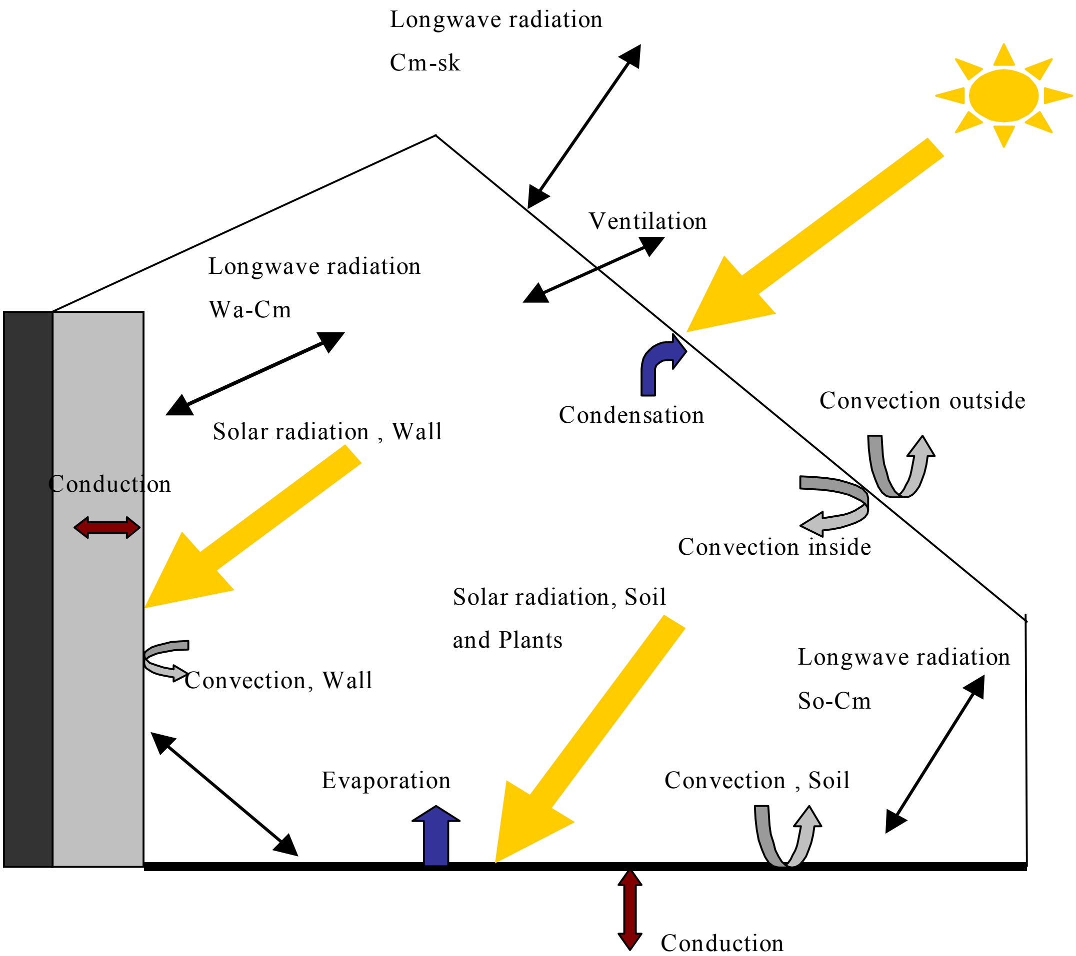

Fig. 6. 1. Schematic illustration of all the energy fluxes occurring in the greenhouse considered by this model

6.1.1.1 Heat balance of greenhouse cover and air

The thermal balance on a layer of covering material can be described by a system of networks connected in parallel and in serial way (see figure 6.2) as follows:

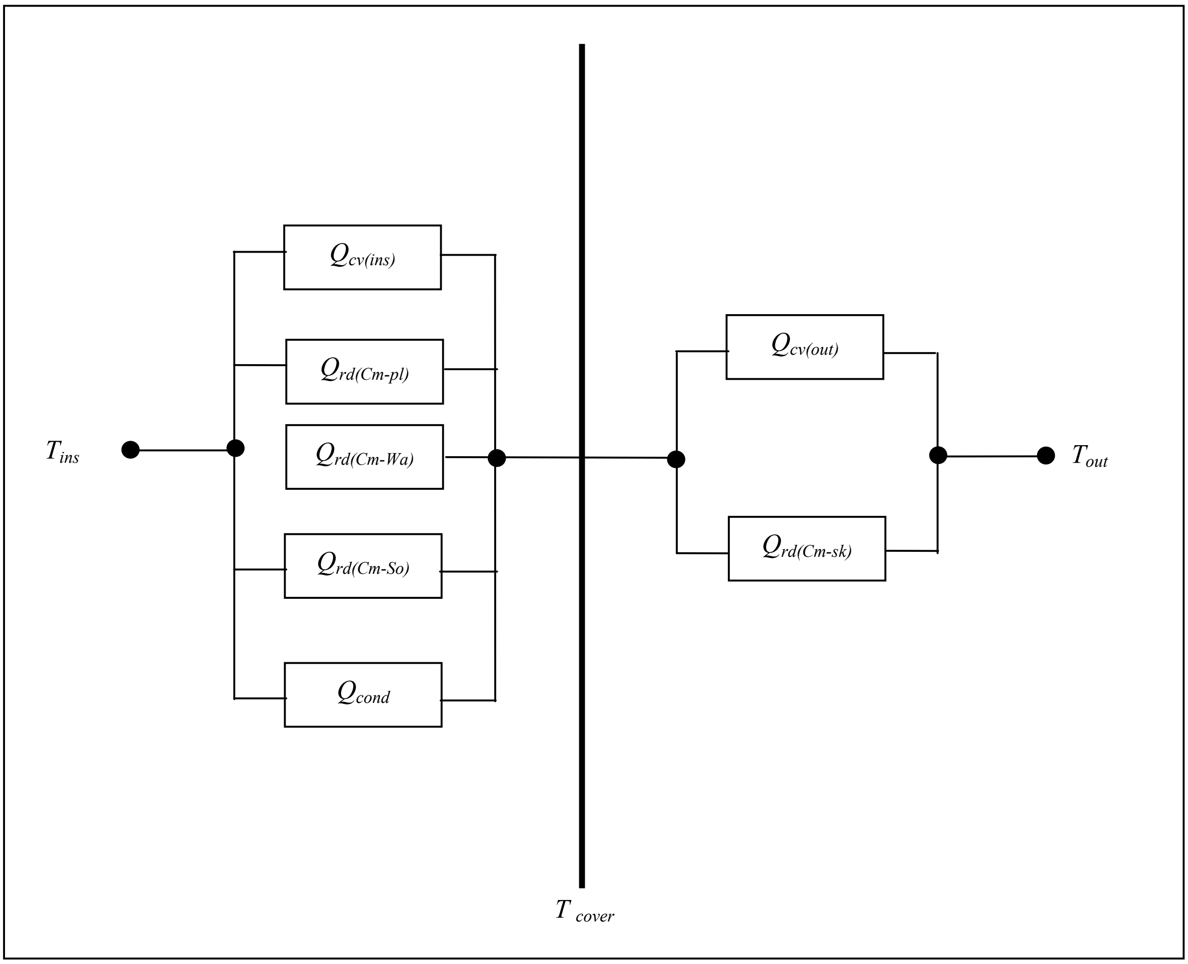

Fig. 6. 2. Heat transfer through the roof of the greenhouse considered by this model

The energy balance equations of both the cover and the air are given in chapter four,4-40 and 4-43 respectively.

6.1.1.2 Heat balance of greenhouse soil and plants

In a greenhouse there are different kinds of heat storage with different time constants such as: cover, air, plants, installations, heating system and soil which should be taken into consideration.

The soil in the greenhouse is considered a large heat storage element (TANTAU 1998). Heat distribution depends on time and depth. For physical models, the soil is divided into different layers. Each layer may have different heat capacity and density. Heat distribution in the soil may vary according to the thickness of soil layers, with decreasing temperature with depth. In the present model, the soil layer is divided unevenly, namely the thinnest at the surface and the thicker towards the bottom, because the soil temperature does not change so much in deep layers (TAKAKURA 1989). The top layer is 1 cm thick but is assumed to be a film surface in the balance equation. This assumption is justified because in practice the soil surface is not smooth and the surface temperature is not well define. This thickness can be reduced for example to 7 mm, , if it is necessary in the simulation.

There are many components involved in heat transfer, all at the surface, as can be shown in fig. 6-1. Those are: direct solar radiation ($Q_{G(So)}$), convective heat transfer ($Q_{cv(So)}$), long-wave radiation exchange between the surface and the other parts of the greenhouse ($Q_{rd(So-Cm)}$, $Q_{rd(So-Wa)}$ and $Q_{rd(So-Pl)}$), heat transfer by conduction to the lower layer ($Q_{cd(So)}$) , not only sensible heat but also latent heat transfer of evaporation (Q_{evap}) while the water movement in the soil is neglected.

The greenhouse-crop system can be considered as a solar collector involving both sensible and latent heat exchanges and its thermal performances can be described in a similar way by using energy balance equation (OKANO et al. 1985, SEGINER and ALBERIGHT 1983; BOULARD and BAILLE 1993). Part of the energy absorbed by the plants is transferred to latent heat due to transpiration. This energy flux resulting from the plants transpiration was mentioned in chapter 4.

6.1.1.3 Heat balance of the concrete north wall

on the wall surface, all types of heat transfer might occur, including absorption of solar radiation, longwave radiative exchange with the surroundings, convective transfer with the inside air, and conductive transfer into the wall. In practice, each element of a building thermal system can be represented by a lumped thermal conductance or a lumped thermal capacitance or a combination of them, interconnected to represent the energy pathways, which are usually idealized to be one-dimensional (BALCOMB 1992). Figure 6.3 demonstrates a thermal network of the north wall used in the model presented here using standard electrical symbols. It shows a simple circuit representing the direct-gain north wall indicated. Node T_{in}

represents the greenhouse air temperature. U_1 is the conductance between the greenhouse air T_{in} and the storage wall surface at T_1. the storage is lumped into one "T-circuit" represented by two equal conductances U_2 and U_3 , and centered heat capacitance C. the system has one solar input, Q_{sol} , and the conductance U_1 is assumed to include long-wave radiation transfer as well as convective transfer.

As mentioned before in chapter 4, the wall thickness is divided into three layers, L1, L2 and L3 which have a thickness of 1, 10, and 19 cm respectively. The three layers have the same physical properties of density, thermal conductivity and heat capacity.

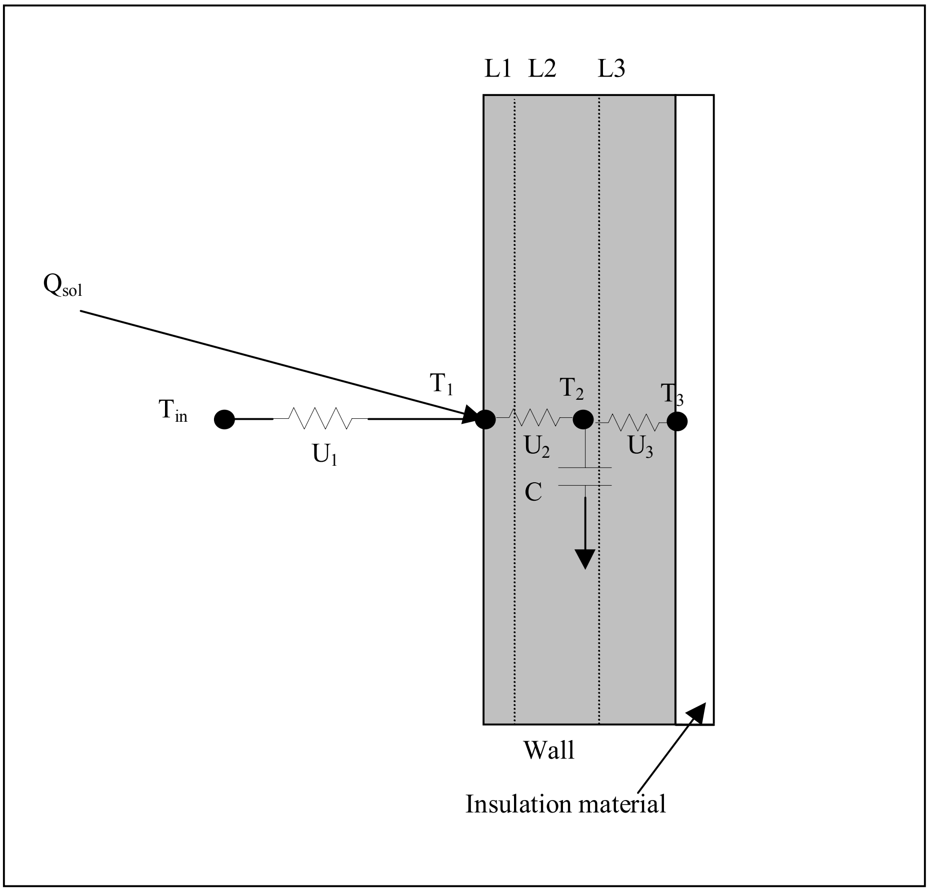

Fig. 6. 3. Thermal network for the north wall considered by this model (variables explanation see text)

The energy balance equation of the wall is given in chapter four 4-40.

6.1.1.4 Model parameters and boundary conditions

6.1.1.4.1 General

The model is based on the fundamental mechanisms that govern the dynamic exchange or storage of heat and water vapour between the various layers which are assumed to be homogenous and infinite in the horizontal plane. Various factors can influence on the behaviour of the model. These factors can be:

(1) greenhouse parameters taken into consideration: these parameters are the typical features of the greenhouse which are divided into five internal layers: the cover, the internal air, the soil, the plants, and the concrete north wall and four boundary layers: the sky, the external air, the sub-soil, and the back wall layers.

They are model inputs and can be divided into two groups (Fig. 6.4). The first group includes parameters supplied by the user such as:

(a) simulation parameters, such as the simulation time,

(b) soil depth considered in the model and the layer's thickness,

(c) soil covering ratio with the plants,

(d) wall thickness and the wall layers thickness

(e) latitude angle, day and month number which were used to calculate the solar radiation at the surfaces.

The second group includes parameters taken from the literature such as:

(a) air exchange number,

(b) heat transfer coefficient at the inside and the outside of the greenhouse,

(c) average value of the wind speed,

(d) the absorptivity of the soil-, wall- and plant-surfaces,

(e) the physical properties of the soil and wall material, such as, thermal conductivity, heat capacity and density

(f) water covering ratio of the soil and plants

(g) the surrounding temperature or the sky temperature.

(2) initial and boundary conditions: Heat transfer fluxes are specified as boundary conditions in all external surfaces. At the wall, soil, roof and plant surfaces, the specified unsteady heat fluxes include absorbed solar radiation, convection and long-wave radiative exchange

between surfaces and sky. The heat fluxes by evaporation, transpiration and condensation are also taken into account in the present study.

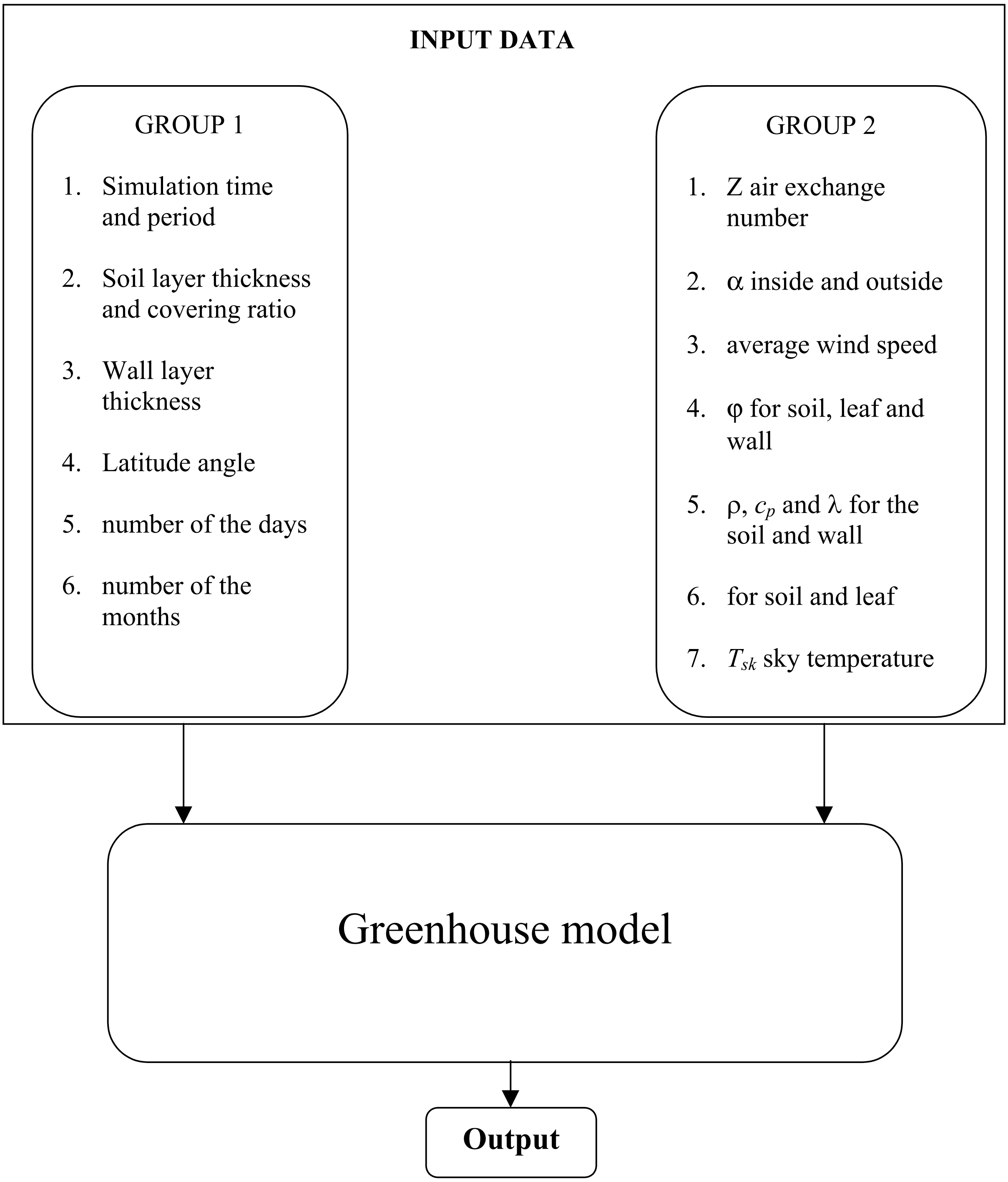

Fig. 6. 4. Illustration of the model inputs

6.1.1.4.2 Optimum parameter values

Performing a sensitivity analysis for a mathematical simulation model is helpful in identifying a key model parameters, the one to which model predictions are sensitive and simulation errors resulting from not definite parameters. The idea underlying behind the methodology of this work is to combine of experimental work (five months) with simulation in order to get a consistent model which can be used to obtain the thermal behaviour of the passive solar greenhouse (PSG) and to perform sensitivity studies that will allow identifying the parameters affecting on the thermal behaviour of the PSG.

With such developed model, it is important to carry out sensitivity analysis or studies for the following purposes:

(1) determining the influence of certain operative and construction parameters of the model on the PSG thermal performance

(2) to select the optimal values of these parameters suitable for this system which give the minimum difference between the measured and predicted results.

The main parameters investigated in the present study are: *heat transfer coefficients* in the inside and outside of the greenhouse since it influences on the temperature all over the greenhouse. It is important to study the parameters that influence on the energy stored in the north wall and in soil, such as *thermal heat capacity*, *thermal conductivity* and *density*. *Surface absorptivity* is also another important parameter which influences on the absorbed solar radiation at the surfaces.

Some other parameters related to the thermal behaviour of the model which can be studied are:

- Long-wave radiation number (dimensionless) which depends on the angle between two surfaces,
- Layers thickness of the wall and soil
- Water covering ratio of the soil and plants.

6.1.1.4.2.1 Heat transfer coefficient

The convection coefficients between the surfaces and the air are assumed to be constant, independent of temperature difference (ALTMYER 1982), though it can be dependent at most on the surface orientation and direction of heat flow. Probably the most widely used values recommended by many literatures (ASHRAE 1981, TANTAU 1983 and BALCOMB 1992) for convection coefficient are shown in table 4.1, chapter four. Figure 6.5 shows the percentage differences between the predicted and measured temperatures as a function of the convection coefficient, at the inside and outside of the greenhouse. It also shows how these percentage differences varies with change of Alpha (α), where it was found to be sensitive to this parameter. This is because the main part of the convective heat from the wall, soil and the cover diffuses into the air of the greenhouse. As it can be seen, the increase in alpha leads to the decrease of the differences between the measured and the predicted temperatures. However, increasing its value above the optimum value increases the differences between the measured and the predicted temperatures. As previously mentioned, the measured data have been taken during the period between 1 April – 31 August 2001 of which four periods were chosen from the second half of the months of April, May, June and August. Each 15 days period was divided to 10 days (15-25 of each month) to calculate the optimal values of the parameters considered in the model and the other five days (between 26-30) for the evaluation.

For calculating the optimal values of the parameters, the following steps were followed:

- First of all, searching the values mentioned in the related literature, for example, α was found to be in the range between 2-5 [$Wm^{-2}K^{-1}$] within the greenhouses. Therefore, during analysis, the start value was chosen to be equal to 1 and the same procedures were followed for the other factors. The evaluation was tested for values ranging between 1 up to more than5. However, it was not presented here because of the high differences observed and thus only the values in the range between 1-5 are presented.

- Analysis and calculation were carried out with a 10 minutes intervals for that 10 days period.

- The observed difference, i.e. the residual was calculated as percentage [%] as follows: Residuals [%] were calculated by considering the maximum value of the difference between the calculated and measured values of the air in the greenhouse. The maximum value was 500 [K] for 10 simulation days. This value was considered as 100 % and the values of the other parameters were calculated as percent compared to the maximum value. The optimum values accordingly calculated of alpha (α) are listed in table (6.1).

- Due to this kind of calculation, a value of 100 % does not appear here on all drawn figures, because its values are outside the range limit of the difference between the measured and the calculated values.

- The optimum value of the studied parameters calculated in April was used for the other months of study (i.e. May, June and August) and was evaluated and found to be not changed and therefore it was used as it is for the other periods of evaluation.

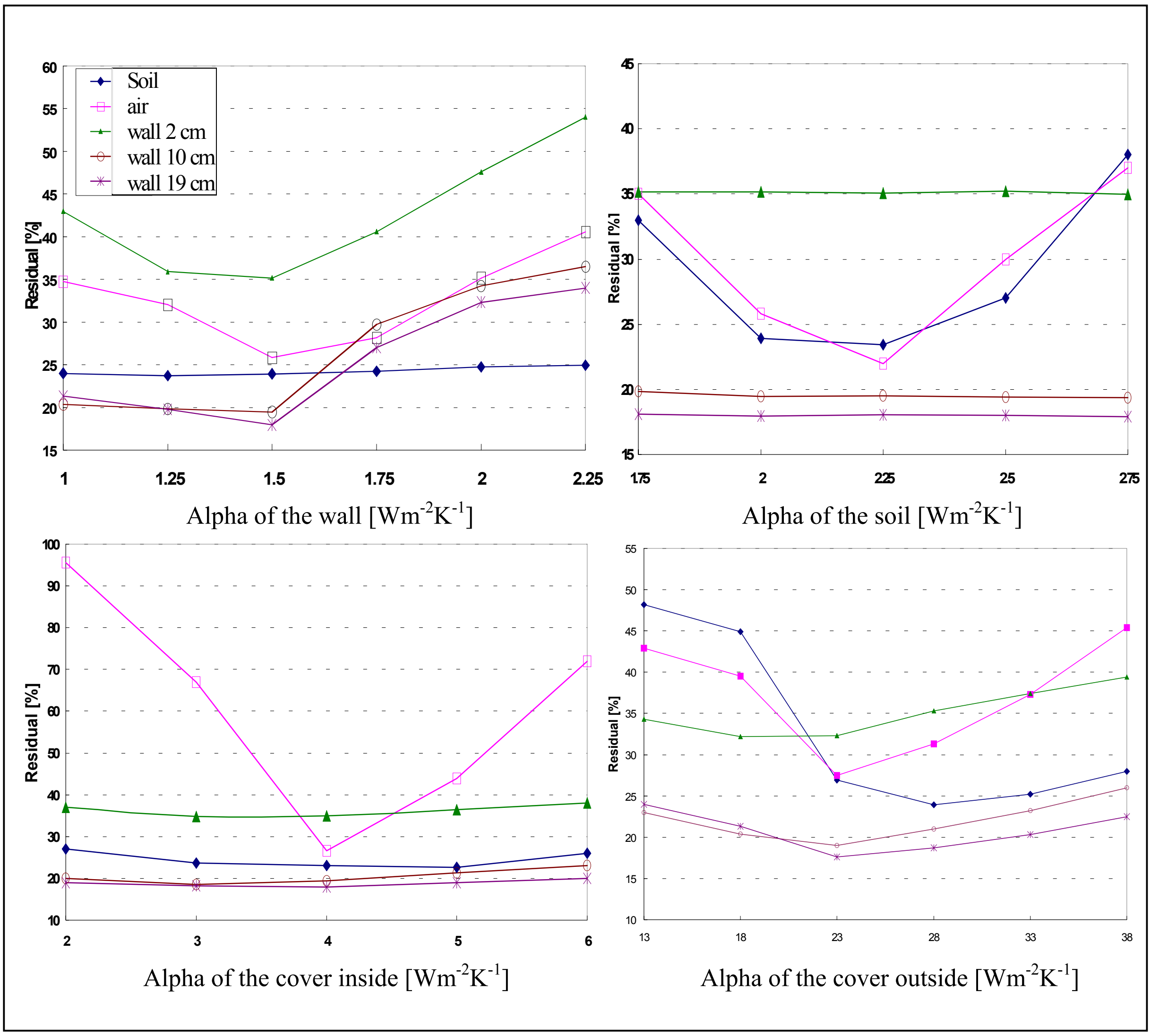

Fig. 6. 5. Effect of heat transfer coefficient (α) on the residual of soil, wall and air

6.1.1.4.2.2 Specific heat capacity

Another important parameter is the specific heat which is a temperature-dependent parameter. However, for the purpose of many engineering calculations, these variations are small and an average specific heat value is usually used for the temperature range considered

(LEWIS 1990). As figure 6.6 shows, there is a visible extreme, at which the percentage differences between measured and predicted is minimal. Too small a specific heat allows the percentage differences to be decreased considerably, which cause in turn high variations in the stored energy on which the temperature is dependent. The increase of the specific heat over the optimum point, however, causes a fast increase in the percentage differences between measured and predicted temperatures.

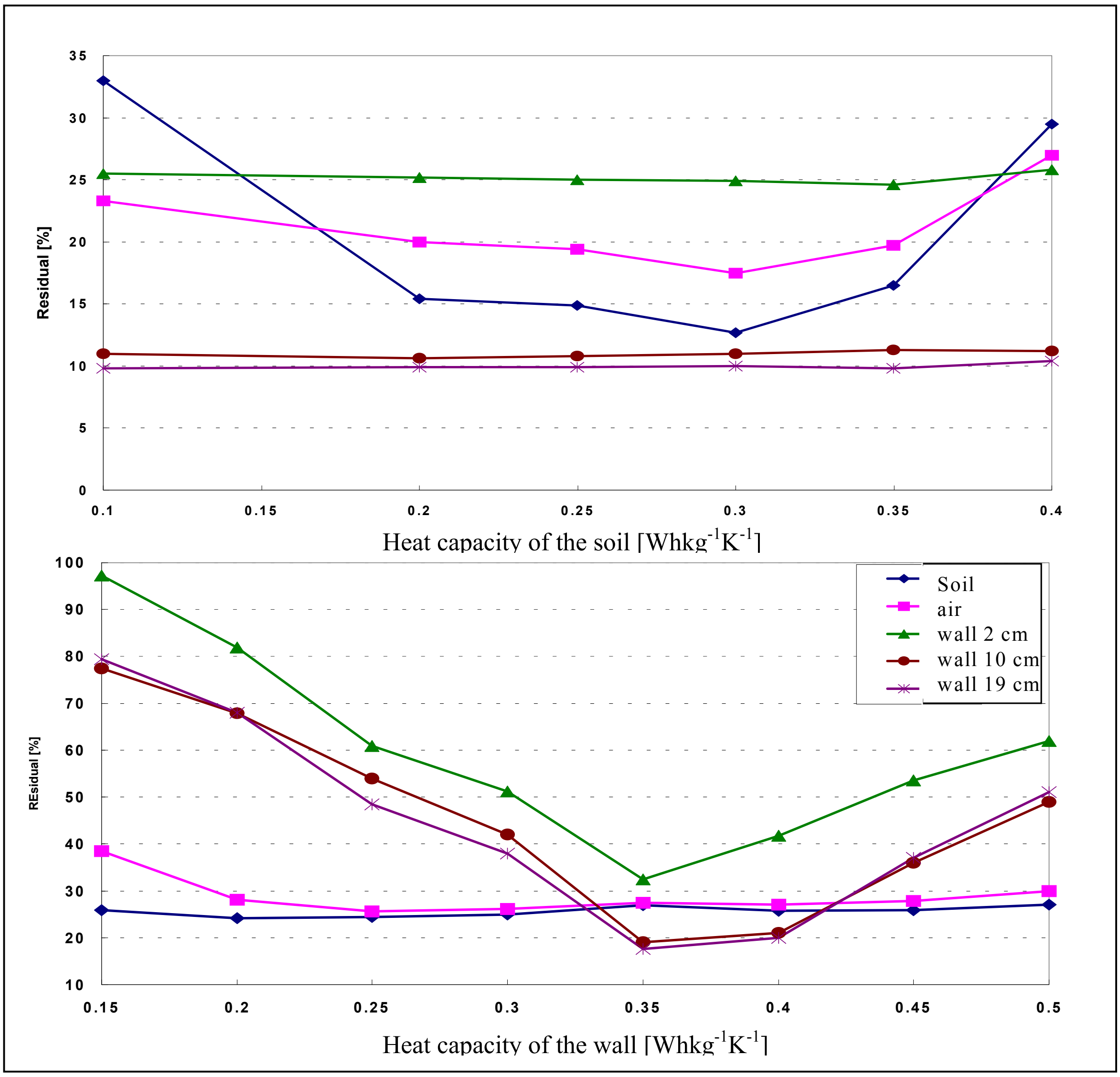

Fig. 6. 6. Effect of heat capacity on the residual of soil, wall and air: (a)heat capacity of the soil, (b) heat capacity of the wall

6.1.1.4.2.3 Thermal conductivity

Thermal conductivity is another important parameter. The influence of the thermal conductivity is pronounced on the charging and discharging cycle of the heat. If the deeper portions of the wall or soil are isolated from the inside air by a layer of low-thermal-conductivity material, they can not then have any role in the heat cycle. Figure 6.7 illustrates the influence of the thermal conductivity of the wall-, and soil-material on the percentage differences between measured and predicted temperatures. It can be observed that, when the thermal conductivity of the wall and the soil is lower or higher than the optimum value, the differences between the measured and predicted temperatures become high. It can also be seen that, the influence of thermal conductivity is bigger on the difference between measured and predicted wall temperature than on the difference between measured and predicted soil temperature.

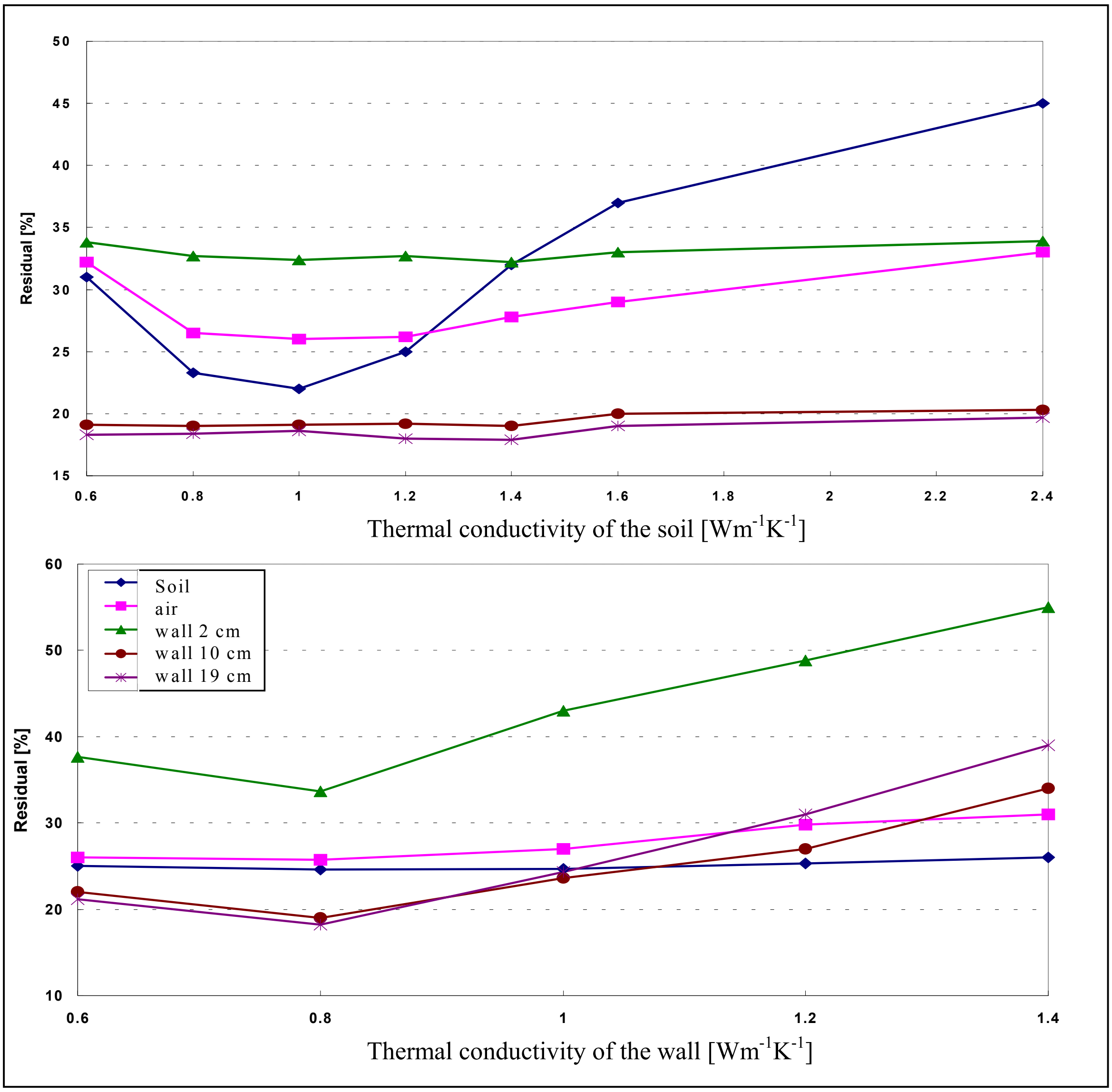

Fig. 6. 7. Effect of thermal conductivity on the residual of soil-, wall- and air temperature

6.1.1.4.2.4 Overview

The optimum values obtained by this study are compared to that found in the literature as it can be seen in the following table (table 6.1).

Table 6. 1: Literature-, and optimum-values of the parameters considered by this model

Parameter	Literature-Values	References	Optimum-Values
α_{inside} [$Wm^{-2}K^{-1}$]	2-5 & < 2 for wall	TANTAU 1983, RAMAN 2001	2.25 for soil, 1.5 for wall and 4 for cover
$\alpha_{outside}$ [$Wm^{-2}K^{-1}$]	4-34	TANTAU 1983, NILES 1992	23
$c_{p(Wa)}$ [$Wh\ kg^{-1}K^{-1}$]	0.245 – 0.55	FAROUKI 1986	0.35
$c_{p(So)}$ [$Wh\ kg^{-1}K^{-1}$]	0.236 – 0.40	FAROUKI 1986	0.30
$\lambda_{(Wa)}$ [$Wm^{-1}K^{-1}$]	0.8 – 1.4	INCROPORA 1990	0.8
$\lambda_{(So)}$ [$Wm^{-1}K^{-1}$]	0.8 – 2.3	ELSHEIKH 2001	1.0
ϕ_{Cm-So} [-]	0.17 – 0.4	STRAUCH 1985	0.25 – 0.40
ϕ_{Cm-sk} [-]	0.5 – 1.0	STRAUCH 1985	0.5
$\zeta_{(So)}$ [-]	0.0 – 0.8	STRAUCH 1985	0.20
$\zeta_{(Pl)}$ [-]	0.40	STRAUCH 1985	0.40

It should be noted that the water covering ratio of the plants was considered as 0.40.

6.1.1.5 Input data and method of solution

The simulation was run after input of average hourly meteorological data. The meteorological data used as input are outside temperature, the inside solar radiation on the soil surface and the solar radiation on the wall. To prepare the input data, a program was written with MATLAB (PALM 1999).

Equations from 4-40 to 4-45 represent a system of 5 equations with 5 unknowns T_{So}, T_{Wa}, T_{ins}, T_{Pl}, T_{Cm} which has to be solved. Usually, the behaviour of the greenhouse system is analyzed for some specified daily histories of the external conditions, and to this end an arbitrary initial condition is used taking advantage of the fact that parabolic equations tend to forget rapidly their initial conditions (KINDELAN 1980). In this way, after integrating the equations with the same external conditions during nine or ten identical day periods, a periodic solution is obtained which is independent of the initial condition and therefore represents the appropriate solution. The same method of solution can be used to analyze the greenhouse response when data for the real ambient conditions existing on a given location are available for a sufficiently long period of time. In this case the results of the simulation for the first 9 or 10 days will depend on the initial condition used, and therefore will not be accurate. However, after this period, the solution obtained will accurately represent the behaviour of the system. This procedure eliminates the need of specifying the deep ground temperature which instead is obtained as an additional result of the simulation.

6.1.2 Model validation

6.1.2.1 Greenhouse air temperature

The simulation results obtained from this model are considered “blind”, since they have not been yet compared with the experimental results from the greenhouse. The comparison between measured and simulated results is very important in order to check out how far the simulated results are from the measured ones. It gives an idea, if there are any obvious errors and prospects about the possibility of improvements that can be achieved by such model.

Air temperature in the greenhouse is considered a very important environmental condition affecting on the plant growth. To investigate the model’s ability to predict and describe the greenhouse climate during different times, simulations were compared with measurements at four periods of 5 consecutive days as follows: the first is between 26-30 April, the second is between 26-30 May, the third is between 26-30 June and the last is between 26-30 August 2001. Figure 6.8 presents the simulation results obtained assuming that the state of the plants-and cover-temperatures, which were not measured, to be equal to the simulated values obtained from the model during the simulation periods. On the sunny days, the inside air temperature reaches its peak value later in the day than the outside air temperature. As expected, this time-lag increases as the thermal mass of the greenhouse components increase. The air temperature inside the closed greenhouse reached the maximal value of 53 °C, while the solar radiation reached the maximal value of 528 Wm^{-2} in August 2001.

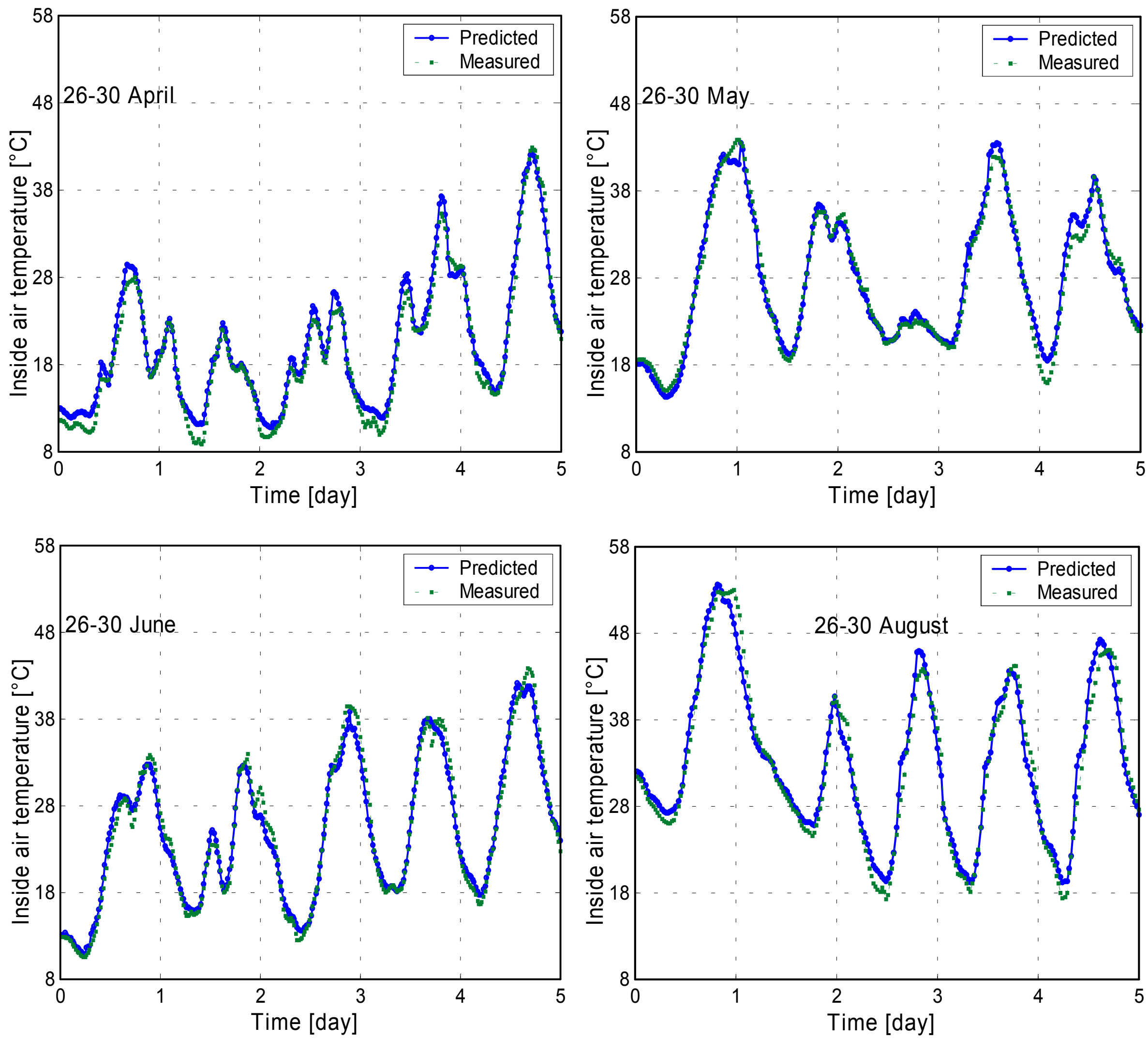

Fig. 6. 8. Diurnal cycles of predicted and measured air temperature inside the greenhouse for 20 days

The figure shows also that the simulated inside temperature followed the same trends as that measured one but with some variations in timing of the peak values. The simulated air temperature sometimes higher, sometimes lower or almost equal the measured variable.

Figure 6.9 represents the differences between the measured and the predicted values of the inside temperature during the simulation periods, where it can be seen that the higher difference occurred in the middle of the day and declined late afternoon and early morning. The maximum differences between measured and predicted temperature profile are 3.23 K in June, while it is 2.75, 3.10 and 3.14 K for April, May and August respectively. This situation can be ascribed to different reasons, such as solar radiation variations and opened doors which was not considered in this model. However, the errors obtained are similar to the common greenhouse climate modeling.

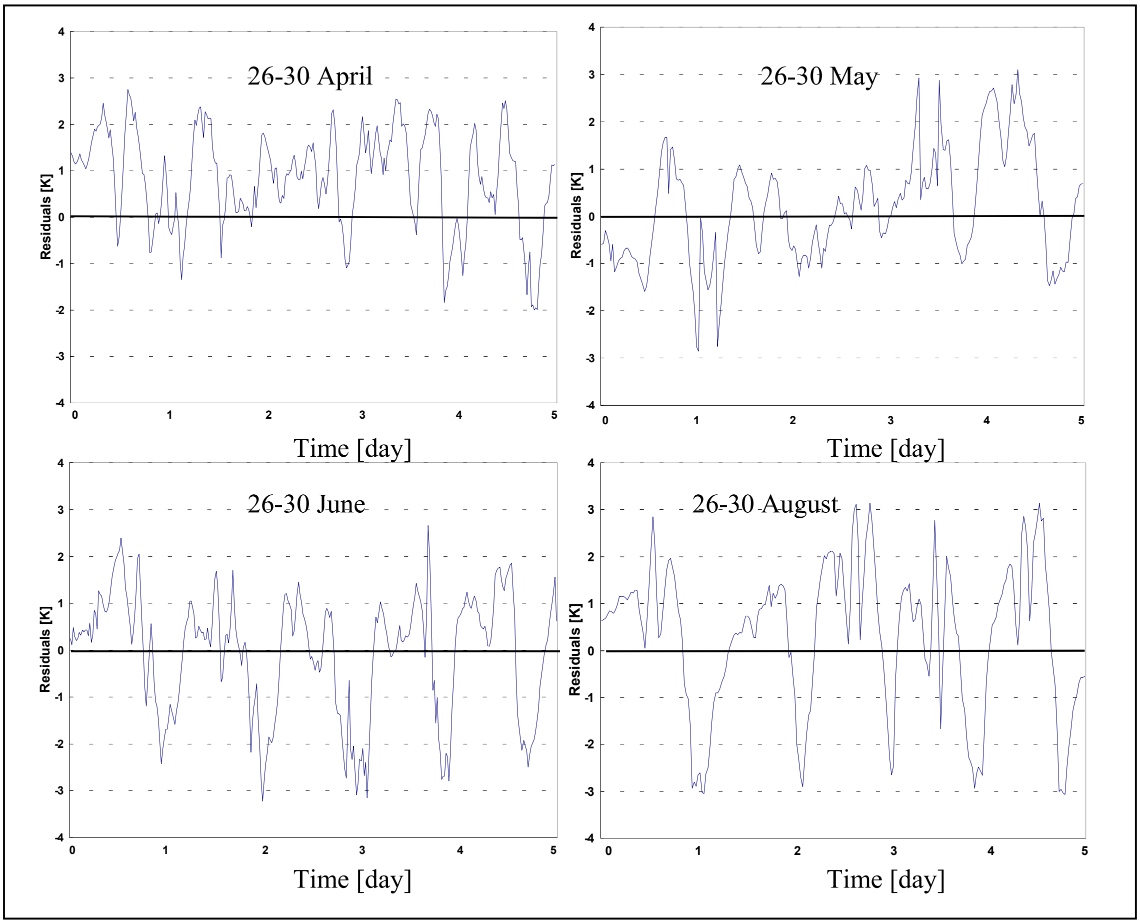

Fig. 6. 9. Residuals of the measured and predicted inside air temperature for the four periods studied

In context of studies of passive solar greenhouse in this model, the distribution of the residuals of the inside air temperatures as a function of measured air temperature, solar radiation and outside temperature were plotted (Fig. 6.11). It can be observed that,

- the points are scattered above and below the zero line,

- For the period between 26-30 April, there was a small disturbance at the beginning of the simulation where the temperatures of both inside and outside the greenhouse were between 10-15 and 8-15 °C respectively. This disturbance can be due to the fact that the model starts the calculation from zero and reach a state less or more than the actual value according to the data used in the simulation and accordingly a difference between the calculated and measured values can be observed at the beginning of the simulation.

In respect to the solar radiation, if all points are considered together, the residual increases with increasing of the solar radiation (Fig. 6.10). However, its effects remain in the acceptable range of the differences observed between the measured and calculated values. On the other hand, the solar radiation is considered the most important factor affecting on the results of the model.

The experimental data (independent variable) were plotted as a function of the simulated ones for the inside air temperature for the periods of 26-30 April, 26-30 May, 26-30 June and 26-30 August (figure see appendix). Although, there is a correlation between the measured and simulated air temperature values, other factors such as greenhouse construction material and measured devices in the greenhouse have also influences on air temperature besides those expressed by the equation 4-41 mentioned earlier in chapter four. Nevertheless, the points scattered above and below the regression line show a good agreement between the simulated versus measured air temperature and over a reasonably prolonged duration.

The correlation coefficients of the greenhouse inside temperature between simulation and measurements throughout all simulation periods of April, May, June and August were 0.991, 0.988, 0.989 and 0.984 respectively (figure see appendix).

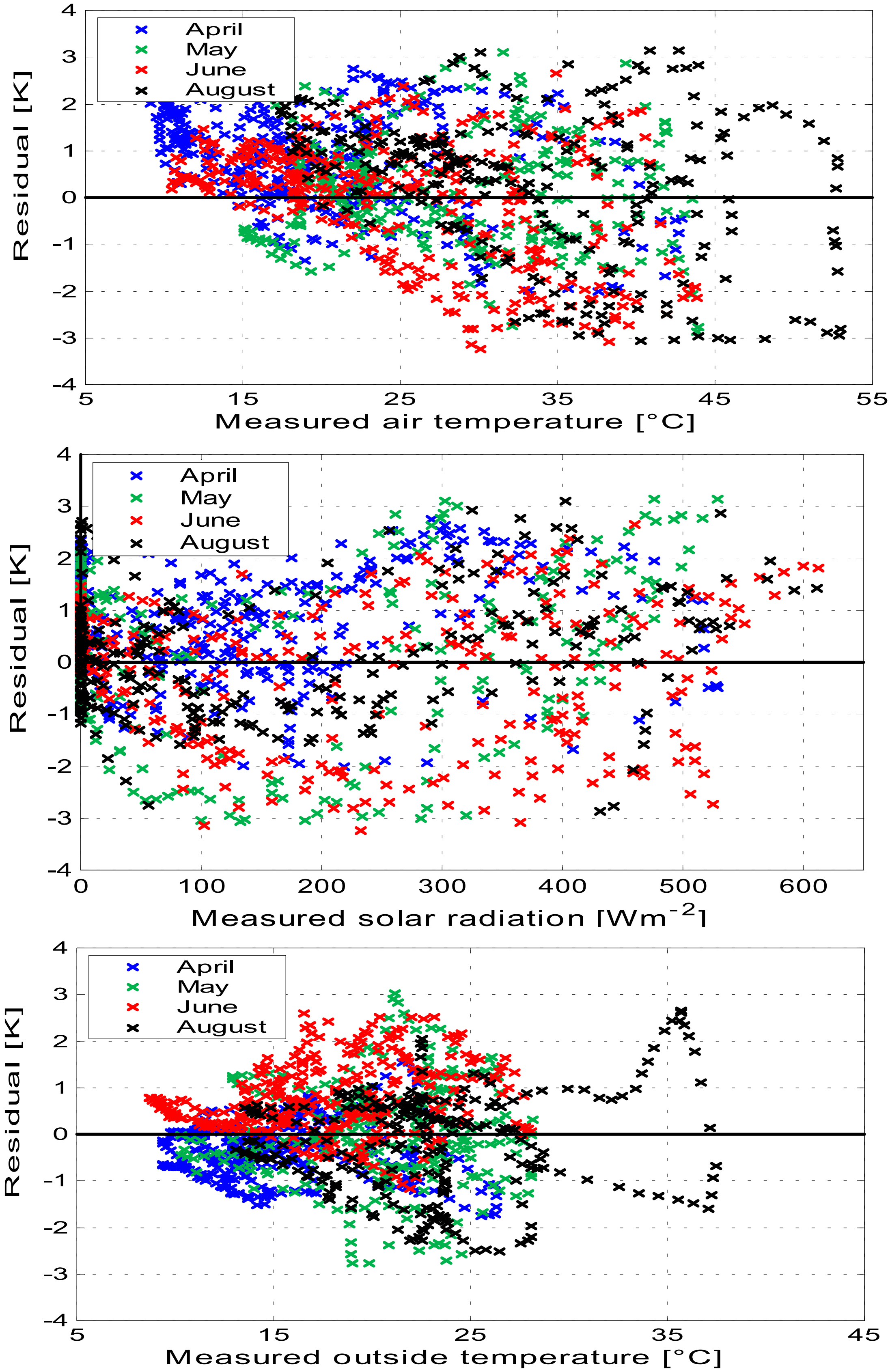

Fig. 6. 10. Plot of residuals (predicted - measured) of the inside air temperature versus: inside air temperature, solar radiation and outside air temperature

6.1.2.2 Soil Surface Temperature

The soil surface microclimate controls near-surface biological processes, including seed germination, plant establishment, and micro-organisms population dynamics. Soil surface microclimate characterized by soil temperature and water conditions can be altered through management. Soil temperature plays an important role in many processes, occurring in the soil, such as chemical reactions and biological interactions. Soil temperature varies in response to exchange processes that take place primarily through the soil surface. These effects are distributed into the soil profile by transport processes and are influenced by different factors such as the specific heat capacity, thermal conductivity and thermal diffusibility.

The simplest mathematical representation of the fluctuating thermal regime in the soil profile is assuming that at all soil depths, the temperature oscillates as a pure harmonic (sinusoidal) function of time around an average value' (HILLEL, 1980). At each succeeding depth, the peak temperature is dampened and shifted progressively over time. The degree of damping increases with depth and is related to the thermal properties of the soil and the frequency of the temperature fluctuations. Plots of temperature versus time were fitted with a sinusoidal function for depths of 1, 10 and 35cm (Fig. 6.11). The highest peak is found to be at 1 cm with 49 degrees, followed by a depth of 10 and 35 cm below the soil surface with accompanying average temperatures of 41 and 27.5 degrees respectively. At depth of 36 cm the fluctuation in temperature is neglected since the temperature remains constant throughout the experimental time (Fig. 6.11). This data clearly shows how damping increases with depth.

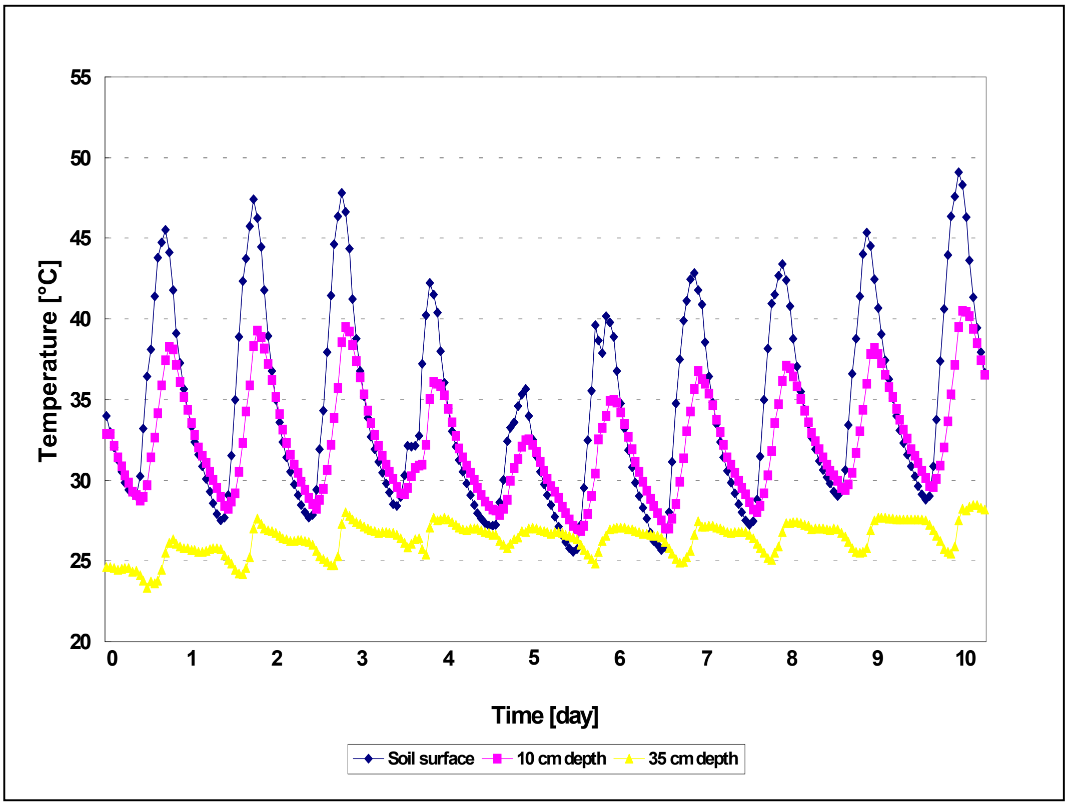

Fig. 6. 11. Measured soil layer temperatures during August 16-25 (2001).

Figure 6.12 shows the time evolution of the simulated and measured soil surface temperatures for 20 successive sunny days. It was observed that the soil surface temperature fluctuated and increased over time from April until August with a maximum value of 49 °C. This can be due to two reasons, the first is the high solar radiation and the second is that the soil surface was influenced by the greenhouse environment. A good consistency can be observed between the simulated soil surface thermal regime and the available field measurements.

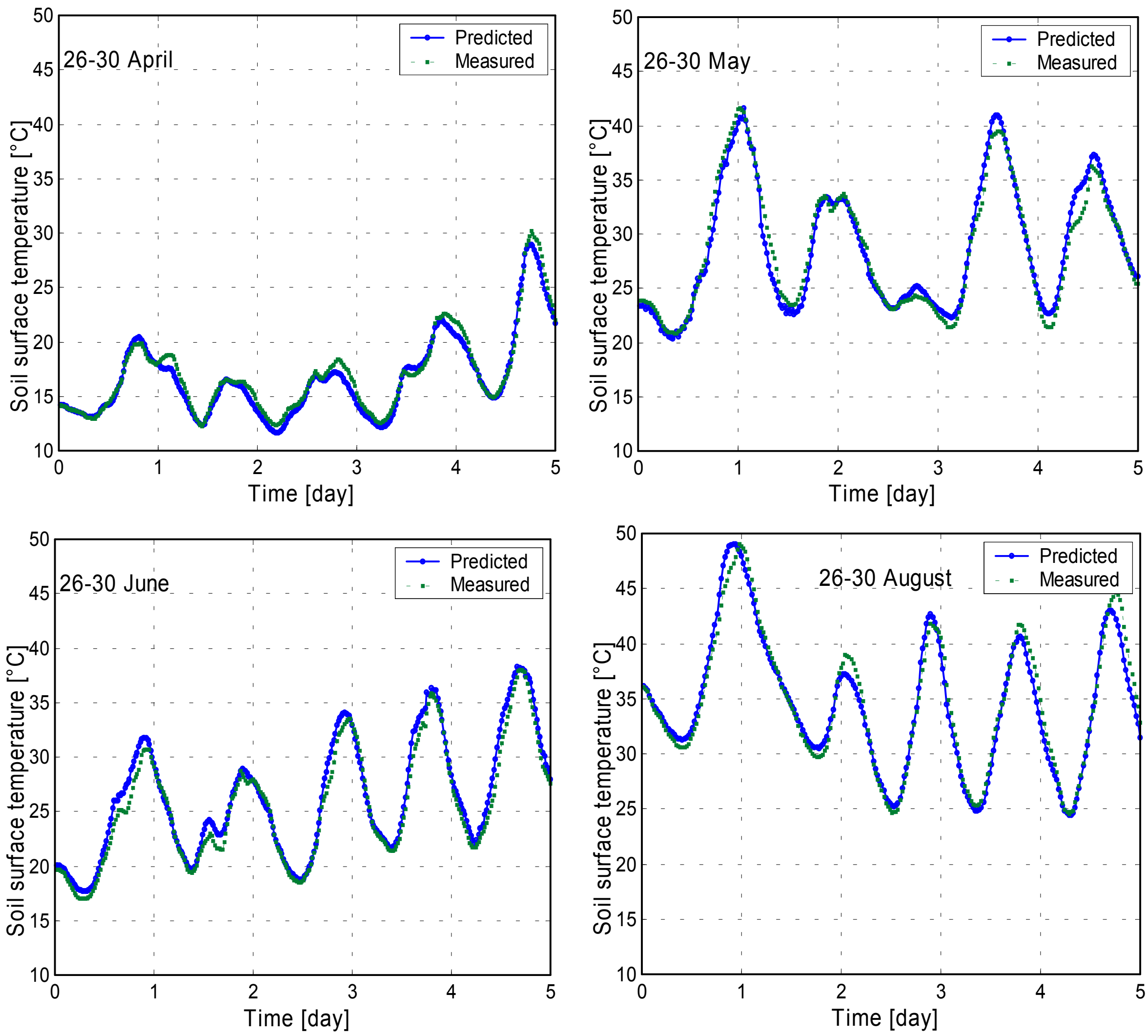

Fig. 6. 12. Diurnal cycles of predicted and measured soil surface temperature inside the greenhouse throughout 20 days

In some days, differences between measured and predicted soil surface temperature profiles could be observed (Fig. 6.13). The difference observed in the absolute maximum temperature between the measured and predicted one was 3.05 K in August, while it were 2.75, 2.45 and 2.65 K in April, May and June respectively. It could be observed that the maximum differences between measured and predicted soil surface temperature occur in the middle of the day and declined at the other times.

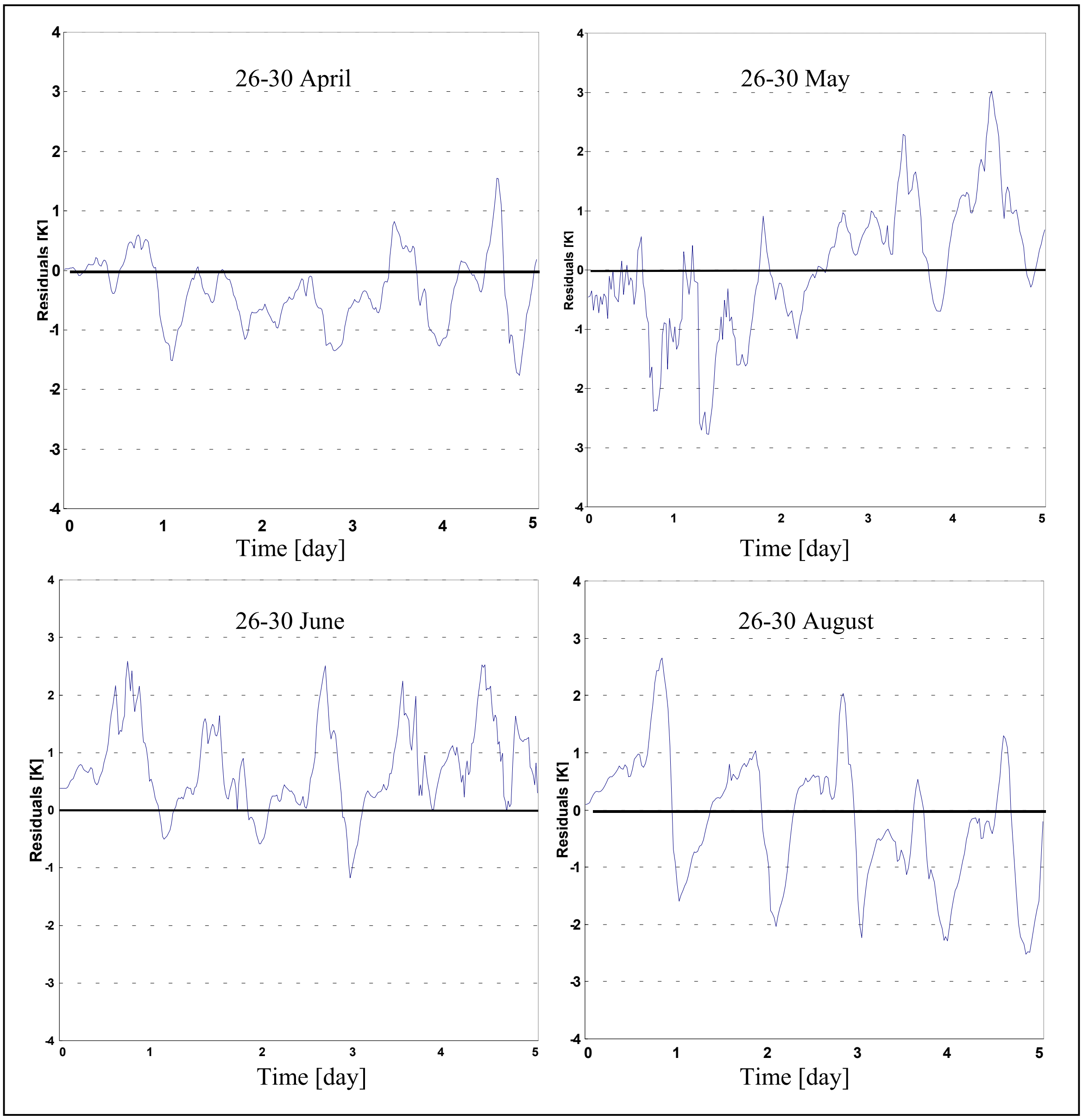

Fig. 6. 13. Residuals of the measured and predicted soil surface temperature for the four periods studied

The accuracy of the model in predicting soil surface temperature was evaluated by studying the effect of soil surface temperature, greenhouse air temperature and solar radiation on the differences between the measured and the predicted temperatures by the model throughout 20 days. The results are illustrated in figure 6.14. It can be seen that the points are scattered over and below zero line and the differences observed between measured and predicted temperature increase with the increasing of solar radiation, soil surface temperature and inside temperature.

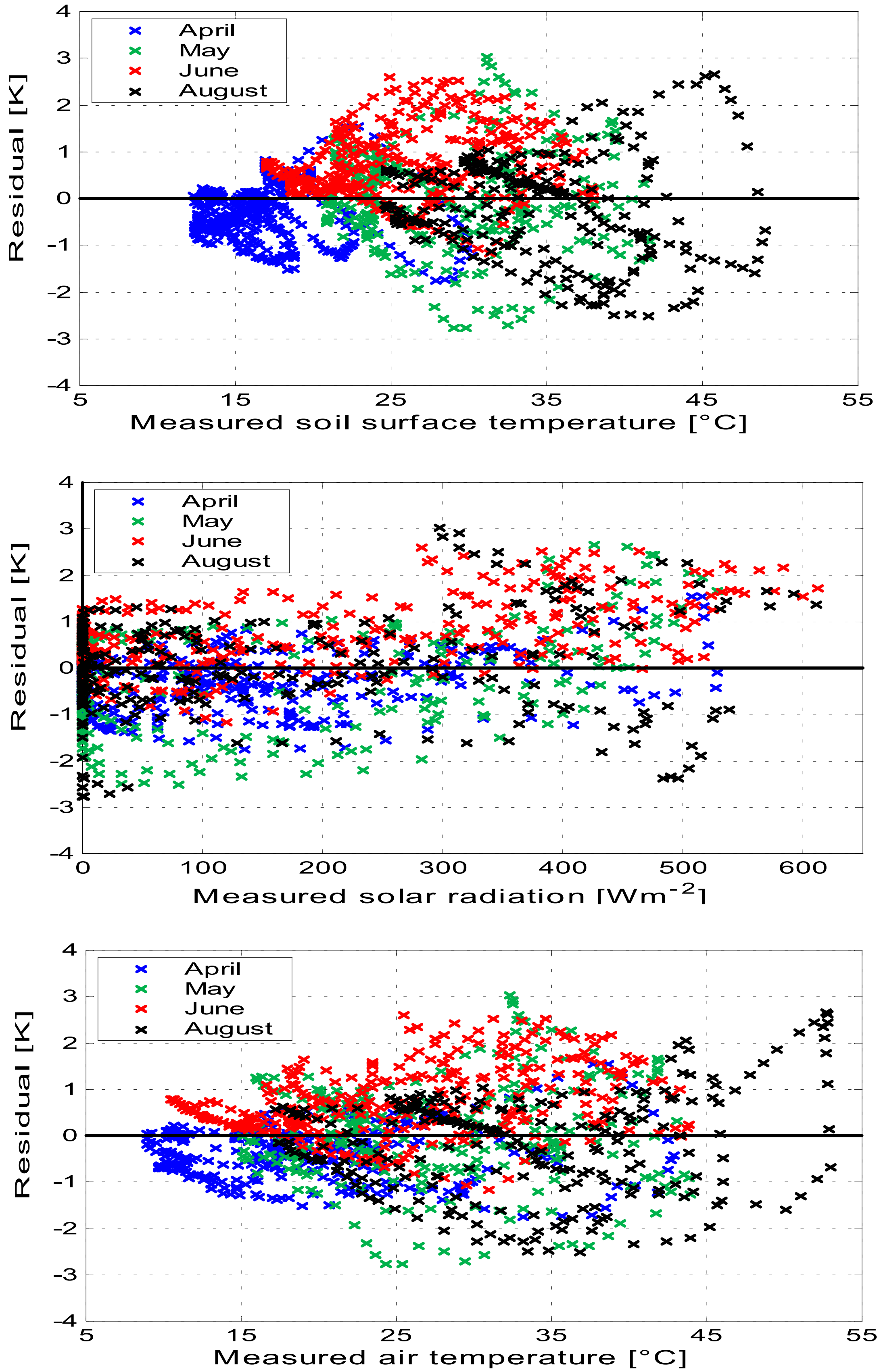

Fig. 6. 14. Plot of residuals (predicted – measured) of the soil surface temperature versus: measured soil surface temperature, measured solar radiation and measured inside air temperature.

The relationship between measured and predicted values of the soil surface temperature throughout the simulation periods are illustrated (figure see appendix). It can be seen that the points are scattered above and below the regression line 1:1 which indicates a good consistency between the predicted soil surface thermal regime and the available field measurements, with correlation coefficients of 0.98, 0.99, 0.99 and 0.98 for the simulation periods: April, May, June and August respectively.

6.1.2.3 Wall Temperature

6.1.2.3.1 General

An important factor in determination of heating loads of the air-conditioned greenhouse is the calculation of the effect of solar radiation through covering material (PE plastic film). Radiation enters into the greenhouse and distributed on the soil, plants and wall surface layers. One part of the absorbed heat is transferred to the inner layer of the greenhouse elements, and the other part is transferred by convection to the air in the greenhouse. Considering what happens at each point inside the wall, the temperature variation is sinusoidal and the heat flow through any plane parallel to the surface is also sinusoidal. The magnitude of the sine wave decreases rapidly as the distance from the surface increases. The phase of the sine wave also changes with distance into the wall. At some point, deep inside the wall, the sine waves are completely out of phase with the sine waves at the surface. Thus the deeper portions of the wall can be counteracting the effect of storage in the outer portions of the wall (BALCOMB, 1979).

The simulation of unsteady heat transfer through the walls of an enclosure is becoming a fundamental element of time-dependant building heat load calculations. HEATNET illustrates this by solving Fourier's one dimensional unsteady conduction equation for heat transfer through a multi-layer wall with or without internal cavity (THOMAS 2002). The heat flow is driven by a convective and radiative input to the internal and external surfaces of the wall.

The objective of the software simulation is to give a full understanding of the parameters affecting on heat transfer through a multi-layer wall under time-dependent internal and external temperature conditions.

The following input parameters should be controlled:

- Number of wall layers,
- Individual layer properties, density, thermal conductivity & specific heat
- Layer thickness
- Internal and external time-dependant temperature.

Output includes:

- Plots of temperature versus distance at selected time intervals through the simulation period
- Temperature time profile for individual locations through the wall profiles.

The temperature ranges and the range of properties included in the simulation are defined by user. Temperature changes over time at interlayer nodes through the wall are studied at a series of intervals during the simulation period (20 days).

As mentioned earlier, the wall was divided into three layers 1, 10 and 19 cm and all layers are considered to have the same thermal properties such as thermal conductivity, density and heat capacity. The results of the comparison between measured and predicted wall layer temperatures are described below.

6.1.2.3.2 Wall surface Temperature

The surface temperature is a key parameter for surface turbulent fluxes and aerodynamic resistance. With the expanding availability of remotely sensored data, the surface temperature is often used as either input or as a validation of soil, vegetation and wall atmosphere transfer models. On the sunny days, the wall surface temperature reaches its peak value later in the day than the inside air temperature. A comparison of measured wall surface temperature with the simulated surface temperature is shown in Fig. 6.15 for the four simulation periods studied: 26-30 April, 26-30 May, 26-30 June and 26-30 August. The figure shows that the simulated wall surface temperature followed the same trends as that measured one, but with some variations specially in the peak values. The simulated wall surface temperature was sometimes higher, sometimes lower or almost equal to the measured variable. The surface temperature of the wall resulting from solar radiation and environment of the greenhouse reached its maximum value in August with 58.24 °C, while it was 37.05, 44.73 and 42.75 °C in April , May and June respectively.

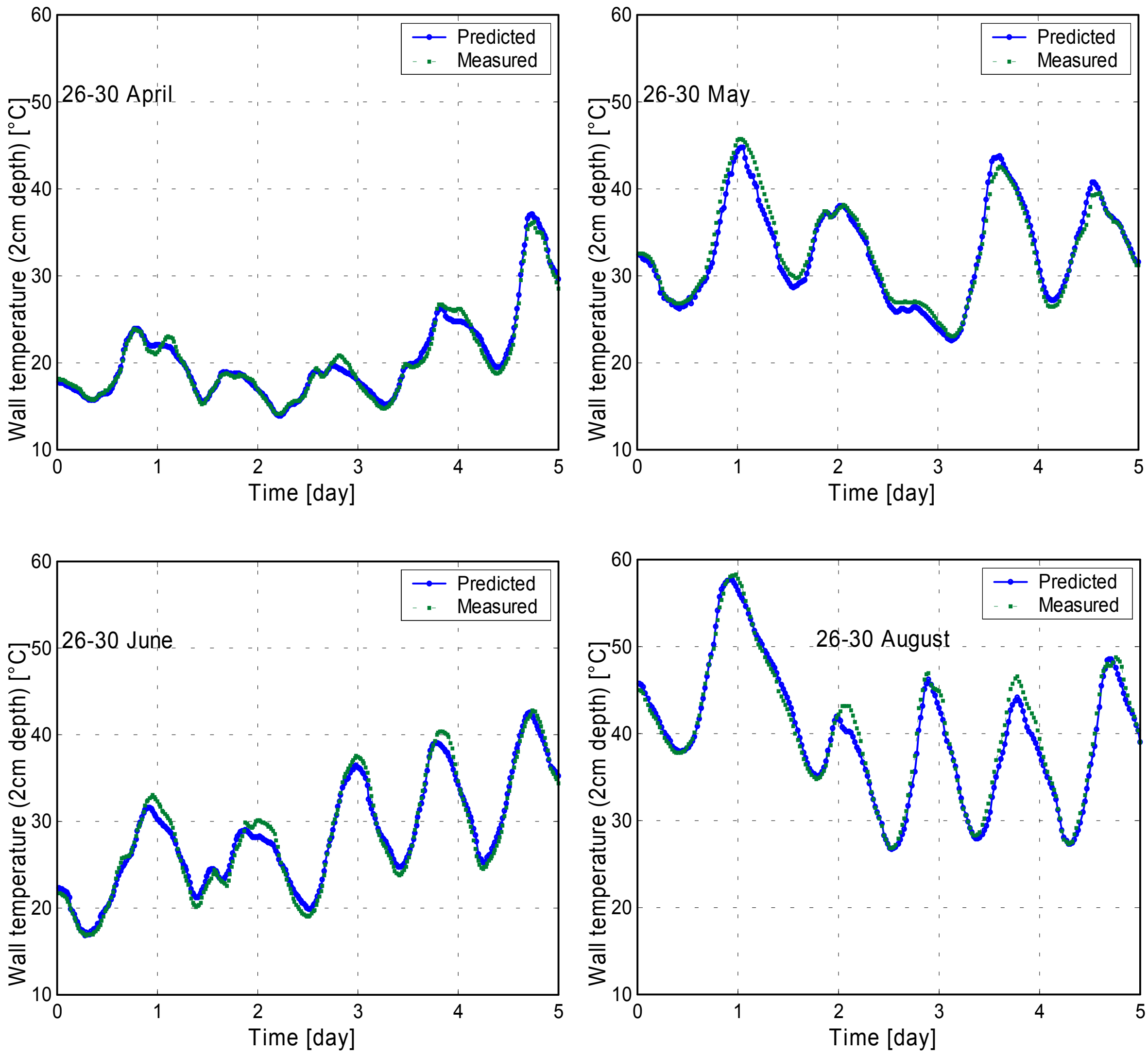

Fig. 6. 15. Diurnal cycles of predicted and measured wall surface temperature inside the greenhouse throughout 20 days

Figure 6.16 illustrates the differences observed between the measured and the predicted values of wall surface temperature for the simulation periods studied. It can be seen that the higher difference is observed in the middle of the day and declined late afternoon and early morning. The maximum difference between measured and predicted temperature profile was 2.99 K in May, while it was 1.56, 2.17 and 2.64 K for April, June and August respectively. This situation can result from different reasons, such as, solar radiation variations, measuring error and error at defining the heat capacitance of the wall material. However, the errors obtained are similar to the general passive solar wall modeling. The standard deviation of the wall surface temperature between simulation and measurements throughout all simulation periods: April, May, June and august were 0.81, 0.92, 0.96 and 1.2 K respectively.

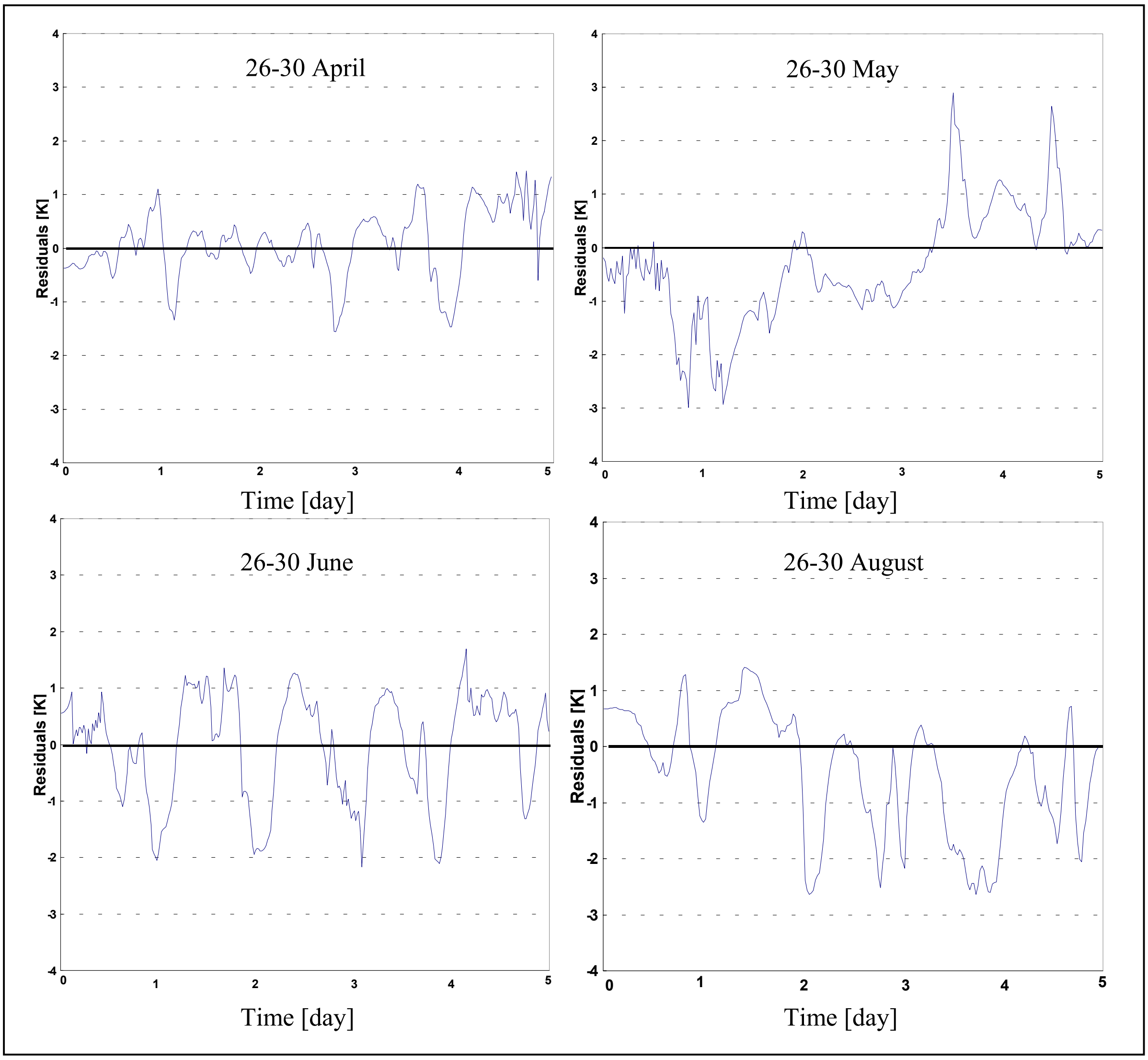

Fig. 6. 16. Residuals of the measured and predicted wall surface temperature for the four periods studied

The relationships among the residual and the wall surface temperature, greenhouse inside temperature and solar radiation are presented in figure 6.17. It can be observed that the important factor which has a considerable influence on the residual is the solar radiation, since the residual increases with increasing solar radiation. This results confirmed that the model output is acceptable for wall surface temperature. The good agreement found between the measured and predicted wall surface temperature identifies that the parameterisation in the model is effective.

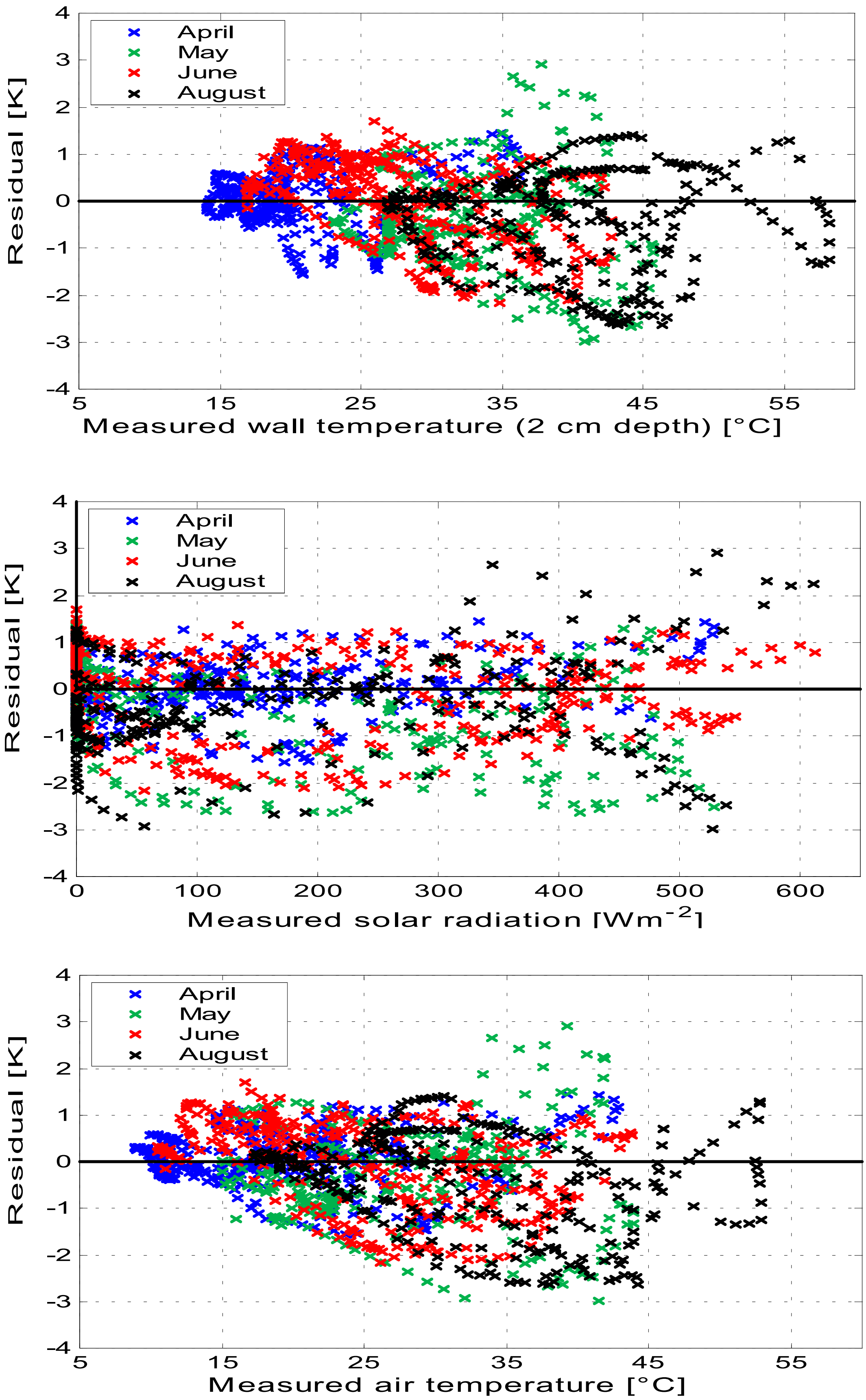

Fig. 6. 17. Plot of residuals of the wall surface temperature versus: measured wall surface temperature, measured solar radiation, and measured inside air temperature

The wall sub-model, which predicts the wall surface temperature, was tested comparing the field experimental data to those simulated ones throughout all simulation periods studied (figure see appendix). The figure shows a good agreement between the measured and the predicted wall surface temperature. The regression lines of the measured (Independent variable) against the simulated (dependent variable) wall surface temperature gave the best fitting correlation coefficients of 0.99 in August, while it was 0.98, 0.99 and 0.99 in May, April and June respectively. However, the points are scattered above and below the regression line 1:1, indicating that there is no systematic error according to the simulation time.

6.1.2.3.3 Wall Second-Layer Temperature

One part of the absorbed heat at the wall surface is transferred to the inner layer of the wall, and another part is transferred by convection to the air in the greenhouse. Wall temperatures change with depth and time of the day. The maximum daily temperature at the second-layer (10 cm from the surface) is delayed even by 2-3 hours until the wall surface temperature reaches the maximum value (Fig. 6.18). It can be seen that the highest peak at 58.24 °C is the temperature recorded at 2 cm, followed by the temperature at 10 cm while the lowest amplitude is the temperature recorded at 19 cm behind the wall surface. This data clearly shows how damping can increase with depth.

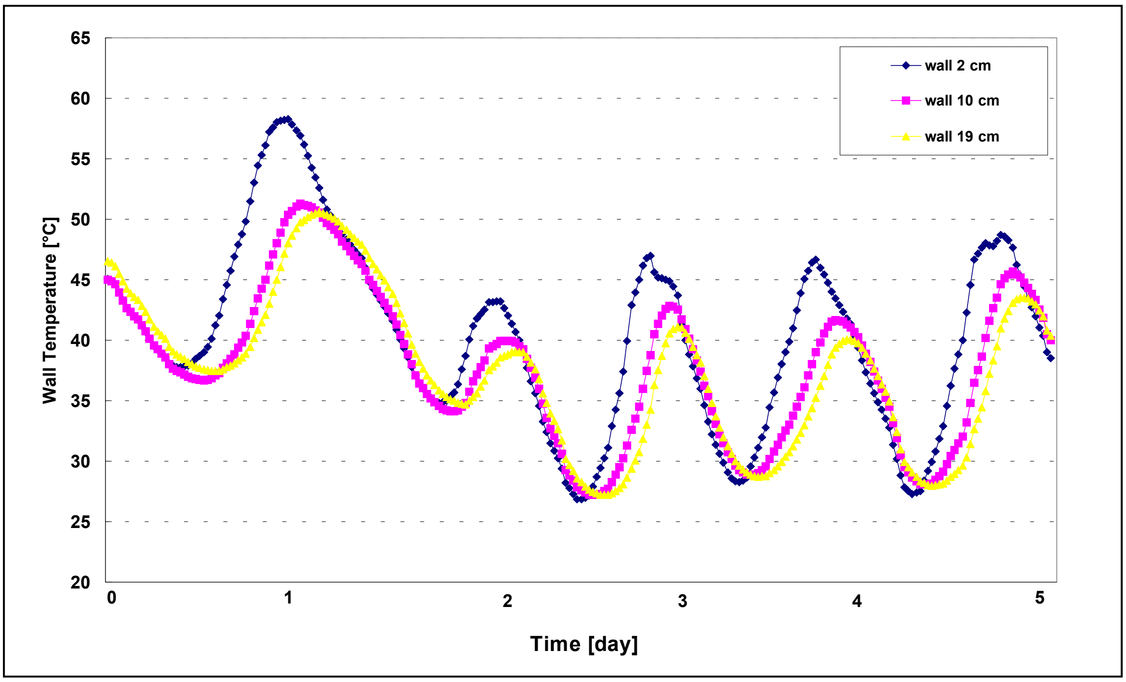

Fig. 6. 18. Measured Wall layers temperature during August 26-30

Figure 6.19 shows the temperature predicted by the model compared with the measured temperature of the second-layer on 26-30 April, 26-30 May, 26-30 June and 26-30 August. The comparison shows a good agreement where the measured temperatures are closed to the predicted values, but with some variations in timing of the peak rates. The simulated wall second-layer temperature sometimes higher, and sometimes lower than the measurements of the given variable.

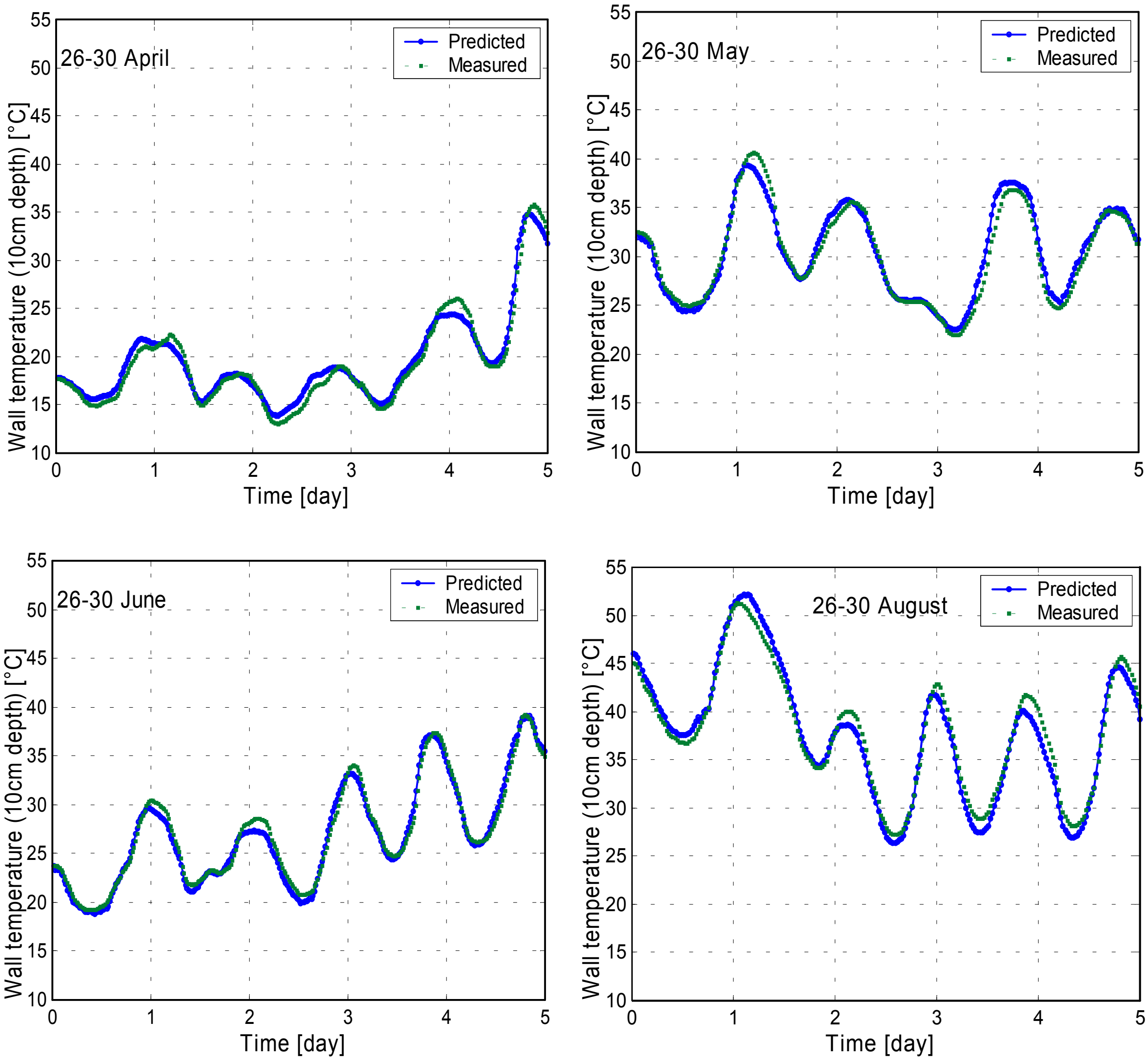

Fig. 6. 19. Diurnal cycles of predicted and measured wall second-layer temperature throughout 20 days

Figure 6.20 shows the error observed between the measured and the predicted wall second-layer temperature. The maximum absolute difference observed between the measured and the predicted temperature amounted to 2.8 K in May.

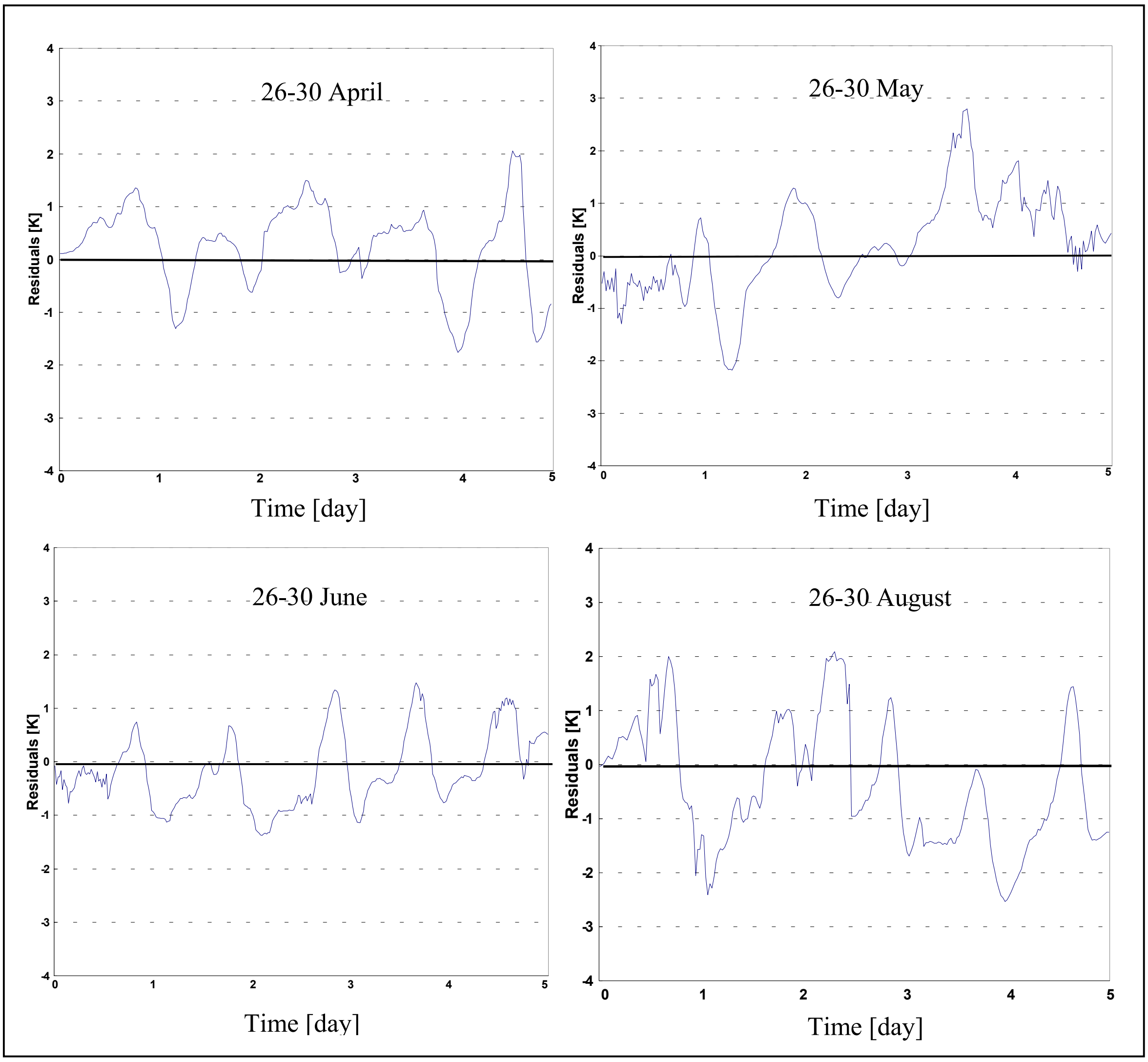

Fig. 6. 20. Residuals of the measured and predicted wall second-layer temperature for the four periods studied

To complete the evaluation of the sub-model predicting wall second-layer temperature, the relationship among residual (differences observed between the measured and the predicted) wall surface temperature, solar radiation, and wall second-layer temperature is carried out (Fig. 6.21). It can be seen that the solar radiation has the most considerable influence on the residual, while the other parameters have neglected effect.

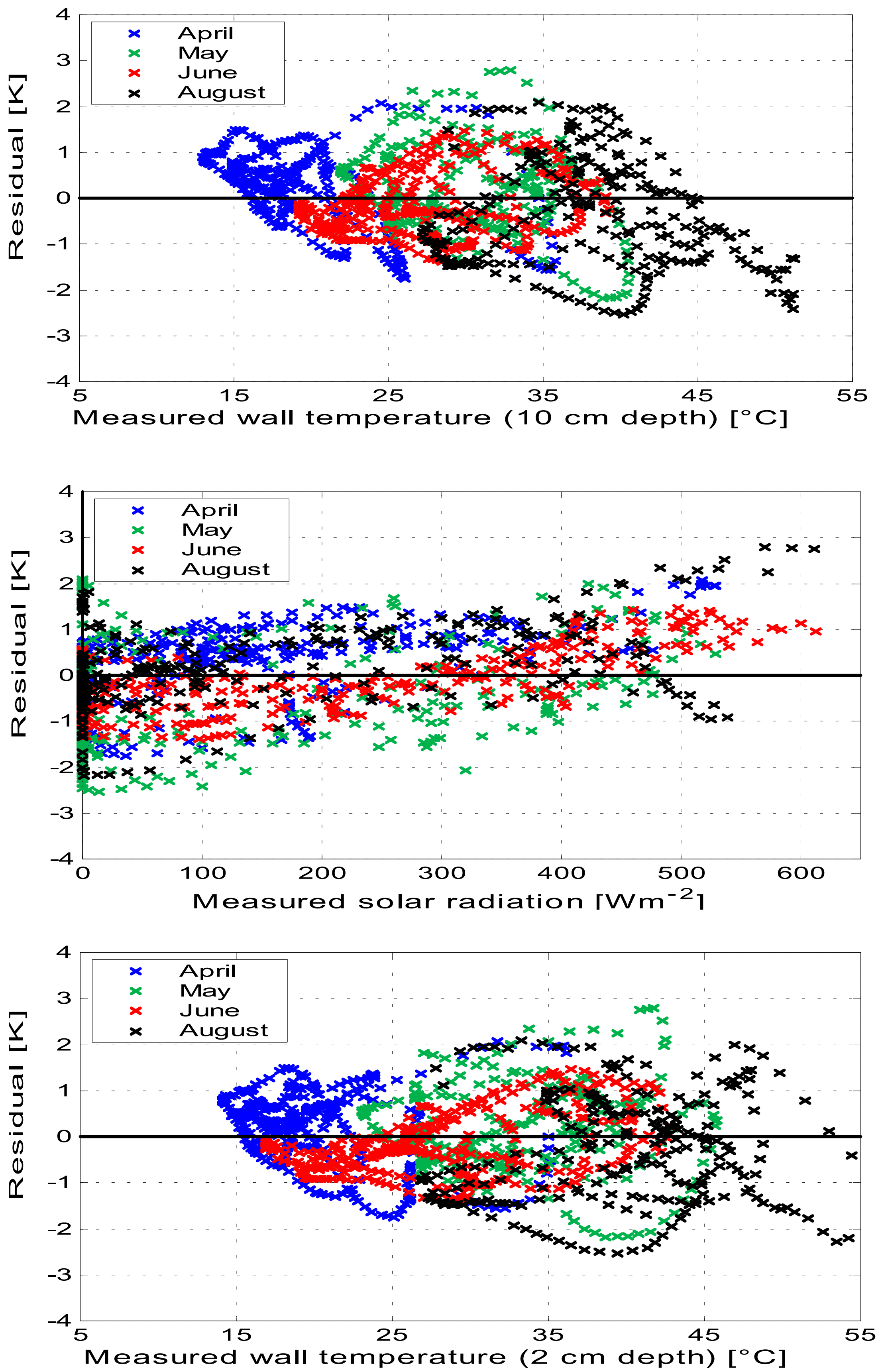

Fig. 6. 21. Plot of residuals of the wall second-layer temperature versus: measured wall second-layer temperature, measured solar radiation, and measured wall surface temperature

The influence of the solar radiation on the residual which was pronounced in August and was clearly observed in figure 6.19. It, however, can not be shown clearly in the figure 6.21 b, because this figure incorporated the residual of four months together.

The field experimental data (measured) were plotted as a function of the simulated ones (figure see appendix). A good correlation between the measured and the predicted temperature was found. The regression lines of the measured (independent variable) against the simulated (dependent variable) wall second-layer temperature gave the best fitting correlation coefficients of 0.988, 0.98, 0.99 and 0.988 for April, May, June and August respectively.

6.1.2.3.4 Wall Third-Layer Temperature

Figure 6.22 shows the measured and predicted wall third-layer temperature values for four typical periods with 5 consecutive days chosen from the measuring period: 1 April to 31 August 2001. In general, a constant agreement between the measured and predicted values was pronounced throughout the whole modeling period, although the night-time simulations showed better consistency with observations than that of the day-time estimates. This is most likely to be due to the fact that more complicated energy and transfer processes existed during the day-time when the solar radiation and air exchange through the greenhouse walls and roof reach their maximal values.

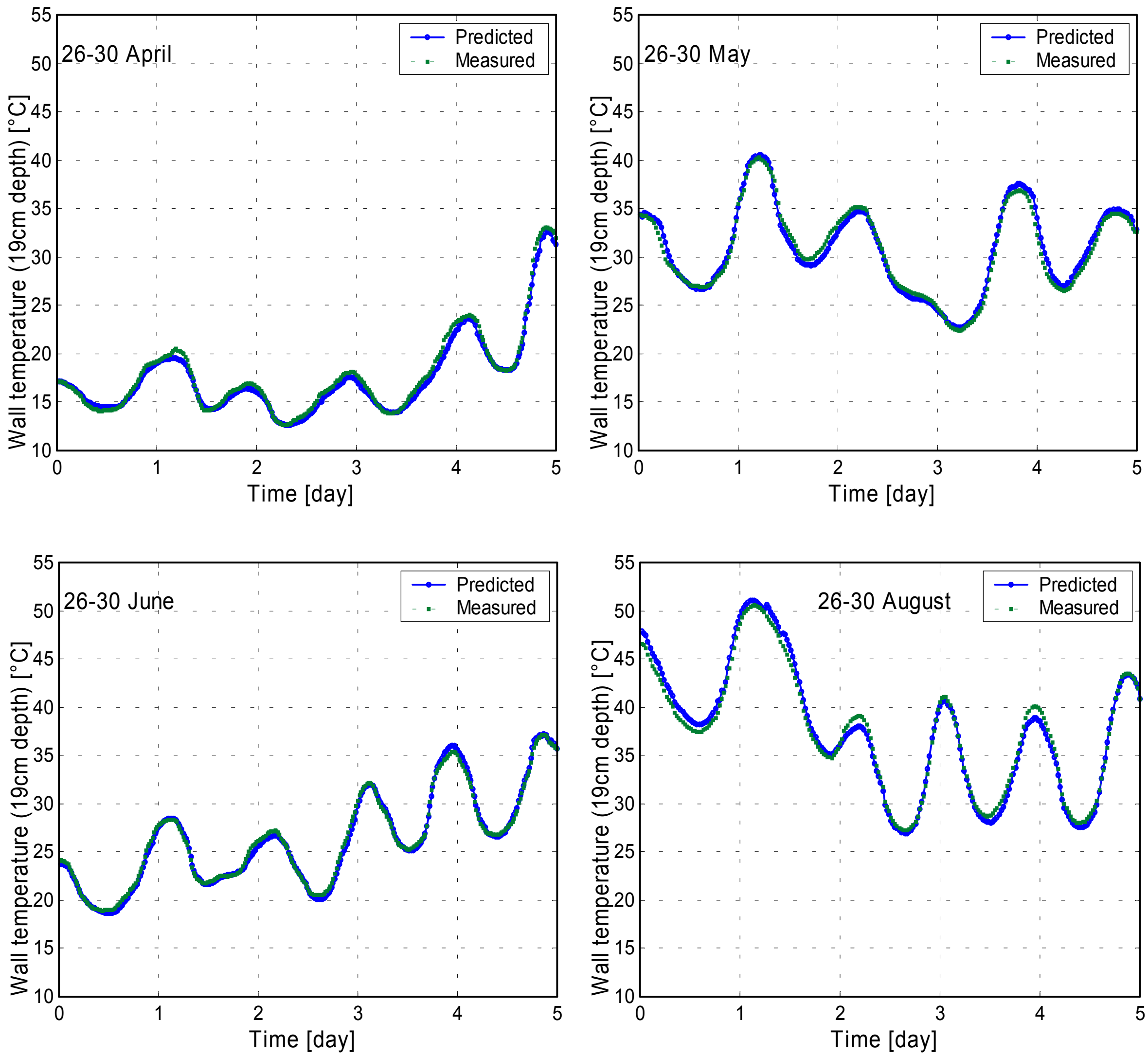

Fig. 6. 22. Diurnal cycles of predicted and measured wall third-layer temperature for 20 days

The differences between measured and predicted wall third-layer temperature were plotted versus time (Fig. 6.23). It can be seen that the differences observed between the measured and the predicted temperature varied over time and reached the absolute maximum value of 1.84 K on May, while it amounted to 0.97, 0.88 and 1.65 K on April, June and August respectively.

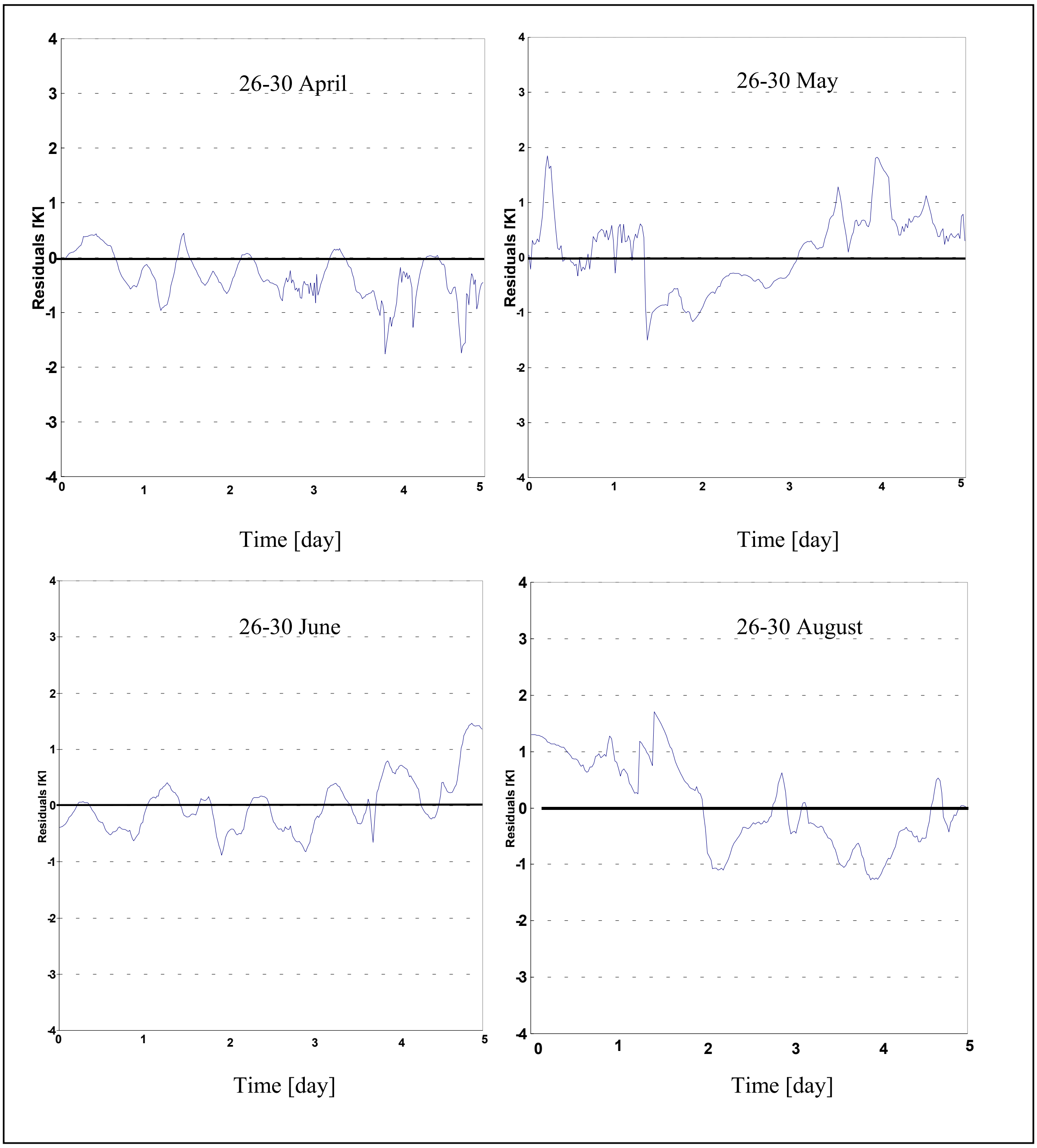

Fig. 6. 23. Residuals of the measured and predicted wall third-layer temperature for the four periods studied

For further validation of the sub-model, the residual of the wall third-layer temperature was plotted as a function of the measured wall third-layer temperature, solar radiation and outside air temperature (Fig. 6.24). The figure shows the difference observed between the temperature predicted by the sub-model and measured ones of the wall third-layer (19 cm from the wall surface) for the all simulation periods studied: 26-30 April, 26-30 May, 26-30

June and 26-30 August. The sub-model performed well, predicting the wall third-layer temperature values with a difference of 7 % from the measured value, while there is a tight band clustered around the zero difference line. The values exhibited a good prediction, with a difference range of ± 2 K . In respect to the solar radiation, the accuracy of prediction did not vary very much with level of the measured radiation.

The wall sub-model predicting the wall third-layer temperature was tested to compare the field experimental data with the predicted one (figure see appendix). The regression lines of the measured (independent variable) against the predicted (dependent variable) present the correlation coefficients for the 1328 available values.

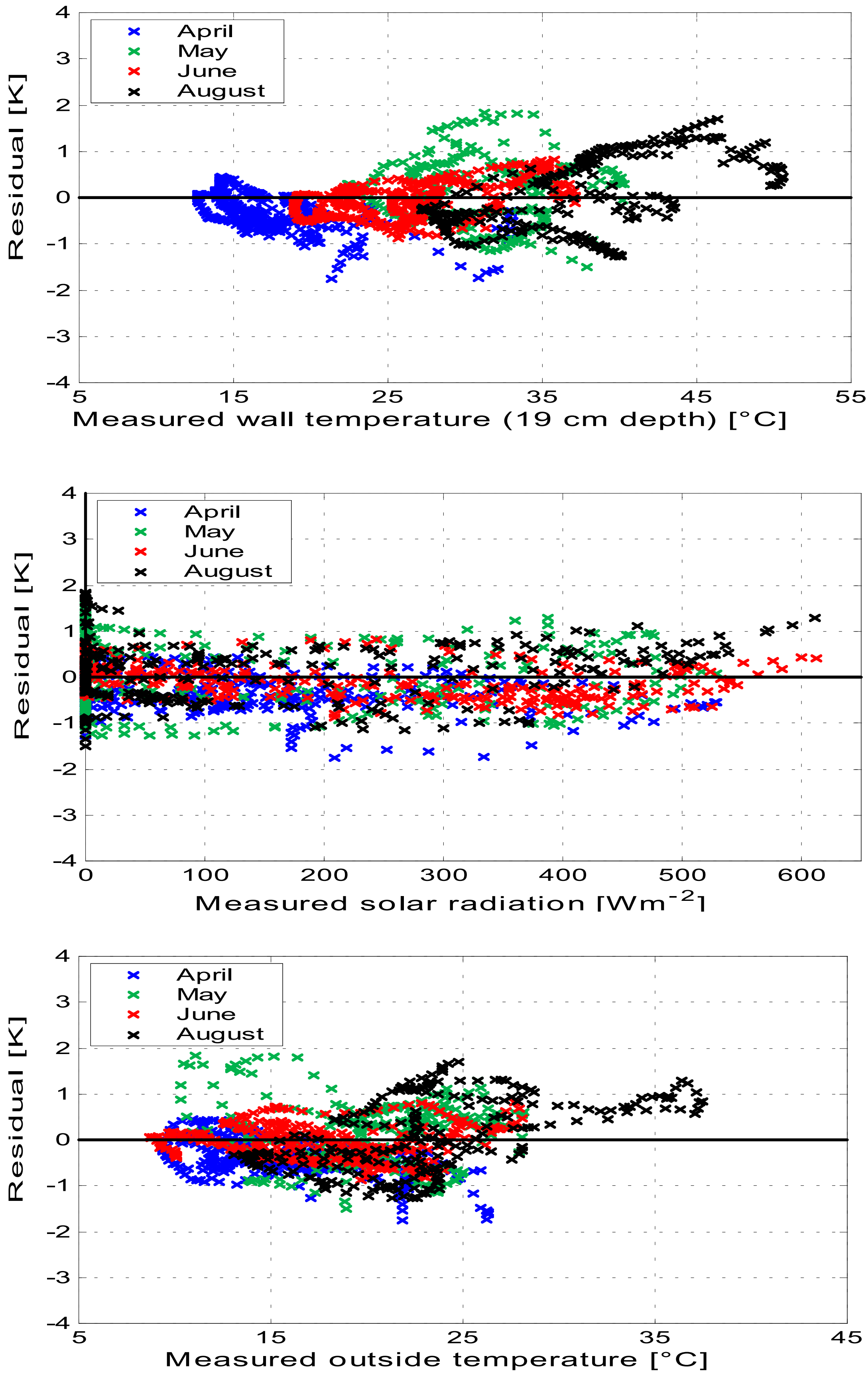

Fig. 6. 24. Plot of residuals of the wall third-layer temperature versus: measured wall third-layer temperature, solar radiation, and outside air temperature

6.1.2.4 **Relative Humidity**

The greenhouse air vapour content is necessary to be known to describe the condensation, evaporation and transpiration, which are considered important factors of the greenhouse heat balance. Moreover, the vapour concentration itself is of interest , because it is important variable that control the risk of pests and diseases. It is assumed that the sources of vapour in the vapour balance are the soil evaporation and the crop transpiration. To evaluate the predicted values of the relative humidity resulted from the model, the greenhouse relative humidity was measured in the period between 26-30 August. While, the other measurements were not considered because of measurement errors. In general, a consistent agreement between the measured and predicted RH was obtained during the entire modeling period, although the night-time simulations were in better overall consistency observations than that of the day-time estimates (figure see appendix). This is most likely due to the fact that more complicated energy and transfer processes exist during the day time when the solar radiation and air exchange through the greenhouse walls and roof reach their maximal. The model performed well, predicting 80 % of the greenhouse inside relative humidity with 10 % difference from the measured values which is the acceptable difference.

7 Model application - A case study at Shebin El-Kom, Egypt

7.1 Site and climate conditions

In the earlier sections, the validity of the developed thermal model for the passive solar greenhouse have been demonstrated. In this section, the applicability of this model to analyse thermal behaviour in the greenhouse at the site of **Shebin El-Kom, Egypt** is highlighted . Since the computer passive solar greenhouse model was accurately validated under different climate days, from April to August 2001 at the institute of Horticulture, Hannover University, it would appear to be reliable to predict the greenhouse air temperature, soil layer temperatures, wall layer temperatures and relative humidity in the greenhouse for different positions and periods of the year.

The climate at Shebin El-Kom (30 54` N) is characterized by a very low and irregular rainfall during a four month winter season. There are many winter nights during which the air temperature drops to or just below 5 °C. There are little clouds. Summer is characterized by warm and sunny days with minimum night temperature between 17 °C and 22 °C and maximum daytime temperatures ranging between 30 °C and 35 °C. These days are sometimes interrupted by heat waves with maximum temperatures of up to 40 °C and relative humidity dropping to 15%. Maximum global radiation reaches about 1100 Wm^{-2} in summer and 600 Wm^{-2} in winter. Figure 7.1 illustrates the climate of the city in summer (a) and in winter (b).

It can be observed that the solar radiation reached the high value of 600 Wm^{-2}, while the night temperature dropped to or just below 5 °C. Therefore, a great amount of thermal energy must be stored at the daytime through a thermal wall and diffuse it at the night to bring the greenhouse to a suitable condition.

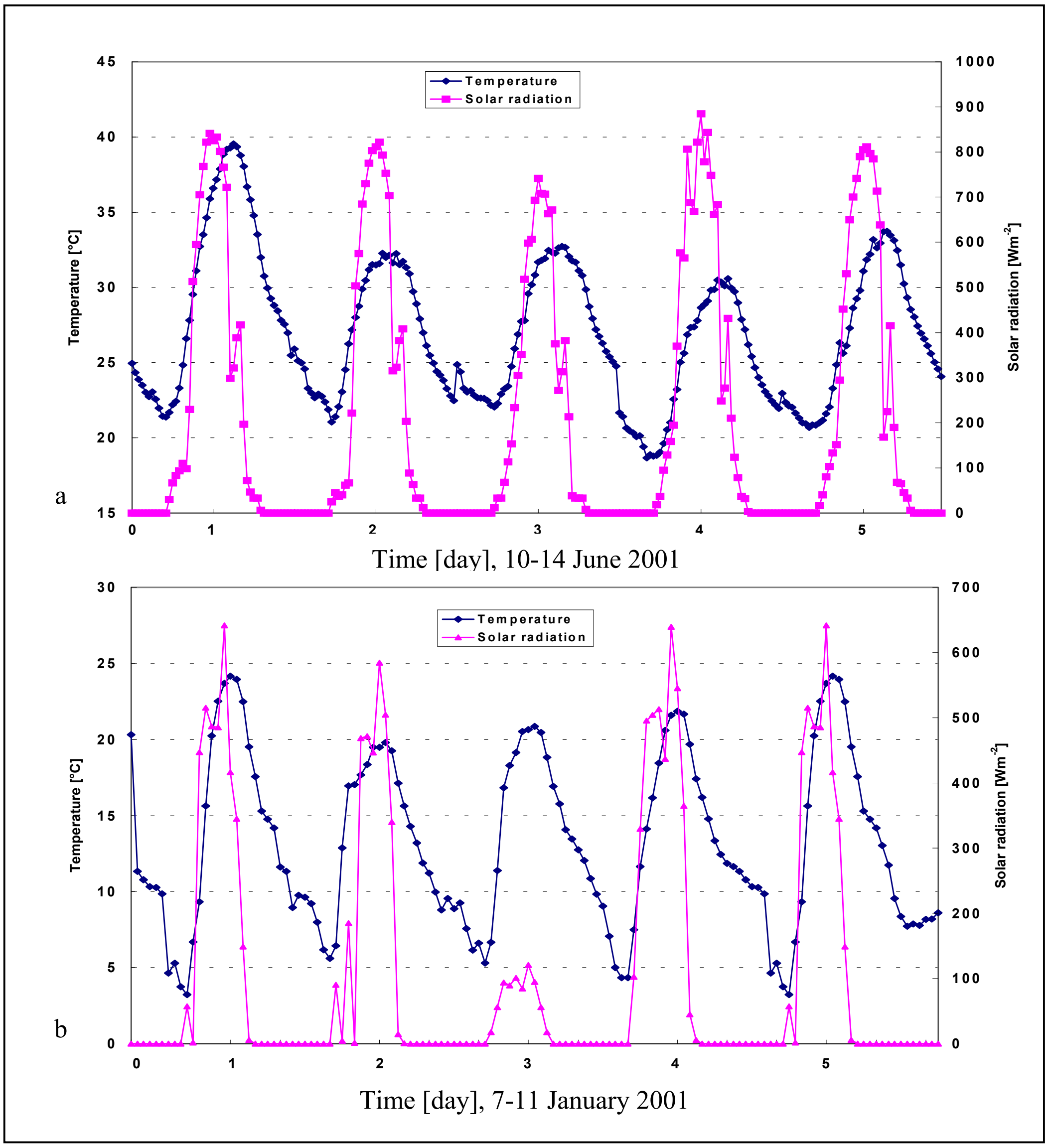

Fig. 7. 1. Measurements of solar radiation and outside temperature at the Shebin El-Kom city in summer (a) and in winter (b) (AMER 2002)

7.2 Simulation results

All simulations were performed with a wall area of 0.6 m^2/m^2 ground area and concrete which has the following thermal properties: density of 1880 [kgm^{-3}], thermal conductivity of 0.8 [$Wm^{-1}K^{-1}$] and heat capacity of 0.35 [$Whkg^{-1}K^{-1}$]. The model was run for 38 days (between 7 Jan. – 14 Feb., 2001) with constant step intervals (one hour) at different wall thicknesses from 0 to 100 cm.

Results of simulation for a typical cold winter nights are shown in figure 7.2 which shows the simulated greenhouse air temperatures with north concrete wall of 40 cm thickness and without wall, together with the outside air temperature. This example was taken from a series of nearly 38 simulated days, with somewhat coldest night temperatures. Ambient minimum and maximum temperatures were 3.44 °C and 24.14 °C , respectively, and the days were clear except one day which had the minimum solar radiation of 120 [Wm^{-2}].

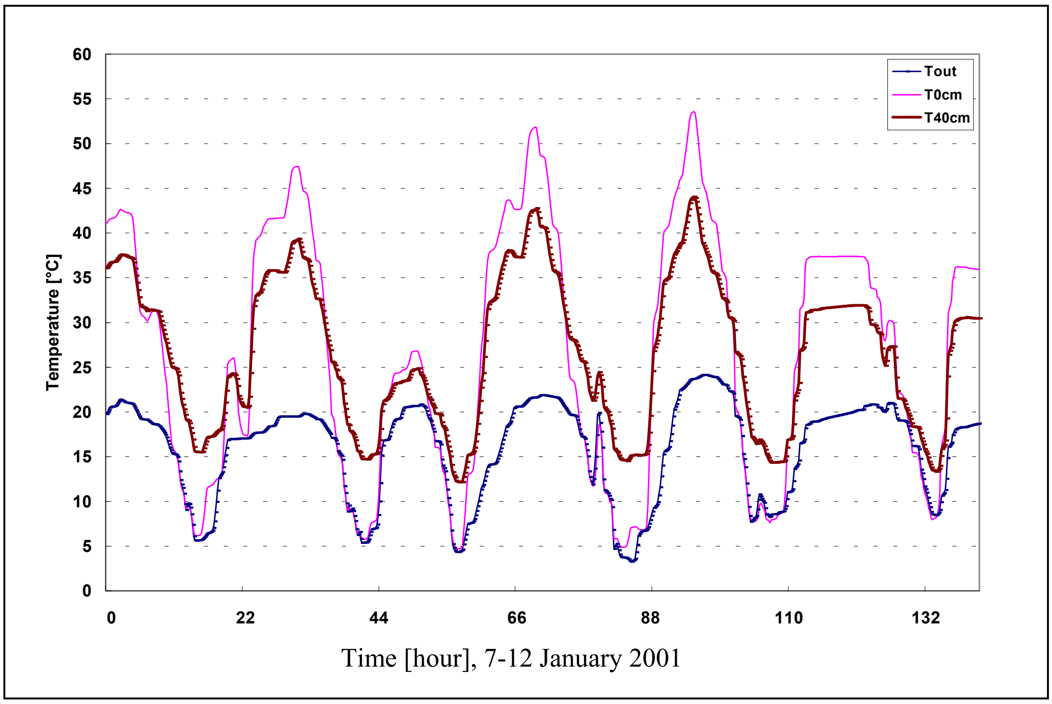

Fig. 7. 2. Ambient temperature (Tout), simulated greenhouse air temperature without wall (T0cm) and with 40 cm concrete wall (T40cm) at Shebin El-Kom, Egypt in January 2001

It can be seen that T0cm is greater than T40cm during most of the daytime (Fig. 7.2). This indicates that the concrete north wall collects solar energy during the daytime. Accordingly, it can be concluded that the wall has high thermal efficiency. It can be observed that the fluctuation of the greenhouse air temperature without wall (T0cm) is greater than that of the greenhouse of 40 cm thick wall (T40cm) and much greater than that of the ambient temperature (Tout). At all night time, the temperature of the greenhouse with concrete wall is greater than both of the ambient temperature and the temperature of the greenhouse without wall. It can further be seen that if the ambient temperature drops just below 5 °C which is critical to the plants, the use of concrete north wall keeps the greenhouse at a suitable air temperature above 10 °C (Fig. 7.2).

7.3 Optimization of the thermal wall thickness

The concrete north wall capacity (thickness) limits the ability of the system to accumulate heat produced irregularly and supply it when heat is needed. As Fig. 7.3 shows, the increase in wall thickness leads to the increase of the average minimum difference night temperature between the inside and the outside air temperature and the decrease of the average maximum difference temperature at the daytime. Yet, increasing its thickness above certain value of 40 cm, resulted in decreasing both of the maximum and minimum difference between inside and outside air temperature. However, this graph is not enough to define and select the optimum wall thickness. Therefore, the effect of the thickness of the wall on the average difference night temperature between the inside and the outside is further demonstrated graphically in Fig. 7.4.

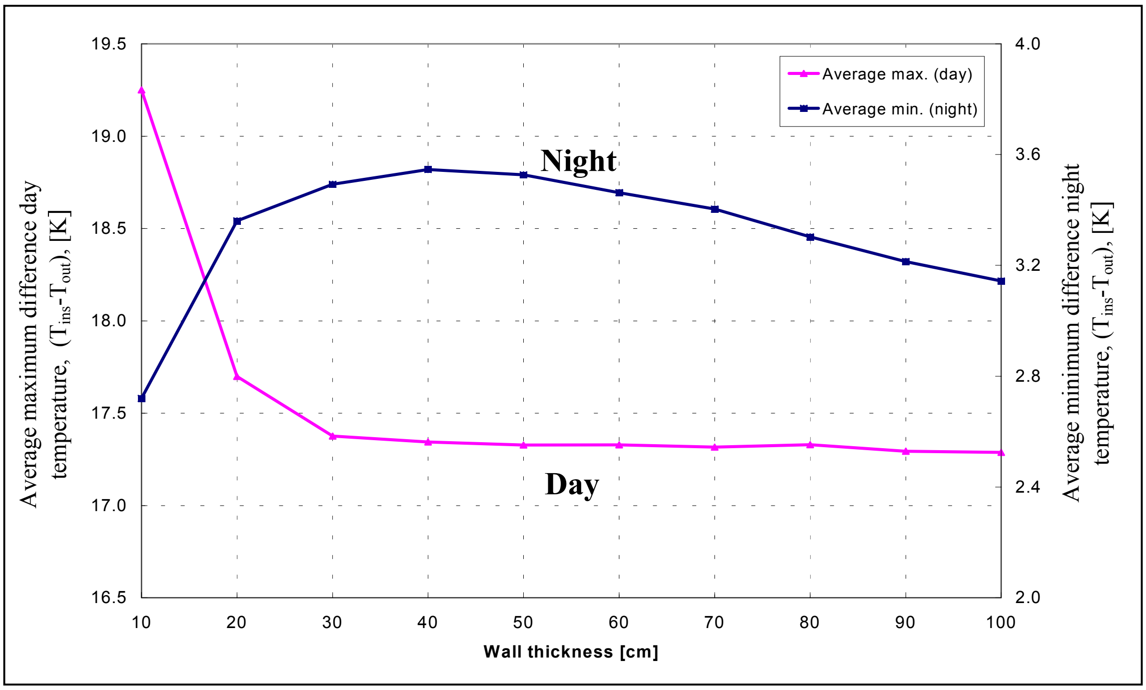

Fig. 7. 3. Effect of wall thickness on the difference between inside and outside temperature at the night (Average min.) and at the daytime (Average max.) for the period of 38 days from 7 January to 14 February

For maximum effectiveness, thermally massive elements should have a large surface area, and a specific thickness based on their optimum diurnal heat capacity. The material and thickness of the wall may be adjusted to achieve the desired time lag in order to provide the majority of heating during the evening and night periods. The simulated results (Fig. 7.4) show that the night average difference temperature increases markedly with increasing thickness of the wall up to a point where the thickness is sufficient to carry over excess daytime solar heat to supply into the greenhouse heating load during the night. There is an optimum thickness for the present case (concrete north wall). The optimum occurs because of a trade-off between increasing performance with increasing thickness of the wall and decreasing performance because of the inability of heat to pass through the wall.

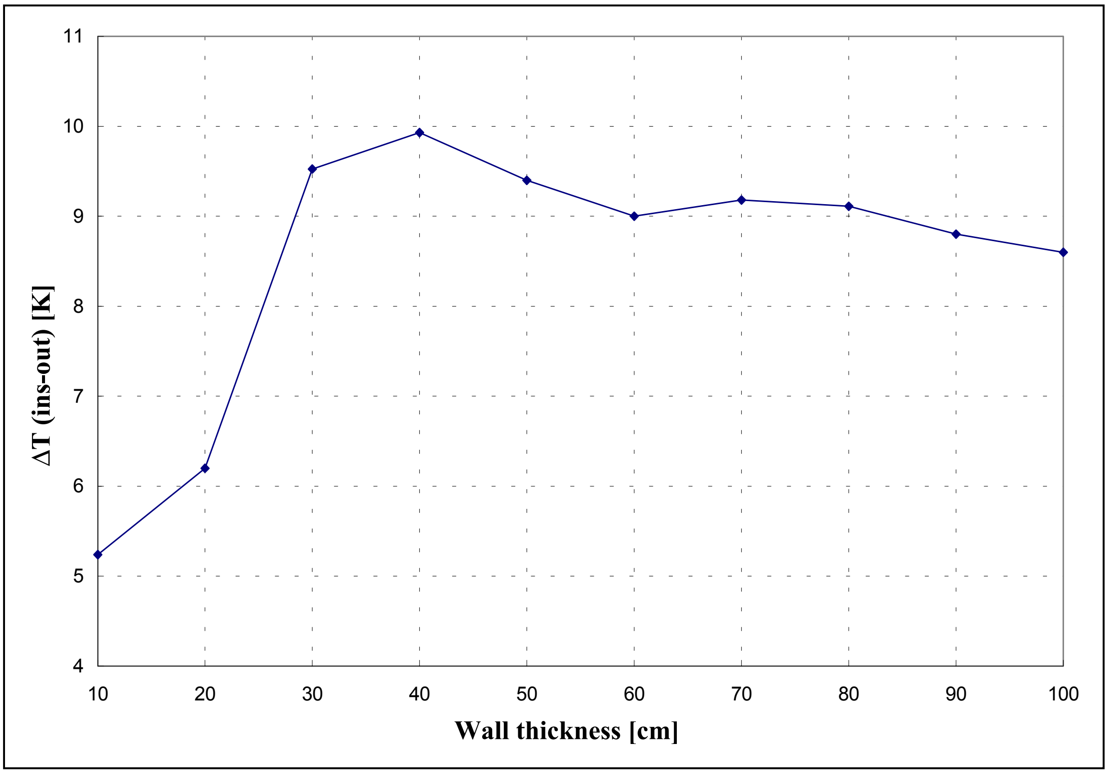

Fig. 7. 4. Calculated optimum wall thickness for Shebin El-Kom, Egypt.

The results obtained can be summarized as follows:

- The night average difference temperature of the wall thickness above 40 cm is decreased. However, the thickness may be reduced to 40 cm with no significant performance penalties occurred.

- The range of wall thickness between 20 and 40 cm can be considered as a transition region. In this region, performance penalties for reduced thickness below 30 cm is becoming significant, but in some cases, it might be considered acceptable as design/cost trade-off.

- Finally, the best wall thickness to be used at winter (Dec., Jan. and Feb.) is 40 cm, which produces the highest difference up to 10 °C of night temperature.

8 Discussion

8.1 General

The term 'solar greenhouse' has been applied almost exclusively to refer to home or community greenhouses, but not commercial greenhouses. Many community greenhouses are strictly passive systems (although with back-up heat in many cases). The passive effect in such greenhouses usually includes additional thermal mass. Water, or masonry, or rock bed thermal storages are commonly used. The mass provides significant tempering and reduces diurnal swings of air temperature. It also reduces the ability of the environmental control system to attain blueprint temperature conditions for good production practice (PARKER 1991).

The net energy benefit of adding passive solar strategies varies with ***climate as well as type, design and size*** of the system used (BALCOMB 1992).

Many systems for greenhouses heating by a passive solar system have been established. For example, the system of THOMAS (1994) in which he used tubes of 0.75-1.25 m diameter filled with water and their filled ratio was 200 m^3/1000 m^2 of the greenhouse area. These tubes were used either plugged (closed) with a radiation permeable plastic or not plugged. Also, a fan for movement of the air was used and consequently heat movement by convection. Another system applied in China, most type of greenhouses are solar heated greenhouses with the using of a north wall, usually they are entitled "Chinese Style Lean-to Greenhouse (CSLG)". During the night, the front roof is covered with straw mat for trapping heat, in the morning when the sun rises, and the air temperature outside the greenhouse gradually goes up, the straw mat is rolled up, and let the solar radiation transmit through. Due to such a character, this kind of greenhouse can provide acceptable environment for growing some vegetables such as cucumber and tomato without any or with only a little auxiliary heat during the winter.

Furthermore, many systems used for heating of buildings have been chosen. Those include a Trombe wall at the south site of the building. This wall can be vented or not vented. Additionally, for the aim of improving the efficiency of this wall, it was isolated using radiation permeable material.

In the present study, a concrete north wall was used as a passive collector and storing element in the greenhouse. The efficiency of the wall in releasing heat energy expressed as the proportion of the energy released to the collected one per collection-release energy cycle which is varies according to radiation and temperature conditions. However, it was found that the maximum difference between greenhouse inside temperature and outside temperature at the night time was 6 K for Hannover at summertime (April - August) and 10 K at winter (Jan. – Feb.) for Shebin El-Kom while in a study of THOMAS (1994), it was 4 K at summertime (May - June). The reasons for the difference might be explained by the fact that the higher wall surface area, the poor thermal properties of the tube materials and the high soil covered ratio with tube prevent the stored heat in the soil to be released to the greenhouse air.

8.2 Modelling

8.2.1 Model comparison

Principally, passive solar greenhouse performance is estimated most frequently using mainframe computer programs to perform hour-by-hour simulation analysis. Energy and moisture balance is achieved by means of a system of many simultaneous differential equations, each depicting energy equilibrium in one of the basic greenhouse elements (nodes), such as air, soil, crop, roof and walls.

Recently, TSILINGIRIS (2002) developed a flexible computer simulation model suitable for the investigation of the dynamic behaviour of structural wall elements, under the effect of time varying driving functions of solar radiation and ambient temperature. He assumed that both wall surfaces are exchanging heat with the internal space and the environment through convection and radiation and that the external wall surface is exposed to the incident solar radiation. Also, KALOGIROU et al. (2002) used a computer simulation program TRNSYS with the same hypotheses of TSILINGIRIS' model to investigate the effects resulting from the use of building thermal mass on the heating and cooling load in Cyprus. In this model, the ventilation was not taken into consideration. FANG and LI (2000) developed a mathematical model for lattice-wall passive solar heated buildings, considering three-dimensional heat conduction in lattice walls. These models were only valid especially for the building and can not be applied for the greenhouses. This is because of the following reasons:

- the wall was assumed to be at south sides of the building zone,
- the plants, latent heat (evaporation, transpiration), ventilation and sun angles were not considered in these models,
- the soil surface only (floor) was considered in the models, which means that the heat storage in the soil was neglected.

In the model described in the present study, the soil and wall nodes are sub-divided into many nodes characterising the thermal conduction in the layers of both soil and wall, which can improve the wall structure. It is assumed here that the solar radiation on the wall is divided into three components: beam or direct, diffuse and reflected radiation, while it was assumed in the models mentioned above as beam radiation only.

The advantage of the current study over KIMBALL (1972) and NAVAS (1998) studies is that the concrete solar collector and storage north-wall was taken into consideration.

8.2.2 Model parameters

The calibration parameters are selected by performing a sensitivity analysis using real greenhouse climate data. Many parameters such as heat transfer coefficient, specific heat, thermal conductivity and density play a considerable role in heat transfer problems when heating or cooling of greenhouses. Analysis of the sensitivity revealed just how necessary it is to use accurate values of those parameters which have a strong effect on the predicted temperature of the soil and wall and consequently on the greenhouse air temperature.

An important parameter affecting on the greenhouse air temperature as a whole is the magnitude of the convection coefficient. A number of studies investigated the model sensitivity to the magnitude of convection coefficient. ANDERSSON et al. (1980) for example, concluded that to correctly predict air temperature as a function of time would require coefficients that are sensitive to changing surface temperature conditions. GADGIL et al. (1982) used a numerical experiment to determine the convection coefficient on the slab floor in a strongly solar heated direct-gain room. In their study, the convection coefficients at the floor in a steady state were found to be 1.7 and 2.7 [$Wm^{-2}K^{-1}$] depending on the room air temperature.

In the present study, however, the convection coefficients were found to be 1.5, 2.25, 4 and 23 [$Wm^{-2}K^{-1}$] at the wall-, soil-, inside cover- and outside cover-surfaces respectively. On the other hand, the coefficient at the soil surface was found to be higher than the coefficient at the wall surface. This might be ascribed to two reasons: the first reason is the evapotranspiration from the plants and the soil surface which causes increased air movement at the soil surface and the second reason is the resistance flow to the air motion at the wall surface. The convection coefficient at the outside cover material was higher than that at the inside surface because of the effect of the wind speed. This results corroborates findings by NILES (1992), TANTAU (1983) and RAMAN (2001).

Another very important parameter influencing on the thermal performance of the greenhouse is the thermal conductivity λ [$Wm^{-1}K^{-1}$]. This property, which is referred to as a transport property, provides an indication of the rate at which energy is transferred by the diffusion process. It depends on the physical structure, as well as on the atomic and molecular weight which related to the state of the matter. It follows that, for a given temperature gradient, the conduction heat flux increases with increasing of thermal conductivity (INCROPERA 1990).

In the present study, the thermal conductivity of the wall was found to be lower than the thermal conductivity of the soil, where it was found to be 0.8 and 1.0 [$Wm^{-1}K^{-1}$] for the wall and the soil respectively. Here, it should be mentioned that this factor i.e. λ can be easily determined by the user for the wall, while it is difficult for the soil because of the variable conditions in it such as moisture content and growth of roots. This value of soil and wall thermal conductivity is in the range limit mentioned in the literature (INCROPERA 1990).

On the other hand, in the analysis of heat transfer problems, it is necessary to study many properties of the matter. These properties are generally referred to as thermophysical properties and include two distinct categories: transport and thermodynamic properties. The transport properties include: the thermal conductivity λ [$Wm^{-1}K^{-1}$] and the kinematic viscosity ν [m^2s^{-1}] (for momentum transfer), while thermodynamic properties pertain to the equilibrium state of a system. Density ρ [kgm^{-3}] and specific heat c_p [$Whkg^{-1}K^{-1}$] are two such properties used extensively in thermodynamic analysis (INCROPERA 1990). The product ρc_p [$Whm^{-3}K^{-1}$], commonly termed as the volumetric heat capacity, measures the ability of a material to store thermal energy. However, to be an effective heat storage element, the product of density ρ and specific heat c_p should be large. Materials of high density which usually have high thermal conductivity are typically characterized by a small specific heats. There is also another important property termed the thermal diffusivity Φ, which is the ratio of the thermal conductivity to the volumetric heat capacity ρc_p and has units of m^2s^{-1}. It measures the ability of a material to conduct thermal energy relative to its ability to store it. Materials of large Φ respond quickly to changes in their thermal environment, while materials of small Φ respond more sluggishly, taking longer time to reach a new equilibrium condition (INCROPERA 1990).

In the present work, the densities and specific heats of the soil- and wall-materials were found to be 1515, and 1880 [kgm^{-3}] and 0.3, and 0.35 [$Whkg^{-1}K^{-1}$] respectively which are in a good agreement with values found in the literatures (KREIDER and KREITH 1985 and INCROPERA 1990).

Concerning the water covering ratio, it was calculated and optimized for both soil and plants, where it was found to be 0.2 and 0.4 for soil and plants respectively. However, it should be noticed that these figures cannot be constant because it varies according to the changing of irrigation system, plant species, and climate conditions.

In summery, it can be said that the most important and critical factors which should be considered in the model are as follows:

- Solar radiation, where it is considered the most important element because the whole system depends on it and without sufficient solar radiation in the given area, the system is not applicable and modeling of the solar radiation is very important and should be exactly designed.
- Heat transfer coefficient (α), because it changes by variation of construction and climate conditions where the model is to be applied.
- Heat capacity of the wall and soil.
- Water covering ratio related to the plants and soil which in turns affect on the evaporation and transpiration.
- Ratio of solar radiation absorption for each of soil and wall.

While, the other factors, such as ϕ (factor depends on the angle between the surfaces), thickness of the soil layers and wall, these can be considered not critical because they can be determined by the user.

8.2.3 Model validation

8.2.3.1 Greenhouse air temperature

Greenhouse air temperature is one of the main factors characterizing greenhouse climate. There are many factors which affect on the inside temperatures, such as the type of the passive heating system and where is it placed, its mass, the air change rate in the greenhouse, the heat transfer coefficient on the wall-, soil- and inside cover-surfaces and weather condition (JOKISALO et al. 2001).

In the present work, the predicted and measured air temperature values for four typical periods of five consecutive days chosen from the measuring period from April to 31 August 2001 were compared. As a whole, a good agreement between the predicted and measured values was obtained during the entire modeling period. Although, the night-time simulations were in overall better agreement with observations than the daytime estimates, the variation was small in the early morning and late afternoon becoming larger in the middle of the day. This is most likely due to the effect of the more complicated energy and water transfer processes existing during the daytime when the solar radiation reaches the maximum. Similar results were reported by ZHANG et al. (1997), TAP (2000), ELSHEIKH (2001). Moreover, the variation between simulated and measured values could be due to different direct and indirect reasons as follows:

The direct reasons include:

(a) The error in defining the heat transfer coefficients on the wall-, soil-, leaf- and inside cover-surfaces.

(b) The convection coefficients between the surfaces and the air are assumed to be constant and independent of temperature difference (ALTMAYER et al. 1982), even though this coefficient must be programmed in correlation with the difference between the surfaces- and air-temperatures.

(c) The thermal properties of the air (density ρ and heat capacity c_p) were neglected in this model

(d) Possible errors in defining the air exchange rate.

(e) The effect of the greenhouse construction materials type was neglected.

(f) Possible measurement errors resulting from the thermocouple and measurement device.

On the other hand, **the indirect reasons** that indirectly influence on the variation between the simulated and measured values of the air temperature can be summarized as follows:

(a) The error in defining the heat transfer coefficient on the outside cover-surface, as well as considering it as a constant value in this model.

(b) Considering a constant sky temperature lowering it by 15 °C than the ambient temperature.

(c) Neglecting the effect of the surrounding glass greenhouses, where the experimental greenhouse was constructed in-between surrounding glass greenhouses which might have some effect on the measured values otherwise.

(d) The water covering ratio of the canopy and soil was constant.

8.2.3.2 Greenhouse relative humidity

One of the most important factors controlling the greenhouse environment is the relative humidity (RH). Several reasons may account for this but the intricate combination of many factors affecting the relative humidity, such as air temperature, evapotranspiration and air exchange, and the difficulty in measuring the relative humidity precisely are considered the most important problems (TAP 2000, PITBLADO 2002).

On a calm, clear day, air temperature tends to rise from sunrise until mid-afternoon and then fall until the next sunrise. If the amount of moisture in the air remains essentially the same during the course of the day, relative humidity will vary inversely with the temperature. That means that, relative humidity will decrease from morning until mid-afternoon and rise again through the evening. Relative humidity also affects the heating and cooling of the air. Since water has a significantly higher `heat capacity` than air, small amounts of water vapor can make considerable changes in the rate at which an air mass can cause changes in temperature (GLOBE 2002).

In the present work, the predicted and measured relative humidity values for one typical period of five consecutive days chosen from the measuring period were compared and shown to be in a good agreement. Though, the night-time predictions were in overall better agreement with measurements than the daytime estimates. However, there was a slight difference between the predicted and measured RH values due to the fact that RH-value depends on both T_{ins} and x_{ins} (water content), and also due to the fact that the relative error of RH depends on the relative errors of the simulated T_{ins} and x_{ins}. At the mid-day, the predicted RH was lower than the measured one, since of the predicted temperature was higher than the measured one. These results are in agreement with the results of ELSHEIKH (2001), TAP (2000) and ZHANG et al. (1997).

8.2.3.3 Greenhouse soil temperature

To reduce the cost of energy for greenhouses, it is important to know not only how air temperature affects plant growth and yield, but also to what extent controlling of soil temperature play a role in the energy saving. Soil temperature is an important parameter in solar energy applications such as the passive heating and cooling of agricultural greenhouses. These applications can be developed by the greenhouse's direct earth contact, which involves partial or total placing of the greenhouse envelope in direct contact with the soil (MIHALAKAKOU 2002), or by the greenhouse's indirect contact, which involves the use of a buried pipe through which air from indoors and outdoors of the greenhouse is circulated and then brought into the greenhouse (MIHALAKAKOU 1994, TOMBAZIS et al. 1990, SANTAMOURIS et al. 1995).

The use of direct or indirect soil-coupling techniques for greenhouse requires knowledge of the ground temperature distribution especially at the surface. It is still commonly believed that soil temperature distribution at any depth below soil's surface remains unchanged throughout the year (MIHALAKAKOU 2002). However, the soil temperatures at shallow depths present significant fluctuations on both daily and annual basis. Accordingly, the heat flow inside the soil is influenced by several parameters, such as solar radiation, greenhouse inside temperature, time of the day and the season of the year, soil properties (thermal conductivity, heat capacity and density), soil texture, etc. which represent a seasonal or irregular variations. For this reason, prediction and estimation of soil temperature is rather difficult, especially near the ground surface where the soil temperature variations are at the highest values.

An analytical model, based on the transient heat conduction differential equation as well as on the energy balance equation at the soil surface is used in the present study to estimate the soil surface temperature. The energy balance equation involves energy exchange between air and soil (sensible-, and latent-heat), heat loss to the lower layers (heat loss by conduction), the solar radiation absorbed by the soil surface as well as the long-wave radiation. This model has been selected because although it is based on heat conduction differential equation, but it takes also into account the prevailing weather conditions and soil properties at any location. The model was validated using extensive sets of measurements for greenhouse soil surface, and a close agreement between the predicted and measured values of soil surface temperature was observed. For most of the time, the model predicts the soil surface temperature with only slight differences can be observed in correspondence with the measured temperature. Reasons for the discrepancies found between the observed and predicted temperatures might be due to the followings:

(i) the assumption of strictly one-dimensional heat transfer.

(ii) possible errors in defining parameters such as thermal properties of the soil (thermal conductivity, heat capacity and density), heat transfer coefficient on the soil surface (which was mentioned above) and soil covering ratio with plants, water covering ratio of the soil and the soil surface absorption which all were assumed to be constant throughout all simulation time.

(iii) It is assumed that the soil layer is divided into three unequal layers (of 1, 11 and 36 cm) and have the same terms of heat capacity, thermal conductivity and density.

In reality, heat transfer under field conditions may be of three dimensional and lateral heat transfer might occur. Water moving laterally carries heat laterally, resulting in decreased vertical heat transfer (SHAO et al. 1998). This may explain why the model tends to over estimate soil temperatures for all depths considered in the present study. Actual measurements of the parameters in the coupled heat and water transfer should increase the accuracy of temperature prediction of the model.

In the present work, a close relationship between soil surface-, and air-temperatures was found. Similar results were pointed out by BERNIER et al. (1990) and ELSHEIKH (2001), where they found a linear relationship between the soil surface-, and greenhouse air-temperatures.

8.2.3.4 Greenhouse plants

Due to their interaction, ideally, all sub-models of the greenhouse crop model should be calibrated simultaneously. However, due to the photosynthesis, transpiration and vapour condensation processes that occur on plant surfaces, leaf surface microclimate can be considerably different from climate of the surrounding air. These differences are especially significant in the greenhouse due to the limited air circulation and the use of heating and misting. Unfortunately, leaf surface temperatures are not measured in the greenhouse due to the limitations of measuring instruments.

The model is designed in a simple way so that only the heat balance for the plants is considered and this is not a real case, where other models which take plant growth into their consideration (such as MONTEITH 1985; STANGHELLINI 1987; JOLLIET and BAILY 1992 and BOULARD and WANG 2000) should then be used when applying the model for a long periods.

In the present work, the heat storage in the plants was neglected due to the poor thermal properties of the grass while it should be taken into consideration if another plant is used.

8.2.3.5 Greenhouse concrete north wall

Solar radiation absorbed by building facades is almost completely lost into the atmosphere through convection and radiation. The case is then different when the wall becomes covered with a transparent thermal insulation which passes solar radiation through it and retains the heat absorbed inside the wall, and thus preventing its escape into the atmosphere. The storage of the heat in the wall, allows for both the passive and active solar energy gain through the so-called hybrid system (RADON and BIEDA 2001). The development of heat transfer analysis for the prediction of the thermal behaviour of structural walls is a problem of fundamental concerns in a broad range of engineering application, estimation of heating and cooling loads in passive solar design.

For solid materials, the characteristics that affect on thermal performance is the product of $\rho c_p \lambda$, where ρ is the density, c_p is the specific heat, and λ is the thermal conductivity. For walls with high heat capacities, the performance increases indefinitely as $\rho c_p \lambda$ increases, but that rate of increase diminishes (Jones 1992). The more the thermal mass, the longer it will take for the stored radiant energy to be released into the greenhouse. Therefore, to meet the requirement of the thermal properties and energy conservation, the temperature distribution in the wall should be investigated. The temperature distribution in the wall can be seen as a cyclic oscillations which have a period of 1 day or 24 hours. This implies that the wall absorbs and stores heat (charging) during the daytime and releases it (discharging) at night (BALCOMB 1981).

In the present study, in order to evaluate the developed model, an experimental greenhouse was built with concrete north wall with the thickness of 20 cm, which was selected from the primary simulation results based on the location (Hannover), wall thickness effect on the greenhouse air temperature and finally the construction cost. Comparison between the measured wall layer-temperatures (three layers) in the greenhouse and the temperature from the model which is estimated based on the assumption of uniformly distributed radiation on the wall surface has shown that the model provides accurate wall layer-temperatures.

There are several reasons for the remaining deviations between the model and measurements. Firstly, there are measurement errors among the thermocouples in the same layer, where the deviation was in the range of 3-4 °C. This can be referred to the assumption of uniform solar radiation on the wall, whereas in reality, this is not true.

Secondly, consideration of one-dimensional heat transfer. Typically, thermal modelers have to use a simplified one-dimensional descriptions of complex walls, which may significantly reduce the accuracy of computer modeling (MCKNIGHT 2001). Furthermore, possible errors in defining the studied parameters can also be another reason for the deviations observed between the model and the measurements.

Further investigations and evaluations of the model were carried out by studying the residuals of the model of wall layer-temperatures *vs*. inside- and outside-air temperature and solar radiation, which has not shown any clear evidence on the influence of the temperatures and solar radiation, especially for the large values on the observed deviations. This means that the model can be used to predict a thermal performance of the wall in a wide range of solar radiation.

8.3 Applicability of the model

8.3.1 Model transferability

Transferability: an important property of generic structures is their transferability. It is the prerequisite for their reuse as model components. If a model has been developed using data at one location, can this help with the analysis at another site? Otherwise, the following two key questions should be answered:

3. If a model has been developed using data at one site, e.g. in Europe, can it be applied for analysis at another site elsewhere?

2. How confident can we be sure that any conclusions we draw at one site are valid at another site?

Problems and solutions of transferability - context relateness:

Models are often constructed to address problems which relate to specific localities, forms of administration and cultures. Especially, when transferring models from one country to another country, the greenhouse model's original operational environment may differ significantly from that into which the model is to be introduced. In such cases the model will not function in the new environment in the same way, nor will it produce the same results as it did in its original context. However, many questions remain to be taken into consideration and answered as follows:

(a) Is it possible to apply the model for another greenhouse of different area and building conditions as well as what are the factors which should be considered?

♦ Concerning the greenhouse building conditions: it can be said that it is of course possible to apply the model for different greenhouses of different building conditions with some modifications to be taken into account as follows:

1. Modifying, the value of heat transfer coefficient (α), since this factor depends not only on the temperature difference found between the air and the surface, but also on the height of the greenhouse wall.

2. Greenhouse and wall orientation, where the greenhouse in the model was in the east-west orientation, while the wall was built in the north site. Therefor, when applying the model to another greenhouse of orientation different from the model, then, this would affect on the radiation ratio received on the wall which means that the orientation in such case should be considered.

♦ Concerning the greenhouse area, two important points should be referred to:

1. The ratio of the whole surface area of the greenhouse to the ground area, where it considered in the model to be 2.5, while it is known that this ratio is approximately around 1.5 (according to TANTAU 2002, personal communication). This is important to be considered, since increasing this ratio leads to the increasing of the heat loss from the greenhouse through convection and radiation. Reducing this ratio would improve the efficiency of the wall thermal performance.

2. The ratio of the wall area to the ground area was considered in the model to be 0.6, while it should be changed when applying the model in a new conditions to find out the optimal ratio, since it affects on the thermal efficiency of the wall.

3. Concerning the whole area of the greenhouse and especially the large areas, the model can be applied if the distribution of the solar radiation on the wall -, and soil-surfaces is considered, while it is considered in the model uniform. Therefore, the distribution of the solar radiation is of considerable importance which should be taken into account when applying the model.

(b) The second question which might be raised is: what happens if the plants grown in the greenhouse are tomato for example instead of grass?

Here, it should be referred to the following:

1. The transmissibility ratio of the solar radiation was considered constant in the model, while it can be varied according to the species, developmental stage of the plant and leaf area as well as plantings density. This is in case where the plants are horizontal, while in case where the plantings are grown vertically, then the shading ratio on the wall should be considered.

2. Water covering ratio is different according to the species and climate conditions. This factor influences in turn on the transpiration of the plants which result in considerable influence on the thermal behaviour in the greenhouse.

(c) The third question concerns the irrigation system applied in the greenhouse. It is important factor since irrigation system may affect on the water covering ratio of the soil surface which in turns influence on the evaporation from the soil leading to variation in their thermal properties.

Because transferability through mere copying may be considered with respect to the above factors as unpredictable and risky, therefore, the transfer of models by adapting them to the various contexts in question is more natural. The main factors playing important role in the results of the developed model were demonstrated earlier in table 6.1.

8.3.2 Usage of the model

The model was designed to be flexible, so that both conventional and unusual simulations can be made, instead of having to carry out costly experiments. The model which can be used as a research tool for providing information, such as expected inside temperature, soil layer-, wall layer-, cover-, leaf-temperatures, relative humidity in the greenhouse and heat transferred to or from any element for any given time during the entire simulation period has been worked out. Furthermore, the model can also be used as a design tool for passive solar systems to investigate the impact of design parameters and also as a tool for identifying design problems. Finally, the model can also be used as a learning tool for the students who are studying heat transfer.

Examples of use

- The model can be used for any situation where a layered construction separates two regions of differed temperature, e.g. building or greenhouse.
- Qualitative demonstration of temperature variation through walls for different constructions
- Calculation of temperature variations for different designs and construction

However, to apply the model for a long time periods (such as an entire season), several time-dependent factors have to be taken into account such as: the growth of the crop (indicate in the model by leaf area and the root distribution with depth), the amount of irrigation applied to the soil (which also varies during the crop growing season) and the lower boundary conditions (at the deepest soil layer) of temperature and moisture.

Model Requirements

- The model requires an up-to-date personal computer running Windows. The computer should be Pentium I or above with 125 megabytes of ram memory to run the model effectively. In addition to Windows, the computer must have MATLAB installed.

- One input file is required by the model: the file contains input data (i.e. boundary conditions of the system). That file should be in comma-delimited ASCII format**.** The file may be as many records as needed and each record must contain the following values in the order listed below:

- Time of simulation, in fractional form (e. g. 0 3600 7200. sec), global horizontal irradiance outside the greenhouse**,** in Wm^{-2}, global irradiance on the wall, in Wm^{-2}, Outside air temperature, in °C and relative humidity at outside, in %

8.4 Practical application of the model

8.4.1 General

Throughout most of their history, simulation programs have been written in a different programming languages according to the situation. An numerical study has been conducted to develop a design model for passive solar greenhouse (PSG). The model is based on established theory about the radiation absorption, heat loss (convection, conduction and long-wave radiation) and temperatures of the greenhouse-elements. It has an easy-to-use graphical interface and provides an accurate prediction of the thermal performance of the greenhouse. Radiation absorption was calculated using the transmittance of the greenhouse cover material, absorptance of the wall -, soil-, and leaf-surfaces, and solar angles, which depend on the time of the day, time of the year and latitude angle (geographyical location). It was assumed that the transmittance of the cover material is constant during the simulation time and not only the solar radiation at the soil-surface, but also the solar radiation at the wall-surface.

8.4.2 Egypt (as an example)

Proper application of the thermal mass in greenhouses can be one of the most effective ways for reducing of greenhouse heating and cooling loads. However, these systems require application of dynamic thermal performance analysis. The dynamic thermal performance of a series of wall assemblies has been analyzed in this work. The model developed in this work has been implemented into an existing simulation application that is capable of modeling transient energy within combined greenhouse elements. The model was used to calculate and optimize both of the inclination of the lighting surface and the thickness of the wall. The selected greenhouse is an greenhouse located at Shebin El-Kom, Egypt. Locally, there are many strong reasons to efficiently utilize solar energy in Shebin El-Kom, Egypt. First of all, from economic point of view, the solar energy is cost-free and continuously renewable resource. Geographically, the chosen place's latitude is 30 54 degrees north which is fairly close to the equator and gives a suitable location for solar utilization. Considering the climate, it has many sunny days throughout the year. On the other hand, however, environment pollution from fossil fuels exceeded the dangerous limit long ago.

There are many factors affecting on the amounts of solar radiation incidence in the greenhouse, such as greenhouse form, as well as greenhouse site and orientation (NASA 2002, PAPADAKIS et al. 1998).

The results presented in this work showed clearly the necessity of an appropriate choice of the inclination angle of the lighting surface which depends on the time of the year and the latitude angle. For example, the optimum angles were 30°, 60° for Hannover (52° 28`) while it was 10°, 50° for Shebin El-Kom (30° 54`) during the summer (April, May, June, July and August) and winter time (January, November and December) respectively. This is due to the larger angles of incidence of solar rays on the roof planes and this is in agreement with the results obtained by DUANSHENG et al. (1991).

The basic optimization criteria is the maximizing of heat gain to the heating of wall. Heat not used for wall heating is partially lost, and partially used for the passive heating of greenhouse inside air. There are two problems to achieve the maximum of heat gain, i.e. determining the temperature swing of storage material and how much is the mass material which should be used. These problems are really related, since the actual problem is to determine how heat penetrates the material and is then returned to the surface at a later time.

Thus the thickness of the wall must not be greater than the equivalent dynamic thickness based on a 24-h period.

The simulated results show that the thickness of the wall has a decisive impact on heat gain levels. A passive gain increases with the increased wall thickness. This increase, however, which is over the optimum wall thickness causes a slow decrease of passive gain for the greenhouse. The optimum thickness was calculated based on the selected location and actual climate data measured at the target study place. The results obtained are in a good agreement with those of BALCOMB (1992), FANG and LI (2000), KALOGIROU et al. (2002). However, BALCOMB (1992) suggested that the thick section of 10-15 cm and 20-30 cm should be used depending on the sun shine, while FANG and LI (2000) as well as KALOGIROU et al. (2002) found that the optimum wall thickness for Beijing (China) and Cyprus were 35- 45 cm and 25 cm respectively depending on the wall material.

Finally, it should be mentioned that the study focused on the optimization of the thermal wall thickness, while the economic aspects have not been considered.

9 Future prospectives

There are many directions still to be investigated with this model. An clearly obvious next step is to implement the model by developing various working applications such those mentioned earlier in section 8.

It should also be possible to augment the model in order to improve it with the following points:

- The solar radiation on the wall (inclined surface 90°) must be calculated as a function of the solar radiation on the soil surface (horizontal), to reduce the number of devices which must be used in the measurements and consequently reducing the costs of the experiments.

- The transmisivity of the cover material should be programmed as a function of the sun angles.

- The air exchange rate should be taken into account on a large scale applications, because it is one of the most important factors affecting the thermal performance (sensible and latent) of the greenhouse.

- The plant growth and the irrigation system should be considered in the model because of their effect on the greenhouse thermal performance (sensible and latent heat balance).

- In order to prevent heat loss from the greenhouse by convection and radiation to the surroundings, especially at the night time, outside of the front greenhouse roofing must be covered with straw mat or any other local materials available and possibility of considering it as an affecting parameter in the model.

- The wall construction should be designed well to increase the thermal performance of the wall. It can be vented, which in turn allows heated air to circulate directly to the greenhouse space.

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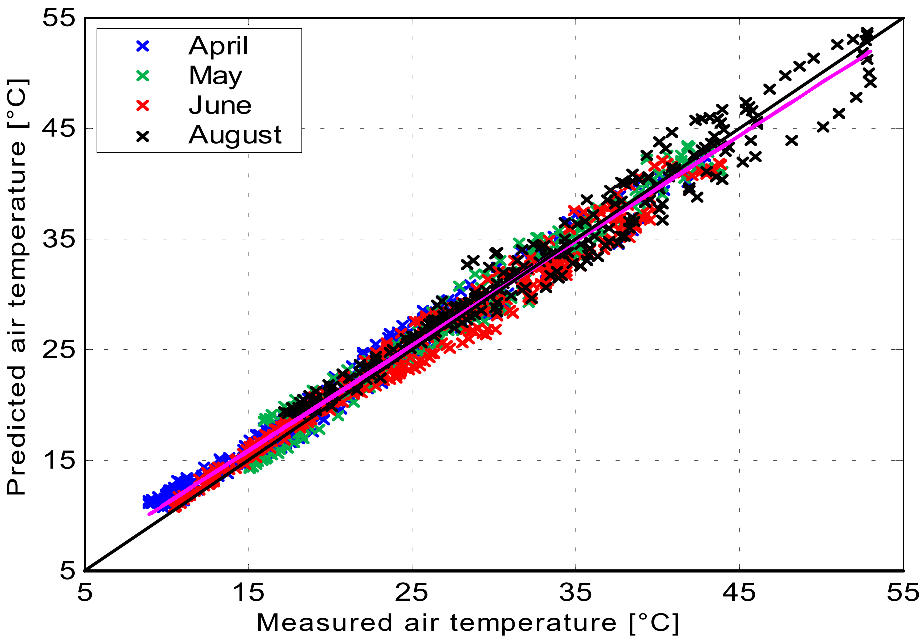

Fig. A 1. Comparison between measured and predicted inside air temperature for the four periods studied, April, May, June and August

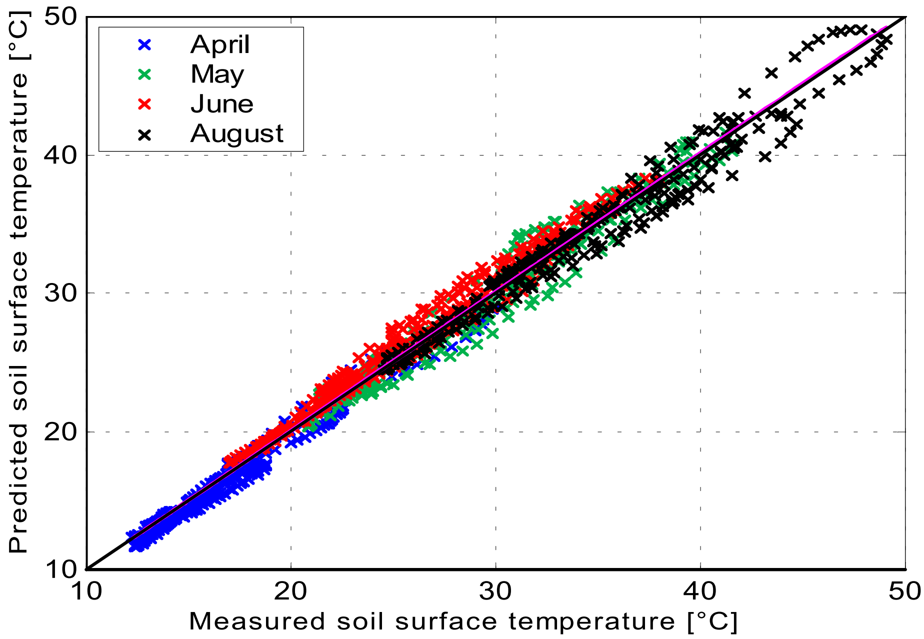

Fig. A 2. Comparison between measured and predicted soil surface temperature for the four periods studied: April, May, June and August.

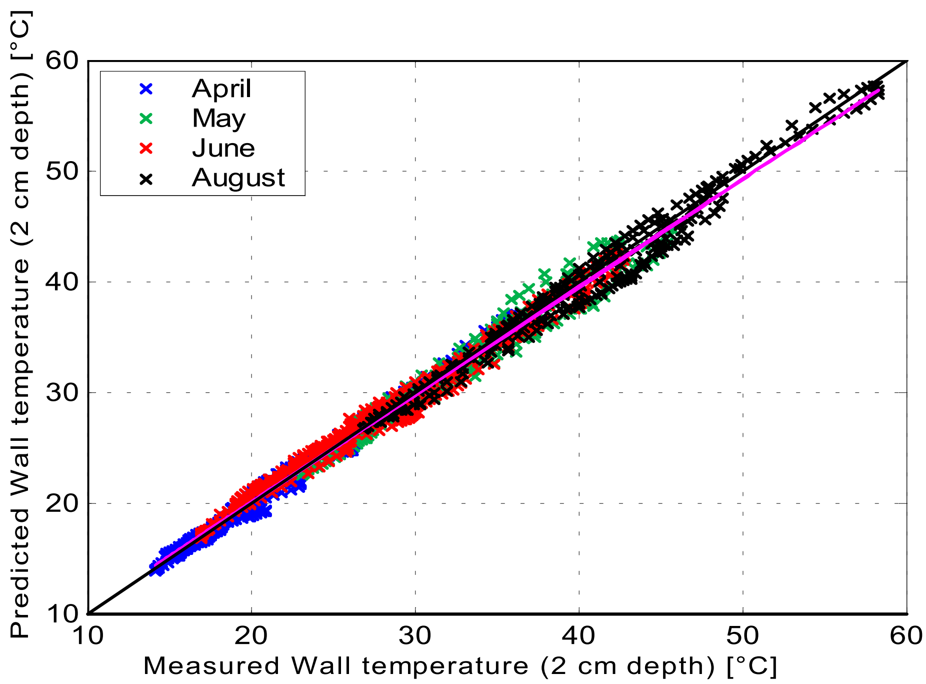

Fig. A 3. Comparison between measured and predicted wall surface temperature for the four periods studied: April, May, June and August

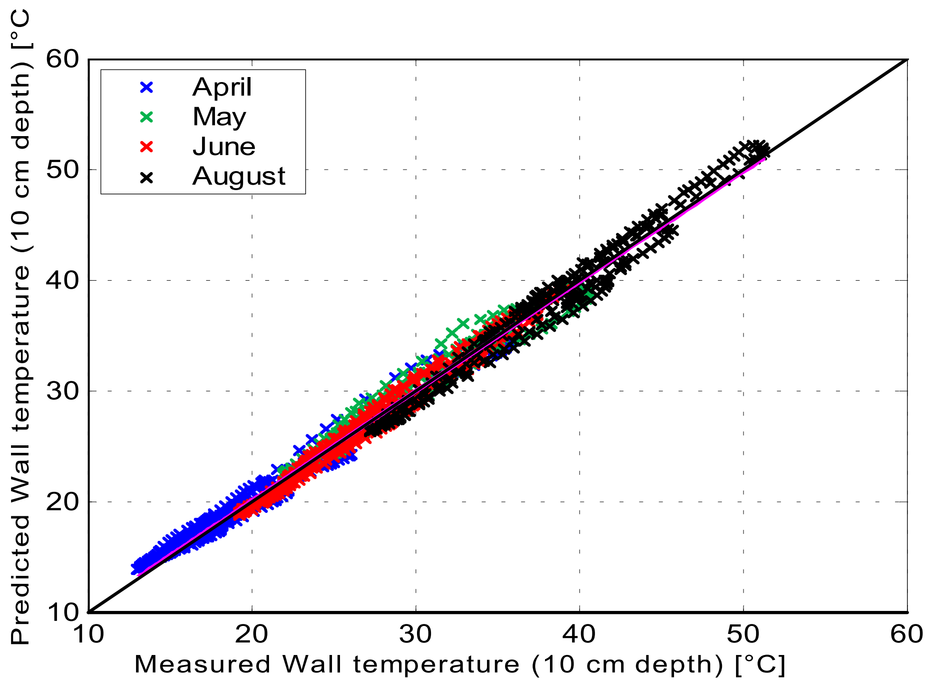

Fig. A 4. Comparison between measured and predicted wall second-layer temperature for the four periods studied: April, May, June and August.

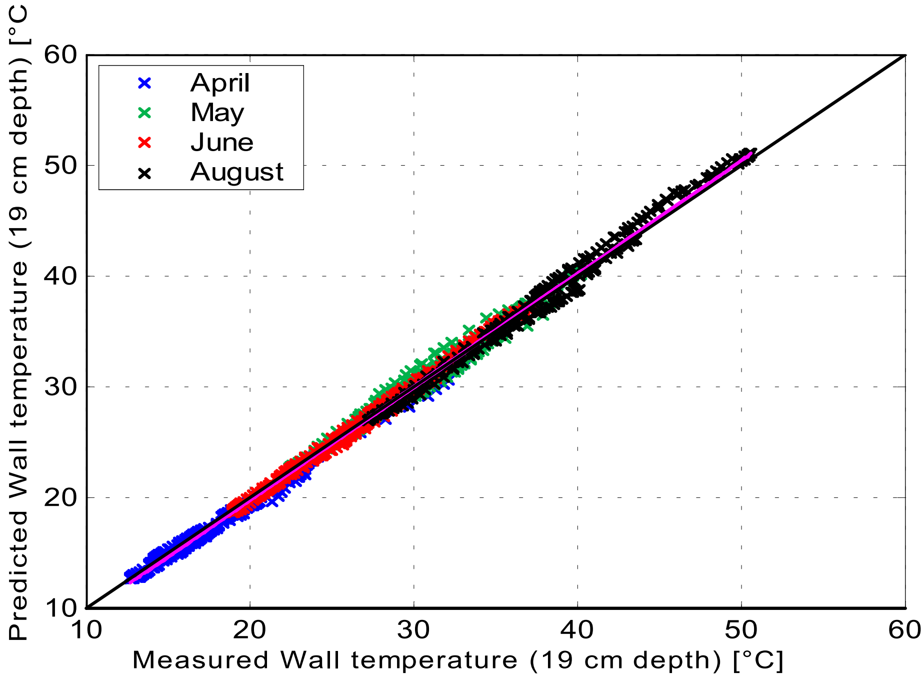

Fig. A 5. Comparison between measured and predicted wall third-layer temperature for the four periods studied: April, May, June and August

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„Who does not thank people, does not thank ALLAH“
Prophet Mohammad (Prayers and peace be upon the Messenger of ALLAH)

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Hannover, / / 2003

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