HEAT AND MASS TRANSFER IN GREENHOUSE AND EFFECTS OF VENTILATION

A project report

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Dedicated

To

My Parents

Declaration

I hereby declare that, I am the sole author of this thesis

"Heat and Mass transfer in greenhouse and effects of ventilation"

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Nomenclature

I	total solar radiation (W/m^2)
T	temperature (K)
F	view factor
ACPH	air change per hour
Q	volume flow rate (m^3/s)
h	convective HTC (W/m-K),
V	volume (m^3)
X	absolute humidity (kg/kgda)
K	mass transfer coefficient (m^2/s)
C	concentration (kg/m^3)
m	mass(kg)
C_{pa}	heat capacity of air (J/kg-K)
C_{pv}	heat capacity of vapor (J/kg-K)
K_{so}	thermal conductivity (W/m^2 K),
$\dot{m}_a$	mass flow rate (kg/s)
A	area (m^2)
W	specific humidity (kg/kgda)
P	pressure (N/m^2)
RH	relative humidity (%)
N	day number
L	characteristics length
θ	zenith angle
M	molecular weight (g/mol)

Greek symbols

ρ	reflectivity
α	absorptivity
ε	emissivity
τ	transitivity
σ	stefan boltzmann ($W/m^2 /k^4$)
ρ	density (kg/m^3)
β	bulk modulus (1/K)
υ	kinematic viscosity (m^2/s)

Subscript

t	top surface (roof)
b	bottom surface (soil)
s	side vertical surface
sk	sky
bt	bottom surface to top surface
tb	top surface to bottom surface
ts	top surface to side surface
tsk	top surface to sky
tp	top surface to plants
sp	side surface to plants
bp	bottom to plants
ti	top surface to inside
ref	reflection
trans	transmission
absr	absorption
p	plants
so	soil
i	inside of greenhouse
o	outside
sat	saturation
d	diffuse
g	greenhouse
so	soil
o	outside
sat	saturation
a	ambient air
v	vapour
atm	atmospheric
b	beam
d	diffuse
ext	extraterrestrial
N	normal
SC	solar constant
f	fluid
rad	radiation
conv	convection
evap	evaporation
cond	conduction
da	dry air

Abstract

The present work stands effort to understand heat and mass transfer and effects of ventilation in greenhouse. Different mode of heat transfer and surface energy balance for different components of greenhouse carried out. Variation of temperature of different components of greenhouse (dry/wet soil, roof, side wall, inside air and moisture) with time for different air change rate was studied in steady and unsteady state conditions. This present study can predict inside climate of greenhouse for given outside condition and greenhouse material properties. Sensible parameters were also studied and it was found that the effect of transmissivity of roof and reflectivity of soil on temperature of different components are linear. It was also found that during night, side walls and roof gets cooled. Our observation concluded that effect of ventilation is more on inside air and very less on roof, soil and side walls temperature.

1 Introduction to greenhouse

1.1 Historical Background

Agriculture production inside protected structures was initiated in France and Netherlands in the 19th century. In 20th century, the technology of greenhouse construction accelerated in Western Europe cold countries. By the end of the fifties of the 20th century the greenhouses technology flowed to the north and center of Europe, extending its influence and benefits to Israel, where a wave of experiments and research in the field had begun. The sixties revealed a new kind of structure covering sheets. They were the flexible, low priced polyethylene sheets, which caused a conceptual revolution in the field of greenhouses. Simultaneously appeared other types of good light transition coverings, such as polycarbonate (a kind of covering made of plastic polymers) leaving behind the traditional glass covering. Nowadays, light-weighted structures with covering made of flexible polyethylene or stiff-flexible polycarbonate are more common and widespread than the earlier rigid glass greenhouses.

1.2 Importance of greenhouse technology

Today the world scenario has been changing from plentiful to limited resources owing to exponential growth of population. This exerts a continuous pressure on land and agriculture and demands a radical change in agricultural practices in years to come. Sustainable ecological environment principles will be guiding in determining the desirability of certain agricultural practices over the other.

Agriculture is not a profession which is chosen voluntarily by many as is the case with much other occupation. Its importance, however, lies with the introduction of new agricultural technologies for the development of industry to attract a section of educated and talented youths. A sense of pride has to be associated with farming for recurrence of green revolution frequently.
In India, the situation with respect to production of food grains is relatively comfortable where as it not that commendable with reference to some other sectors like horticulture. Agricultural planners have been emphasizing the use of advance biotechnological practices to get breakthrough in yield potential and production of crops. At the same time, an emphasis has to be laid to improve the efficiency of agricultural inputs in the farming systems. This need is felt to search improved and new alternative technologies for intensive agriculture within the socio-economic constraints of any nation. Thus every square meter piece of land must produce manifolds with cropping.

Greenhouse cultivation as well as other modes of controlled environment cultivation has been evolved to create favorable micro climates in which crop production could be made possible all throughout the year or part of the year as required. Greenhouse food production offers a means for moving forward with greater degree of environment control. The extant of control vary from more protection from rain to complete environment control. Major factors influenced are light, temperature, atmospheric condition and the root environment. Crop growth for a given variety is controlled by its environment. The growth is inhibited when any of the factors becomes restrictive. Therefore the environment should be suitably regulated to tap the full potential of the given crop and plant type. Greenhouse is frames of inflated structure covered with transparent material in which the crops are grown under controlled environment conditions. These are large enough to allow a person to walk within the structure to carry out cultural and operational activity. Sometimes it is referred as surfaced covered cultivation. Crop micro climate in surface covered cultivation, is segregated from the ambient environment and the extent of segregation depends on type of surface cover. This provides the basis for environment control (Tiwari, 2012).

1.3 Classification of greenhouse systems

Greenhouse structures of various types are used for crop production. Although there are advantages in each type for a particular application, in general there is no single type of greenhouse, which can be constituted as the best. Different types of greenhouses are designed to meet the specific needs. The different types of greenhouses based on shape, utility, material and construction are briefly classified below in **Error! Not a valid bookmark self-reference.**.

1.4 Problem statement and objectives

Most plants require day temperatures of 21 to 26 ^{0}C and control on humidity for growth. Getting crop throughout the year in open field is not possible due to varying conditions like local weather. Greenhouse solves some of these problems.

A greenhouse allows control of the environment in which plants grow even if they are not suited to the local climate or out of season. Greenhouse is basically a building made up of transparent material such as glass, where we control the light, temperature, ventilation and amount of water that plants receive. Greenhouse also protect plants from foreign invaders such as insects, diseases etc. and hence production increases manifolds. Greenhouses are of different shapes and sizes, with different functions. Closed greenhouse is not economical in cooling and dehumidifying the greenhouse air, which is why a semi-close greenhouse has potential in saving the needed energy. The warmer temperature in a greenhouse occurs because incident solar radiation passes through the transparent roof (and walls) and is absorbed by the soil, plants, and inside air, thereby turning them warmer. Also, since the structure is not open to the atmosphere, the hot air cannot escape via convection; the temperature inside the greenhouse thus rises. Ventilation is one of the most important components in the greenhouses. Without proper ventilation, greenhouses (and their growing plants) are prone to problems stated above. The main purpose of ventilation is thus to (a) regulate the temperature and (b) humidity to the optimal level for a given type of plants.

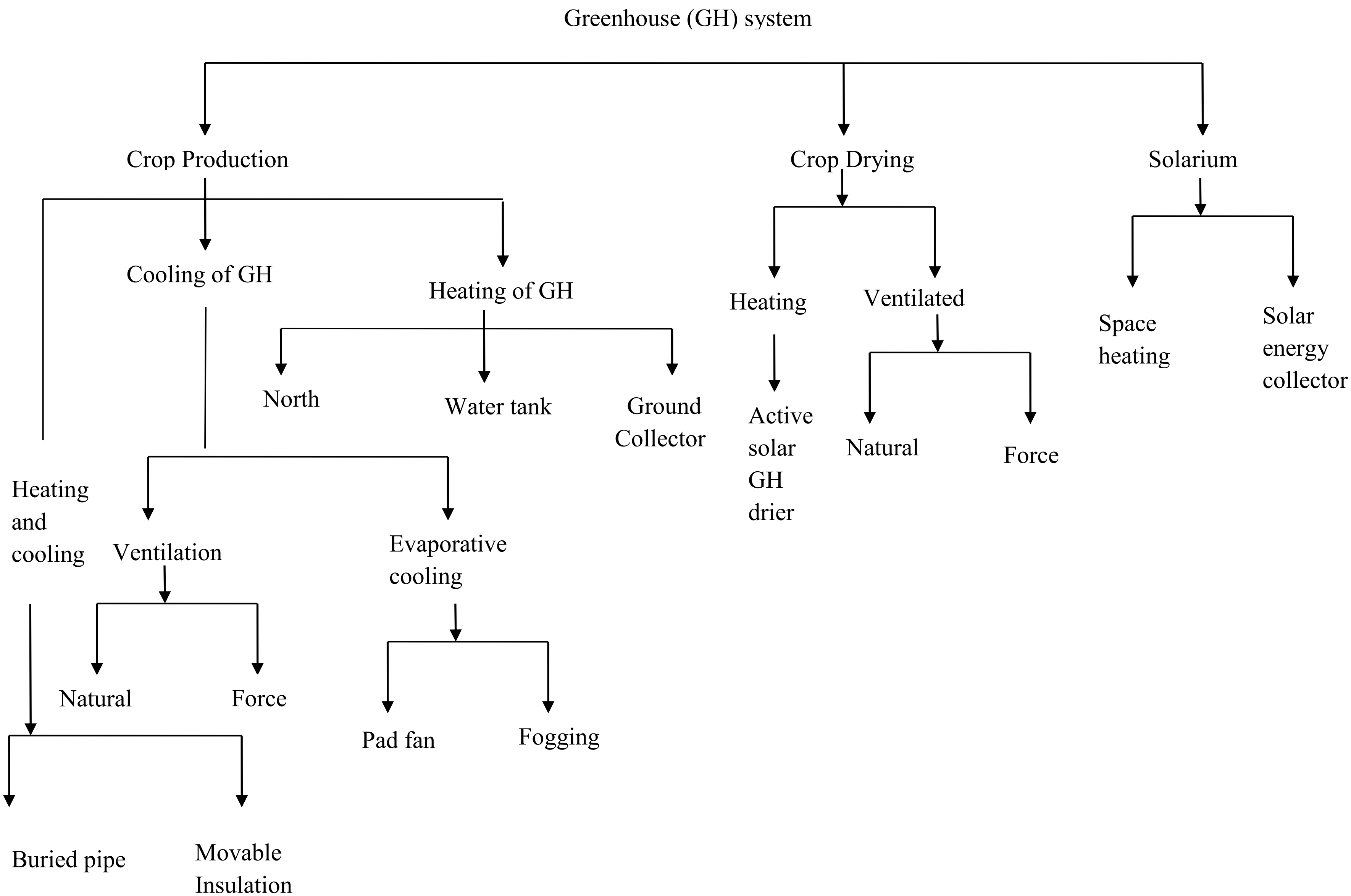

Figure 1: Classifications of greenhouse systems (Tiwari, 2012)

Ventilation also ensures (c) supply of fresh air for photosynthesis and plant respiration, and (d) may enable important factor for growth of greenhouse crop. Ventilation is achieved via use of vents and recirculation fans. Location and distribution of vent is very crucial. The roof slope is important in deciding the amount of solar radiation entering the greenhouse; sometimes these slopes have also been used for harvesting rainwater. By manipulating structure, design, and ventilation, microclimate of a greenhouse can be altered.

A Smart Greenhouse would be a Wi-Fi enabled and cloud controlled environmental system that allows a farmer to make precise adjustments to his / her environment remotely. There are currently a few companies developing such technology for greenhouse operations.

Greenhouse is thus an interesting topic for research as it is directly associated with the basic necessity of human i.e. controlled, healthy, and more volume of food in a given volume of field. At present, energy saving greenhouse is at high demands since they optimize the use of water.

Greenhouse inside climatic condition is governed mainly by outside ambient condition. Inside condition of greenhouse (dry and wet condition of soil and plants) also effects greenhouse condition.

Major objectives of this project are as follows -

- To understand heat transfer and mass transfer in greenhouse.
- To understand and estimate ventilation requirements to achieve micro climate inside greenhouse
- To study and understand parameters that affects greenhouse climate.
- Method of controlling microclimate of greenhouse.
- Development of MATLAB code to predict greenhouse microclimate for given outside climatic condition using a lumped model approximation.
- Estimation of radiation, convective, and latent heat exchanges between different surfaces of the greenhouse, such as soils, side walls and plant will be done. The results will be analyzed and shown graphically at the end. We expect this research to come up with a controlled code which would predict the variables in a given greenhouse at a given location

1.5 Literature review

The determination of energy consumption in greenhouse glass was first performed during 1960s - 1970s and then study of climate control and ventilation was performed during 1980s
Nisen (1969), Nijskens (1985), Kozai (1978) studied the quantity and quality of radiation through transparent covering. During this period only sketch studies were done for convection heat transfer.

Perfectly stirred approach (Udink ten cate, 1980) has been employed to model heat and mass transfers. It was assumed that temperature, humidity and CO_2 content are uniform inside the greenhouse.

Modeling and experiment of heat transfer balances were done to determine greenhouse climate and control such as heating, cooling, humidification, de-humidification (Van Meurs & Stanghellini, 1989, Isaan-chou, 1991 Jolliet, 1994 bailey et al 1997)

Natural ventilation is the easiest, cheapest and the most practical means to modify micro-climate of greenhouse. Air exchange is not only sufficient for temperature distribution, but also for good mixing of internal and outside air (Bailey, 2000).

Beza (2007) performed a CFD study in which he varied slope of the roof and relate the ventilation rate, he observed that for low wind speed (2 m/s), there was no increase in ventilation rate as the slope of the greenhouse increased but at higher wind velocity the effect of slope on ventilation rate became much larger as the roof slope increased further its effect on ventilation rate becomes much smaller.

When natural ventilation is used, greenhouse are ventilated via opening in the roof, sides or both and vent arrangement may differ drastically among different greenhouse design (Bournet and Boulard, 2010)

Ventilation can be improved by micro-change in screen pore level, change of effective size in openings and change in whole geometry as described by Ailey (2003)

To improve ventilation, Teitel et al. (2009) investigated the effect of screen inclination on flow parameters downstream from the screen by using experiment and CFD data. The experiment data and CFD result were in good agreement for inclined screen placed at either 45 or 135^0.

Innovative (selective surface) cover materials have the potential to save energy, reduce pest pressure and improving summer growing conditions (Stanghellini and Montero, 2010).

Sonneveld et al. (2010) described a new prototype greenhouse that they have developed, which combines reflection of near infrared radiation with electrical power generation by means of PV. The reflection of results improved climatic condition of greenhouse near infra radiation.

Bodalan Ciprian (2014) carried out theoretical research on heat transfer between greenhouse and environment and concluded that the direction of heat exchange in greenhouse is variable accumulation of heat during the day can become a loss of heat at night and vice versa, also he added that the total energy balance of a greenhouse make obviously how radiation energy absorbed is used for transpiration, evaporation, sensible heat of the air and warming soil.

Shigeki (2014) concluded that water consumption can be reduced by using greenhouse technology for agriculture in desert area. He analyzed the effect of ventilation, sprinkler water and solar radiation on changes in temperature and humidity in greenhouse

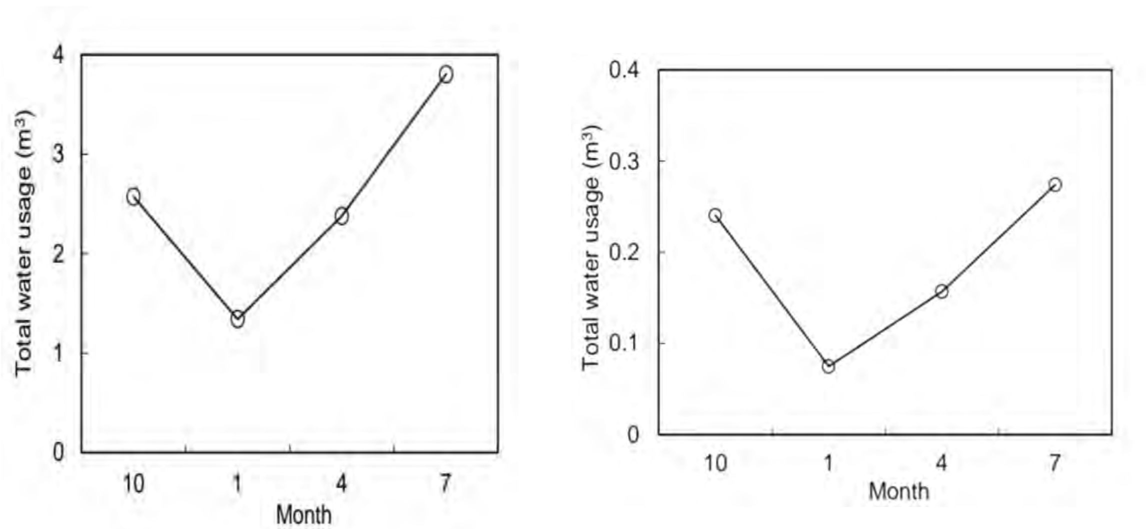

Figure 2: Variation of water usage with time (figure taken from Shigeki, 2014)

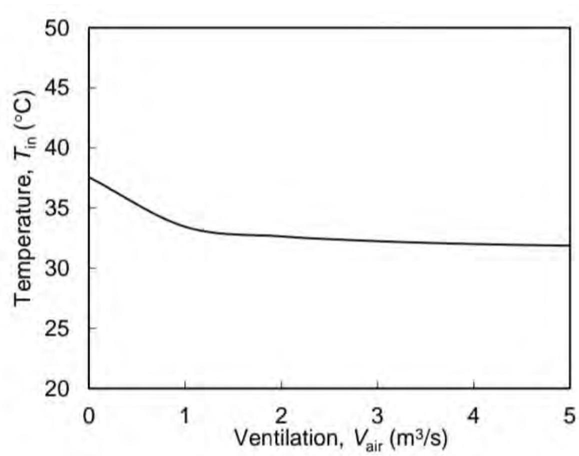

Figure 3 Variation of greenhouse temperature with ventilation.

(Figure taken from Shigeki, 2014)

Figure 3 shows that effect of ventilation on the greenhouse inside temperature (keeping ventilation, solar radiation, sprinkle water controlled), it is very clear from the plot that temperature becomes constant up to ventilation rate 1.5 m^3/s (approximately). Afterward, there is no significant change in greenhouse inside air temperature with ventilation rate.

(Hirasawa Shigeki, 2014) Compared the water consumption between cultivation of orchid in desert area (Saudi Arabia) without and with greenhouse (keeping ventilation, solar radiation and sprinkle water controlled) it is very clear from the above two figure that water consumption reduces very significantly. Without greenhouse total water usage in one day in July was 3.8 m^3/s and with greenhouse 0.3 m^3/s.

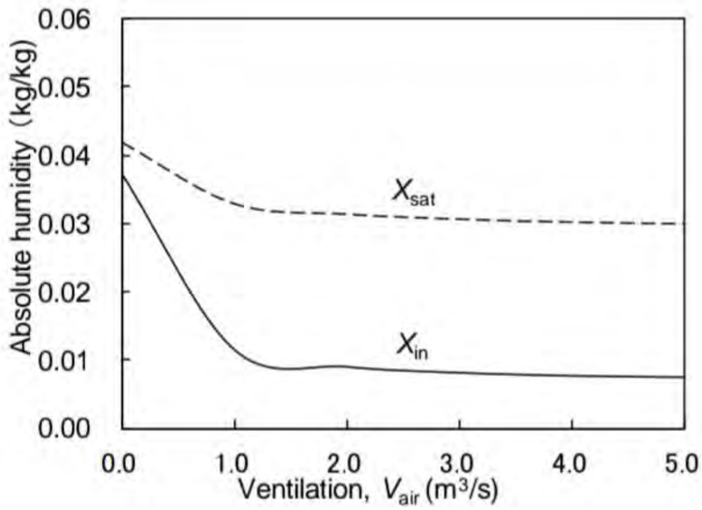

Figure 4: Variation of absolute humidity with ventilation
(Figure taken from Shegiki, 2014)

Figure 4 shows the calculation result of effect of ventilation on absolute humidity (X_{in}) inside green house. X_{sat} is saturated humidity corresponding to greenhouse inside temperature. Humidity decreases rapidly when ventilation is less than 1 m^3/s. after that humidity is almost uniform.

2 Thermal Modeling of Greenhouse

2.1 Introduction

In this chapter, thermal modeling of a greenhouse for steady and unsteady conditions has been carried out. Energy balance equations for roof, inside air, side wall, dry soil, wet soil, plants and water mass have been formulated. The different modes of heat transfer and energy terms of the equations are explained in details. In case of wet soil, evaporation loss and specific humidity calculations were done.

The MATLAB code that solves the set of steady and unsteady equations is explained. Convective heat transfer coefficients, mass transfer coefficient, view factors and properties of wet soil and air are also discussed in this chapter. The assumptions that were used during construction of thermal model are given.

2.2 Methods – Modeling of greenhouse for surfaces, soil, inside air and plant temperature

Thermal modeling requires the use of energy balance equations for the different components of greenhouse system for given climatic conditions. The energy balance equation simply states that at any given location, or node, in a system, the heat into that node is equal to the heat out of the node plus any heat that is stored. In our model, we identified different types of heat exchanges happening within and outside the greenhouse, in the presence of ventilation also. Once we identified these terms, we then proceed to construct energy (heat) balances for different surfaces, viz., Surface Energy Balance (SEB), individually. The whole set of equations were finally solved using a MATLAB code with appropriate initial and boundary conditions. The incident solar radiation (I), and the ambient conditions are inputted, along with the different materials (of various surfaces in the greenhouse) properties in the code. Note that the solar insolation is a function of time and day of the year.

The problem is thus very rich and complex. An accurate modeling is thus difficult to achieve. Our major objective is to predict the dependent variables in a greenhouse (such as temperatures and evapotranspiration) using a lumped model system (given the solar radiation intensity and ambient conditions).

Precisely, we aim to model the greenhouse such that the soil temperature, greenhouse average air temperature, greenhouse roof temperature, side wall temperature and canopy temperature can be estimated by SEB; this would predict the (micro) climate of the greenhouse.

2.3 Elements of heat transfer in greenhouse

Models of heat transfer in a greenhouse are radiation, convection, conduction, evaporation and ventilation (Figure 5: Energy transfer in greenhouse) that directly affects crop production. In greenhouse, the solar radiation not only falls directly on the greenhouse roof but also on the side walls. Depending on the properties of these materials, the incoming radiation is reflected, some transmitted and the rest absorbed. A part of this radiation enters the greenhouse and strike other surfaces (such as plants or soil), where the heat is again redistributed in different forms of energy depending on these surface properties.

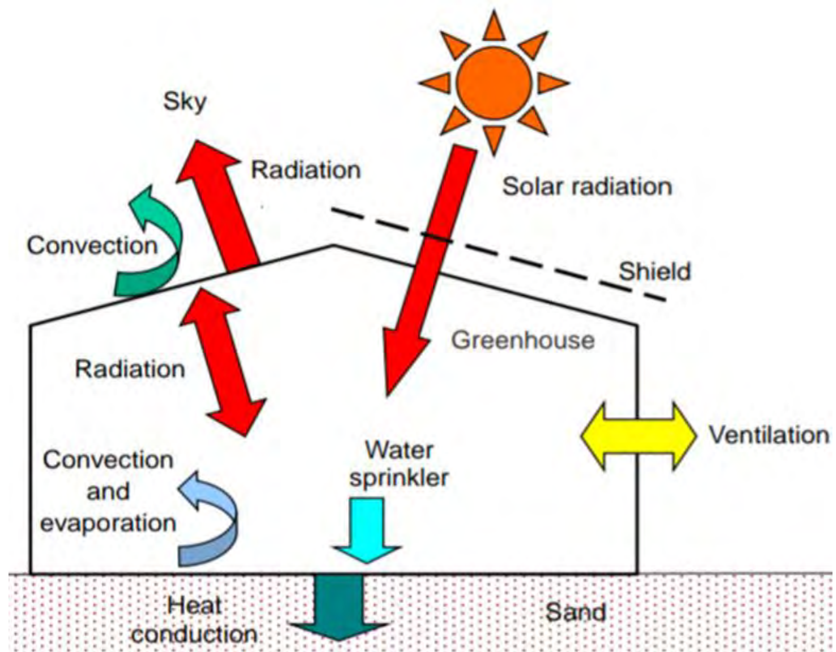

Figure 5: Energy transfer in greenhouse (Hirasawa & Shigeki, 2014)

Figure 6: Greenhouse located at GKVK, Bangalore`

2.3.1 Convection

Convection is the mode of heat transfer that takes place between surface and fluid. It is one of the critical modes of heat exchange in the greenhouse. Convection takes place between greenhouse surfaces (roof, soil, sidewall and canopy) and air (inside and outside air). Soil surface loses heat to the greenhouse air by convection and increases temperature of inside air and outside ambient of the greenhouse.

The type of convection depends on the greenhouse design, ambient condition and the ventilation rate. In well ventilated greenhouses there are forced convection, while in closed greenhouse, free convection are expected to dominate. It is thus important to gauge the convection within and outside the greenhouses. Depending on the outside wind speed, we may get forced, free or mixed convection regimes over the side vertical walls and flat / inclined roofs. In our present analysis we assume natural convection is occurring inside and outside of the greenhouse.

2.3.2 Ventilation

Ventilation is the air that is exchanged between ambient and greenhouse. Ventilation (i.e. incoming of cold less humid incoming air and exiting of warmer humid air) is an essential process in greenhouse to maintain steady and comfortable-for-plants microclimate (temperature and humidity). Higher temperatures may result in poor plant growth and there may be need for frequent watering and fans. Fan running duration can be reduced hence power by good design of natural convection. In natural convection, greenhouse roof and side wall vents operates on the principle that heat is removed by a pressure difference created by wind and temperature gradients.

Higher ventilation is required during summer and while it is lesser in winter. As per standard ventilation requirements of greenhouse in winter are generally about two to three air changes per hour while in summer it is sixty air changes per hour.

2.3.3 Radiation

Radiation is the heat transfer that takes place between sun and surfaces and also among greenhouse surfaces. Direct solar energy falls on the roof and side walls of a greenhouse. Some part of radiation is absorbed, some gets reflected and rest gets transmitted. Absorbed part of radiation increases temperature of surface. Transparent roof and side cover allow short wavelength radiation to pass but they are opaque to long wavelength radiation.

Solar radiation varies with day number and time. Once the greenhouse surface and soil surface get heated there is radiation interaction among them. Shield/ shading outside or inside the greenhouse reduce the radiation level on the soil/plants.

2.3.4 Evaporation

Evaporation is an important heat transfer process. In greenhouse evaporation occurs from the wet soil and leaves. Evaporation increases the enthalpy of greenhouse air and humidity. Inside air relative humidity plays an important role to govern mass loss by wet surface and plants. Relative humidity of wet soil surface and leaves are assumed 100 % saturated with water.

2.3.5 Conduction

Conduction in the greenhouse takes place within soil, the upper surface temperature of soil decreases or increases with depth depending upon outside weather condition. Conduction is more in dry soil as compared to wet soil because temperature difference in dry soil case is more than the wet soil condition. Here to note that thermal conductivity of wet soil is higher than that of dry soil due to moisture content in wet soil. Therefore, the water in wet soil is the transfer agent for thermal conductivity. Temperature of soil at a depth of 0.15 m has been assumed to be average daily temperature of greenhouse inside air. (Hirasawa & Shigeki, 2014).

2.4 Steady state energy balance of components of greenhouse

Figure 7 shows the schematic representation of a greenhouse model chamber which receives direct solar radiation at its top surface (roof). Solar radiation was assumed normal to the roof surface at all times. The side vertical surface receives only a constant diffuse radiation (50W/m^2) because during the peak radiation hours the contribution of the beam radiation on vertical wall is insignificant compared to the total radiation.

Solar radiation is intercepted at the top surface. Some of this radiation gets transmitted into the greenhouse while rest gets reflected back in the atmosphere. The top surface can heat up, as it absorbs some of the incoming solar radiation. The hot top surface can now radiate heat to the other surfaces of the greenhouse. In addition, the transmitted radiation will also heat-up the bottom surface of the greenhouse.

Energy balance equations for the roof, soil, side vertical surfaces, soil and inside air are written. As we know, in steady state no energy is absorbed by the components of greenhouse hence algebraic sum of all incoming energy is equal to the sum of outgoing energy. Energy balance equations for each of these greenhouse components are presented below.

2.4.1 Energy equation for top surface (Roof)

Greenhouse roof (Figure 8) receives direct solar radiation (I_{rad}), some part of it, is absorbed (I_{absr}). Some part gets reflected (I_{ref}) and rest are getting transmitted (I_{trans}). The roof exchanges heat with other surfaces, inside and outside air by radiation and convection. $I_{rad\text{-}roof\text{-}sky}$, $I_{rad\ \text{-}roof\text{-}soil}$, $I_{rad\ \text{-}roof\text{-}soil}$ are the net radiation heat exchange to sky, soil and side wall. $I_{conv\text{-}roof\text{-}ambient}$, $I_{conv\ \text{-}roof\text{-}air}$ are convective heat transfer between roof, outside and inside air.

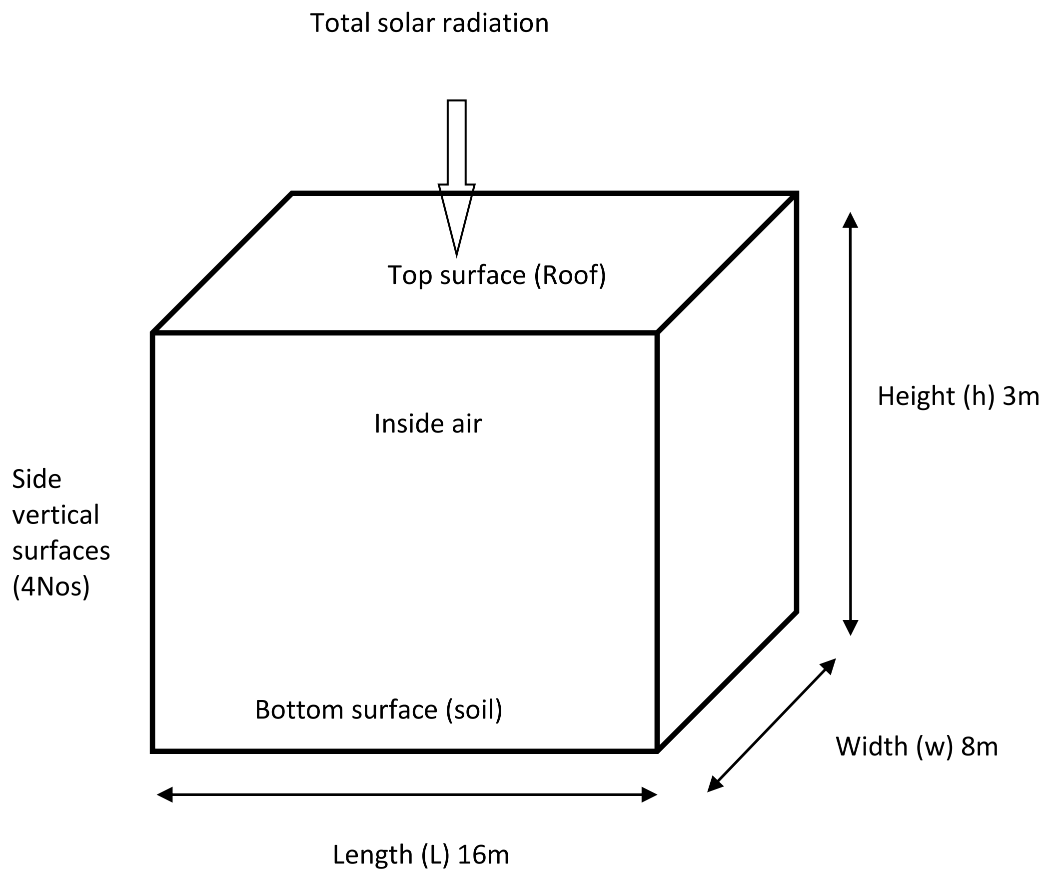

Figure 7: Schematic of greenhouse model chamber

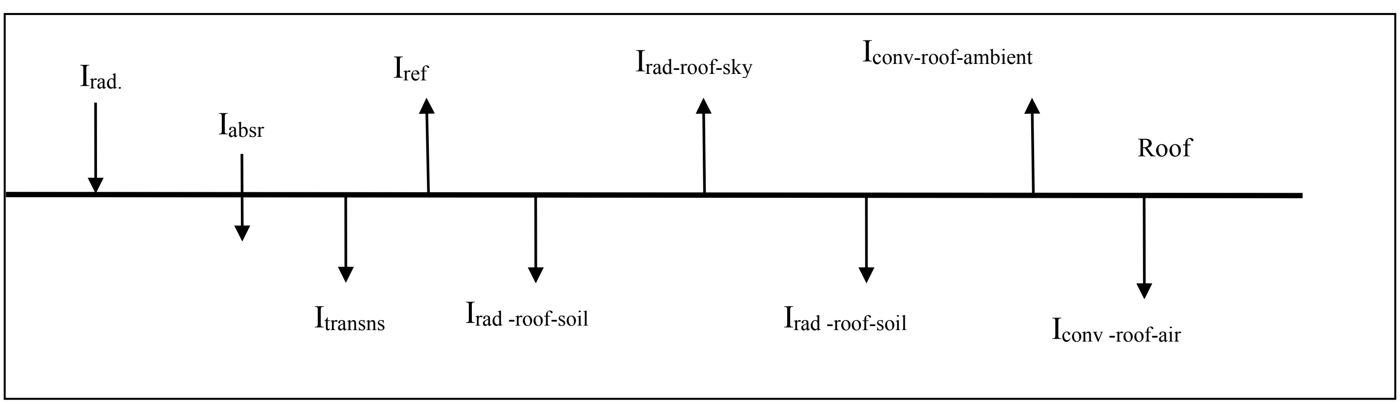

Figure 8 Surface energy balances for roof

$I_{rad} - I_{ref} - I_{trans} - I_{rad-roof-sky} - I_{rad-roof-soil} - I_{rad-roof-sidewall} - I_{conv-roof-ambient} - I_{conv-roof-inside\ air} = 0$

$(I - I\rho_t - I\tau_t)A_t - F_{tsk}\varepsilon_t\varepsilon_{sk}\sigma(T_t^4 - T_{sk}^4)A_t - A_tF_{tb}\varepsilon_t\varepsilon_b\sigma(T_t^4 - T_b^4)A_t - A_t4F_{ts}\varepsilon_t\varepsilon_s\sigma(T_t^4 - T_s^4)A_t - h_{to}(T_t - T_o)A_t - h_{ti}(T_t - T_i)A_t = 0 \ (1)$

2.4.2 Energy equation for bottom surface (Soil)

Transmitted radiation (I_{trans}) from roof is received by the soil surface as shown in Figure 9. A part of it is absorbed ($I_{absr-soil}$) by the soil. Some part gets reflected ($I_{ref-soil}$) and the rest get transmitted ($I_{trans-soil}$) to the soil beneath. $I_{rad\ -roof-soil}$ and $I_{rad-soil-sidewall}$ is the net radiation heat exchange between soil – roof and soil-sidewall. Soil also conduct heat within, if soil surface is at higher temperature it loses heat and vice versa. Soil heats inside air by convection $I_{conv-soil-inside\ air}$. Soil also evaporates depending upon whether it is wet or dry condition. $I_{evap-soil-inside\ air}$ is the heat transfer from wet soil to inside air.

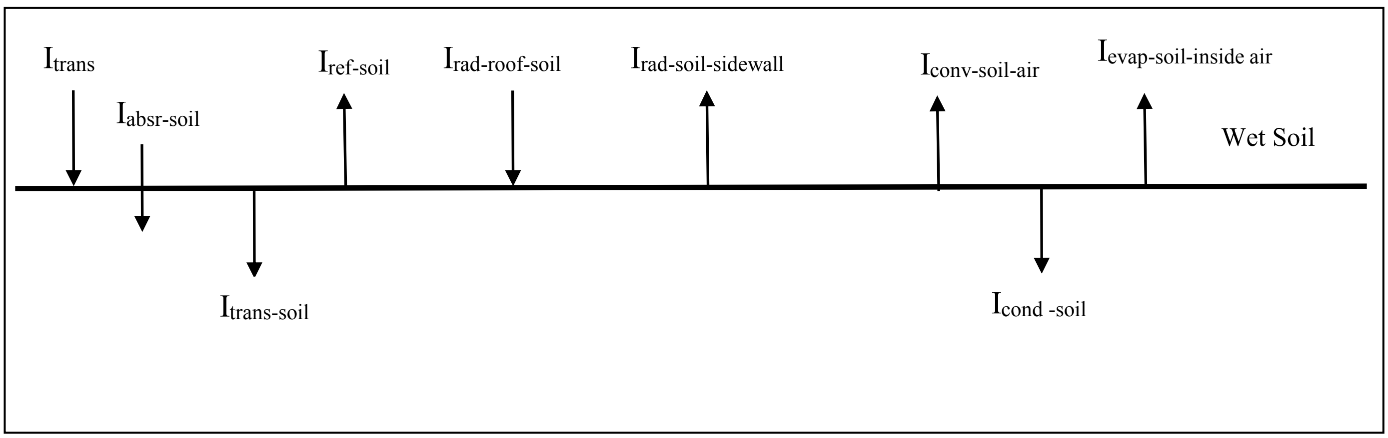

Figure 9: Surface energy balances for soil surface

$I_{trans} - I_{ref-soil} - I_{trans-soil} + I_{rad-roof-soil} - I_{rad-soil-sidewall} - I_{conv-soil-inside\ air} - I_{evap-soil-air} - I_{cond-soil} = 0$

Dry soil condition

$(I\tau_t - I\tau_t\rho_b - I\tau_t\tau_b)A_b + F_{tb}\sigma\varepsilon_t\varepsilon_b(T_t^4 - T_b^4)A_t - F_{bs}\sigma\varepsilon_t\varepsilon_s(T_b^4 - T_s^4)A_b - h_{bi}(T_b - T_i)A_b - K_{so}\frac{(T_b - T_{sl})}{l}A_b = 0 \ (2a)$

Wet soil condition (Evaporation from soil)

$(I\tau_t - I\tau_t\rho_b - I\tau_t\tau_b)A_b + F_{tb}\sigma\varepsilon_t\varepsilon_b(T_t^4 - T_b^4)A_t - F_{bs}\sigma\varepsilon_t\varepsilon_s(T_b^4 - T_s^4)A_b - h_{bi}(T_b - T_i)A_b - K_{so}\frac{(T_b - T_{sl})}{l}A_b - \dot{m}_w h_{fg} = 0 \ (2b)$

2.4.3 Energy equation for side walls

Similar to roof, energy balance for side vertical wall is shown in Figure 10. Here area of all four side walls are combined and only one equation has been written. Also note that the side wall receives only a constant diffuse radiation (50W/m^2) during both day and night.

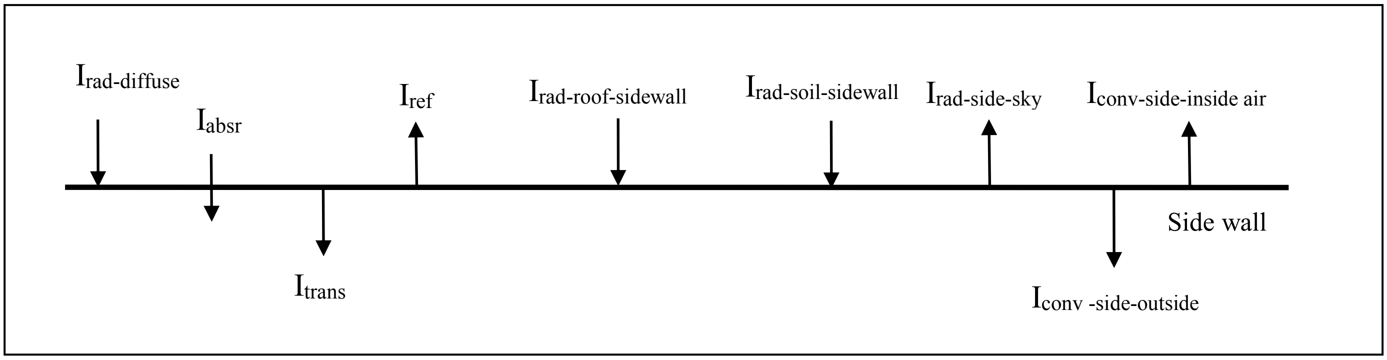

Figure 10: Surface Energy balance for side wall

$$I_{rad-difuse} - I_{ref} - I_{trans} + I_{rad-roof-sidewall} + I_{rad-soil-sidewall} + I_{rad-side-sky} - I_{conv-sidewall-inside\ air} - I_{conv-sidewall-ambient} = 0$$

$$(I_d - I_d\rho_s - I_d\tau_s)A_s - F_{ssk}\varepsilon_{sk}\varepsilon_s\sigma(T_s^4 - T_{sk}^4)A_s + F_{ts}\sigma\varepsilon_t\varepsilon_s(T_t^4 - T_s^4)A_t + F_{bs}\varepsilon_b\varepsilon_s\sigma(T_b^4 - T_s^4)A_b \quad - h_{si}(T_s - T_i)A_s - h_{so}(T_s - T_0)\ A_s = 0 \quad (3)$$

2.4.4 Energy equation for inside air

Inside air receives heat from greenhouse inside surfaces (roof, soil and side wall) by convection and temperature and enthalpy of incoming air is increased. In wet soil condition evaporative heat transfer tales place between wet soil surfaces and inside air and thus further increases enthalpy and moisture content of greenhouse inside air.

Dry soil condition

$$h_{ti}(T_t - T_i)A_t + h_{bi}(T_b - T_i)A_b + h_{si}(T_s - T_i\,)A_s - \dot{m}_a(C_{pa}(T_i - T_0) + (X_g - X_a)h_{fg} + C_{pv}(X_gT_i - X_aT_o))] = 0 \ \ (4a)$$

Wet soil condition (Evaporation from soil)

$$h_{ti}(T_t - T_i)A_t + h_{bi}(T_b - T_i)A_b + h_{si}(T_s - T_i\,)A_s + h_{pi}\big(T_p - T_i\big)A_p + \dot{m}_{ws}h_{fg} - \dot{m}_a\ (C_{pa}(T_i - T_0) + (X_g - X_a)h_{fg} + C_{pv}(X_gT_i - X_aT_o))\ (4b)$$

2.4.5 Water mass balance of inside air

In dry soil condition, since there is no mass transfer to the inside air, hence moisture content in the inside air and outside air will be same. $\dot{m}_a X_{amb}$ is the rate of mass of water vapor (kg/s) entering inside greenhouse and as there no mass addition ,so specific humidity of the greenhouse air (X_g) will be equal to ambient humidity (X_{amb}).

Dry soil condition

$$\dot{m}_a X_{amb} = \dot{m}_a X_g$$

$$X_{amb} = X_g \quad (5a)$$

Wet soil condition (Evaporation from soil)

In wet soil condition, since there is water vapour transfer to the inside air, hence moisture content in incoming air and outgoing air doesn't remain equal. $\dot{m}_{ws}$ is the rate of mass of water vapour addition to the inside air specific humidity of the greenhouse air (X_g) increases (depending upon the condition of outside air relative humidity and ventilation rate) and may reach to a maximum saturation specific humidity. If inside air gets saturated with water vapour, there is no evaporation from the soil.

$$\dot{m}_a X_{amb} + \dot{m}_{ws} = \dot{m}_a X_g \quad (5b)$$

2.5 Plants steady state energy balance equation

In our thermal modelling we have not written separate energy equation for plants. The wet soil equation is replaced with plants equation with suitable modifications in the properties. Plant leaf is assumed saturated with water like wet soil and evaporation rate will be estimated using same relation that is used to calculate evaporation from water surface. The area covered by the plants may be specified. Conduction is not considered in plants.

$$(I\tau_t - I\tau_t\rho_p - I\tau_t\tau_p)A_p + F_{tp}\sigma\varepsilon_t\varepsilon_p(T_t^4 - T_p^4)A_t + F_{sp}\sigma\varepsilon_p\varepsilon_s(T_s^4 - T_p^4)A_t - h_{pi}(T_p - T_i)A_p - \dot{m}_{wp}h_{fg} = 0 \quad (6)$$

2.6 Unsteady state energy balance of components of greenhouse

For time dependent analysis energy balance equations were modified. Unsteady state solution is dynamic in nature. Energy balance of each component of greenhouse is carried out. In this analysis difference between incoming energy and outgoing energy is the rate of change of internal energy of different components of the greenhouse.

Energy balance equation for each of the greenhouse components are given below –

2.7 Unsteady state energy balance equations -Dry soil, No Plants

Roof

$$m_t C_{pt} \frac{dT_t}{dt} = (I - I\rho_t - I\tau_t)A_t - F_{tsk}\varepsilon_t\varepsilon_{sk}\sigma(T_t^4 - T_{sk}^4)A_t - F_{tb}\varepsilon_t\varepsilon_b\sigma(T_t^4 - T_b^4)A_t - F_{ts}\varepsilon_t\varepsilon_s\sigma(T_t^4 - T_s^4)A_t - h_{to}(T_t - T_o)A_t - h_{ti}(T_t - T_i)A_t \qquad (7)$$

Soil

$$m_{so} C_{pso} \frac{dT_b}{dt} = (I\tau_t - I\tau_t\rho_b - I\tau_t\tau_b)A_b + F_{tb}\sigma\varepsilon_t\varepsilon_b(T_t^4 - T_b^4)A_t - F_{bs}\sigma\varepsilon_t\varepsilon_s(T_b^4 - T_s^4)A_b - h_{bi}(T_b - T_i)A_b - K_{so}\frac{(T_b - T_{sl})}{l}A_b \qquad (8)$$

Side walls

$$m_s C_{ps} \frac{dT_s}{dt} = (I_s - I_s\rho_s - I_s\tau_s)A_s + F_{ts}\sigma\varepsilon_t\varepsilon_s(T_t^4 - T_s^4)A_t + F_{bs}\varepsilon_b\varepsilon_s\sigma(T_b^4 - T_s^4)A_b - F_{ssk}\varepsilon_{sk}\varepsilon_s\sigma(T_s^4 - T_{sk}^4)A_s - h_{si}(T_s - T_i)A_s - h_{so}(T_s - T_0)A_s \qquad (9)$$

Inside air

$$m_{ga} C_{pa} \frac{dT_i}{dt} = h_{ti}(T_t - T_i)A_t + h_{bi}(T_b - T_i)A_b + h_{si}(T_s - T_i)A_s + \dot{m}_a C_{pa}(T_0 - T_i) \qquad (10)$$

2.8 Unsteady state energy balance equations -Wet soil, No Plants

Roof

$$m_t C_{pt} \frac{dT_t}{dt} = (I - I\rho_t - I\tau_t)A_t - F_{tsk}\varepsilon_t\varepsilon_{sk}\sigma(T_t^4 - T_{sk}^4)A_t - F_{tb}\varepsilon_t\varepsilon_b\sigma(T_t^4 - T_b^4)A_t - F_{ts}\varepsilon_t\varepsilon_s\sigma(T_t^4 - T_s^4)A_t - h_{to}(T_t - T_o)A_t - h_{ti}(T_t - T_i)A_t \qquad (11)$$

Soil

$$m_s C_{ps} \frac{dT_b}{dt} = (I\tau_t - I\tau_t\rho_b - I\tau_t\tau_b)A_b + F_{tb}\sigma\varepsilon_t\varepsilon_b(T_t^4 - T_b^4)A_b - F_{bs}\sigma\varepsilon_t\varepsilon_s(T_b^4 - T_s^4)A_b - h_{bi}(T_b - T_i)A_b - \dot{m}_{ws}h_{fg} - K_{so}\frac{(T_b - T_{sl})}{l}A_b \qquad (12)$$

Side wall

$$m_{so} C_{pso} \frac{dT_s}{dt} = (I_s - I_s\rho_s - I_s\tau_s)A_s + F_{ts}\sigma\varepsilon_t\varepsilon_s(T_t^4 - T_s^4)A_t + F_{bs}\varepsilon_b\varepsilon_s\sigma(T_b^4 - T_s^4)A_b - F_{ssk}\varepsilon_{sk}\varepsilon_s\sigma(T_s^4 - T_{sk}^4)A_s - h_{si}(T_s - T_i)A_s - h_{so}(T_s - T_0)A_s \qquad (13)$$

Inside air

$$m_{ga}C_{pa}\frac{dT_i}{dt} = h_{ti}(T_t - T_i)A_t + h_{bi}(T_b - T_i)A_b + h_{si}(T_s - T_i)A_s + \dot{m}_{ws}h_{fg} + + \dot{m}_a C_{pa}(T_0 - T_i) \quad (14)$$

Water mass Balance

$$\dot{m}_{ws} - \dot{m}_a X_g + \dot{m}_a X_{amb} = m_{ag}\frac{dX_g}{dt} \quad (15)$$

2.9 Unsteady state energy balance equations for components of greenhouse – Wet soil, Plants

Roof

$$m_t C_{pt}\frac{dT_t}{dt} = (I - I\rho_t - I\tau_t)A_t - F_{tsk}\varepsilon_t\varepsilon_{sk}\sigma(T_t^4 - T_{sk}^4)A_t - F_{tb}\varepsilon_t\varepsilon_b\sigma(T_t^4 - T_b^4)A_t - F_{ts}\varepsilon_t\varepsilon_s\sigma(T_t^4 - T_s^4)A_t - F_{tp}\sigma\varepsilon_t\varepsilon_p(T_t^4 - T_p^4)A_t - h_{to}(T_t - T_o)A_t - h_{ti}(T_t - T_i)A_t \quad (16)$$

Soil

$$m_{so}C_{pso}\frac{dT_b}{dt} = (I\tau_t - I\tau_t\rho_b - I\tau_t\tau_b)A_b + F_{tb}\sigma\varepsilon_t\varepsilon_b(T_t^4 - T_b^4)A_b - F_{bs}\sigma\varepsilon_t\varepsilon_s(T_b^4 - T_s^4)A_b - F_{bp}\sigma\varepsilon_p\varepsilon_b(T_b^4 - T_p^4)A_t - h_{bi}(T_b - T_i)A_b - \dot{m}_{ws}h_{fg} - K_{so}\frac{(T_b - T_{sl})}{l}A_b \quad (17)$$

Side walls

$$m_{so}C_{ps}\frac{dT_s}{dt} = (I_s - I_s\rho_s - I_s\tau_s)A_s + F_{ts}\sigma\varepsilon_t\varepsilon_s(T_t^4 - T_s^4)A_t + F_{bs}\varepsilon_b\varepsilon_s\sigma(T_b^4 - T_s^4)A_b - F_{ssk}\varepsilon_{sk}\varepsilon_s\sigma(T_s^4 - T_{sk}^4)A_s - F_{sp}\sigma\varepsilon_p\varepsilon_s(T_s^4 - T_{sp}^4)A_s - h_{si}(T_s - T_i)A_s - h_{so}(T_s - T_0)A_s \quad (18)$$

Inside air

$$\frac{d}{dt}[m_a(C_{air}(T_i - T_0) + (X_g - X_a)h_{fg} + C_v(X_gT_i - X_aT_o)) + \dot{m}_a C_{pa}(T_i - T_o)] = h_{ti}(T_t - T_i)A_t + h_{si}(T_s - T_i)A_s + h_{pi}(T_p - T_i)A_p + \dot{m}_{wp}h_{fg} + \dot{m}_a C_{pa}(T_i - T_o) \quad (19)$$

Water mass Balance

$$m_a\frac{dX_g}{dt} = \dot{m}_{wp} - \dot{m}_a(X_g - X_{amb}) \quad (20)$$

Plants energy balance

$$m_p C_{pp}\frac{dT_p}{dt} = (I\tau_t - I\tau_t\rho_p - I\tau_t\tau_p)A_p + F_{tp}\sigma\varepsilon_t\varepsilon_p(T_t^4 - T_p^4)A_t + F_{sp}\sigma\varepsilon_p\varepsilon_s(T_s^4 - T_{sp}^4)A_t - h_{pi}(T_p - T_i)A_p - \dot{m}_{wp}h_{fg} \quad (21)$$

2.10 Development of MATLAB Code for steady and unsteady state solutions

A MATLAB code has been developed which solves set of equations, taking a set of input parameters like ambient conditions, incoming solar radiation and material properties. MATLAB solves system of nonlinear equation using numerical technique.

Similarly for unsteady state, a set of ordinary algebraic differential equation are treated in MATLAB and solutions are obtained from set of equations. Input and output variables are tabulated in **Table 1**

Table 1 Input and output parameters for MATLAB code

Input parameters to MATLAB Code	Output from MATLAB Code
Greenhouse dimensions Length(L), Width (W) ,height(H) Bottom surface (A_b) Top surface(A_t) Side surface (A_s) **Ambient conditions** Temperature (T_0),Humidity(X_{amb}), Total solar radiation (I),Diffuse radiation((I_d),) day number and time **Greenhouse surfaces emission and material properties** Emissivity ε, Transmissivity(τ), reflectivity(ρ) Specific heats (C_p) **Outside air properties** Specific heat(C_{pa}) **Ventilation rate** ($\dot{m}_a$) **View factors** $F_{ssk}, F_{bt}, F_{st}, F_{bs}$ etc.	**Temperatures** Roof (T_t), Soil (T_b), Side surface (T_s), Inside air (T_i) Plants (T_P) **Specific humidity** Inside air (X_g)

2.11 Total solar radiation

The intensity of extra-terrestrial solar radiation (I_{ext}) measured on a plane normal to the radiation on n^{th} day of the year is

$I_{ext} = I_{sc}\{1.0 + 0.33cos\left(\frac{360n}{365}\right)\}$ (Duffie, Beckmen, & Hottel, 1991)

Beam radiation $(I_{Nb}) = I_{ext}\tau_b$, where $\tau_d = d_0 + d_1 e^{-\frac{m}{cos\theta_z}}$

Diffuse radiation $(I_{Nd}) = I_{ext}\tau_d$, where $\tau_d = 0.271 - 0.939\tau_d$

d_0, d_1, m, θ_z are the constants depends on location and altitude (Tiwari, 2012)

Total solar radiation is the sum of diffuse and beam radiation $(I) = I_{Nb} + I_{Nd}$

2.12 Heat transfer and mass transfer coefficients

Calculation of convective heat transfer coefficients

Type of convection between surfaces and inside and outside air were assumed to be natural convection and convective heat transfer coefficients for the same have been calculated by using Nusselt –Rayleigh correlations as shown in the Table 2 (Sachdeva, 2008). Values of convective heat transfer coefficient vary from 2 to 5 (W/m^{2}K) in entire temperature range of greenhouse surfaces and air temperatures. Raleigh number also estimated and found that values in the range of natural convection that is less than 10^9.

Table 2 Convective heat transfer coefficients

Horizontal surfaces	Convective HT coefficient	Raleigh Number(R_a)
Top surface (Top-Inside air)	$h_{ti} = \frac{K_a}{L} 0.15\, R_a^{\frac{1}{3}}$	$\frac{g\beta(T_t - T_i)L^3}{\nu\alpha}$
Top surface (Top-Outside air)	$h_{to} = \frac{K_a}{L} 0.15\, R_a^{\frac{1}{3}}$	$\frac{g\beta(T_t - T_o)L^3}{\nu\alpha}$
Bottom surface (Bottom-Inside air)	$h_{bi} = \frac{K_a}{L} 0.27\, R_a^{\frac{1}{4}}$	$\frac{g\beta(T_b - T_i)L^3}{\nu\alpha}$
Vertical surfaces		
Side wall (Side-Inside air)	$h_{si} = \frac{K_a}{L} 0.59\, R_a^{\frac{1}{4}}$	$\frac{g\beta(T_s - T_i)L^3}{\nu\alpha}$
Side wall (Side-Outside air)	$h_{so} = \frac{K_a}{L} 0.59\, R_a^{\frac{1}{4}}$	$\frac{g\beta(T_s - T_o)L^3}{\nu^2}$

Calculation of mass transfer coefficients and evaporation loss

When both heat and mass transfer are occurring simultaneously then mass and convective heat transfer coefficients are related as under. (Holman & Bhattacharyya, 2008).

Mass transfer coefficient

$$K = \frac{h_{bi}}{\rho C_p}$$

where h_{bi} is the convective heat transfer coefficient between inside air and wet soil surface

Lewis number is assumed 1 for water vapour mixture (Holman & Bhattacharyya, 2008)

Estimation of mass loss

$$\dot{m}_w = K(C_b - C_i)A_b$$

Where,

$$C_b = \frac{P_{wb} M_w}{R_0 T_b}, C_i = \frac{P_{wi} M_w}{R_0 T_0}$$

C_b = Concentration of water vapour at the bottom wet surface $\left(\frac{kg}{m^3}\right)$

C_i = Concentration of water vapour in the greenhouse air $\left(\frac{kg}{m^3}\right)$

The concentration at the surface C_b is the corresponding saturation conditions at the bottom wet soil surface temperature.

P_{wb} =Partial pressure of water vapour corresponding to water surface (wet soil) surface temperature(T_b)

P_{wi} =Partial pressure of water vapour corresponding to inside temperature (T_i)

Saturation pressure is calculated using relation, $P_s(T) = \exp\left(25.317 - \frac{5114}{273+T}\right)$ (Tiwari, 2012)

2.13 View factors estimation

View factor is defined as fraction of intercepted energy. View factors between surfaces are estimated using reciprocity theorem, shape factor algebra and from the chart -shape factors for parallel rectangles (Sachdeva, 2008) as follows

$F_{tt} + F_{tb} + F_{ts} = 1$

$F_{bb} + F_{bt} + F_{bs} = 1$

$F_{ss} + F_{st} + F_{sb} = 1$

$F_{ss} = 1 - F_{st} - F_{sb}$

$F_{ss} = 1 - \frac{A_t}{A_s} F_{ts} - \frac{A_b}{A_s} F_{bs}$

2.14 Calculation of specific humidity of ambient air

Specific humidity (W) of outside air were calculated using relation

$$W = \frac{0.622P_v}{(P_{atm} - P_v)}\left(\frac{kg}{kgda}\right)$$

Similarly, specific humidity in saturated condition

$$W_{sat} = \frac{0.622P_{vsat}}{(P_{atm} - P_{vsat})}\left(\frac{kg}{kgda}\right)$$

Also, relative humidity

$$RH = \frac{WP_{atm}}{(W + 0.622)P_{vsat}}$$

Saturation pressure (P_{vsat}) and partial pressure of water vapour (P_v)at temperature (T) will be calculated by the relation -

$$P_{vsat}(T) = \exp(25.317 - \frac{5114}{273+T}) \text{ (Tiwari, 2012)}$$

$$P_v = RH \times P_{vsat}$$

2.15 Wet soil and air properties

Thermal conductivity of soil is taken $K_s = 1.1 \left(\frac{W}{mK}\right)$. It is also susmed that tempearture of sand at depth 0.15 m is avarage temperature of greenhouse inside air. (Hirasawa & Shigeki, 2014). Wet soil is assumed fully saturated and heat conduction is one dimensional i.e. in depth.

Following values of air and water properties are used in calculations.

$T_0 = 300K, P = 101.325\ kPa, C_{pa} = 1.004 \frac{kJ}{kgK}, C_{pw} = 1.84 \frac{kj}{kgK}, \nu = 26.54X10^{-6} \frac{m^2}{s},\ k_f = 2.624X10^{-3} \frac{W}{mk}, h_{fg} = 2260 \frac{kJ}{Kg}$,

2.16 Sky temperature

The effective temperature of the sky is usually calculated from the following simple empirical relations in which temperature is expressed in K. where T_{amb} is ambient temperature.

Sky temperature

$$T\text{-}_{sk} = T_{amb} - 6$$

2.17 Assumptions

Followings assumptions are taken during thermal modeling of greenhouse. These are very reasonable assumptions and don’t affect results much.

- Greenhouse is modeled as a lumped model.
- Total solar radiation falls normally on the roof surface and diffuse radiation at sidewall is not considered. Inclination of radiation is not considered.
- A constant diffuse radiation (50W/m^2) are assumed, that falls normally on the four side walls.
- Natural convection for both inside and outside greenhouse.
- Wet soil and plants are assumed saturated with water.
- Temperature of soil at depth 0.15m is average temperature of greenhouse air for a day that is 298 K. (Hirasawa Shigeki, 2014)
- Location of ventilation is not identified, it is assumed that outside air enters from one side (16 m x3m) and leaves from other side.
- No evaporation from roof and side walls.
- Air absorpitivity is neglected.
- Temperature gradient is not considered in inside air and within polyfilm material

3 Simulations of different cases

3.1 Introduction

Validation is most important part to check reliability of outcome of the thermal model. By the validation we will be ensured that prediction by the model is acceptable or not. It confirms that model works well. Total solar radiation, ambient temperature, and relative humidity data, measured by CAOS/IISc for 21^{st} -24^{th} March, 2019 (Bangalore), were used as input parameters other input parameters (Greenhouse dimensions, material properties, view factor) are as discussed in chapter 2. We have assumed in entire analysis that all vertical side wall receive a constant diffuse radiation $50W/m^2$. The validation has been done for steady state condition only. Results, greenhouse soil, inside surface inside air, roof, side wall temperature and moisture in inside air were obtained from the solution obtained by MATLAB Code and verified.

Validations of thermal model were carried out by three different ways.

1. Validation by selective surfaces like white, black and transparent
2. Steady state surface energy balance of components of greenhouse

3.2 Simulation by selective surfaces like white, black and transparent

In this approach of validation, greenhouse surfaces were assumed ideal surfaces and following four cases were checked and analyzed. There is no air exchange between outside and greenhouse. Emission properties of ideal surfaces were taken for calculations as under.

Table 3 Emission properties of black, white and transparent surface

Surface	Emissivity	Reflectivity	Transmissivity
Black	0.9	0	0
White	0.9	1	0
Transparent	0.9	0	1

3.2.1 Black soil, transparent roof and side wall

Soil surface was assumed black and roof and side walls were transparent. The solar radiation transmitted through the roof and side walls is absorbed by the black soil surface. Temperature of the soil is exposed to highest during the day time when solar radiation falls on the roof. Results obtained by the model are shown Figure 11. It can be seen that soil temperature is highest (approximately. 90^0C at noon) among all surfaces.

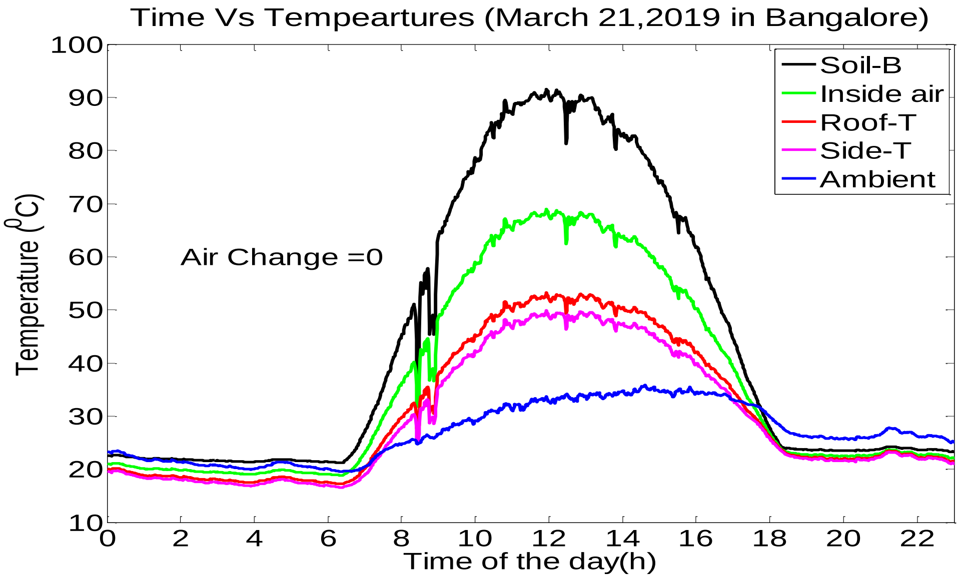

Figure 11: Variation of soil (black-B), inside air, roof (transparent-T), sidewall (transparent-T) and ambient temperature with time

3.2.2 Black roof, transparent side wall and reflective soil

In this case, roof surface were assumed black, side wall fully transparent and soil completely reflective. Solar radiation is absorbed by the roof. As expected temperature is the highest.
(Red color line in Figure 12)

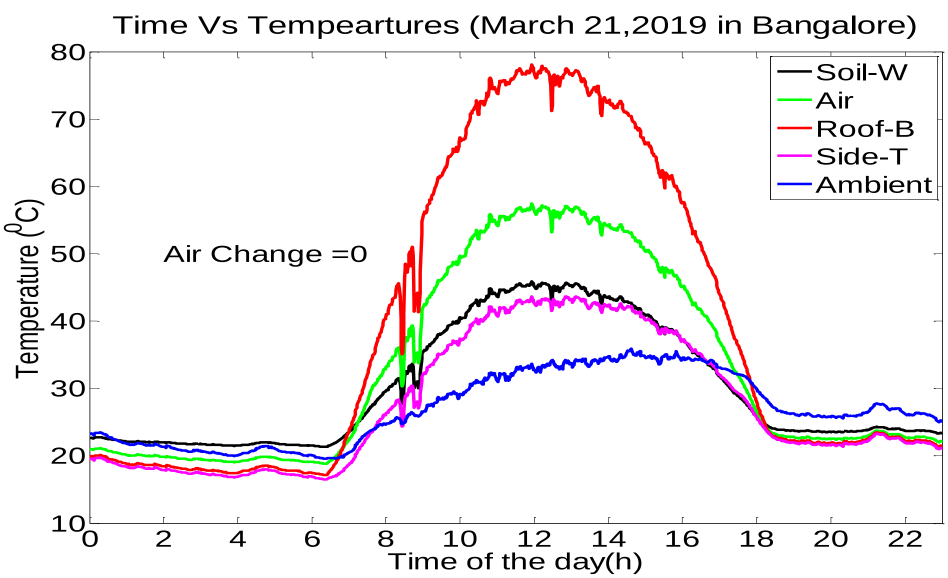

Figure 12: Variation of soil (White-W), inside air, roof (black-B), sidewall (transparent-T) and ambient temperature with time

3.2.3 Black side wall, transparent side wall and reflective soil

In this case, side wall was assumed black, roof transparent and soil completely reflective. As we have assumed in entire analysis that side wall only receive a constant diffuse radiation 50W/m^2.

This entire diffuse radiation is absorbed by side wall, roof and soil doesn't absorb any radiation. As seen in Figure 13 temperature of side is seen to be highest than the soil and roof surface. Figure **13**

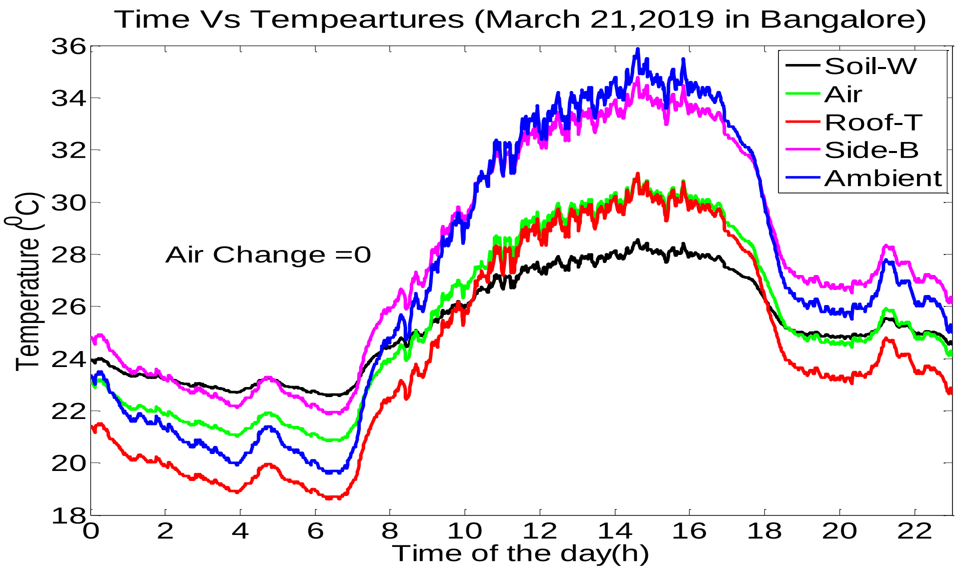

Figure 13: Variation of soil (White-W), inside air, roof (transparent-T), sidewall (black-B) and ambient temperature with time

3.2.4 Reflective soil, transparent roof side wall

Here, side wall and roof were assumed fully transparent and soil completely reflective, and no total solar radiation is absorbed any surface. Temperatures of the all surfaces i.e. side wall, roof and soil were found same and less then ambient temperature as plotted in Figure 14.Temperature is less than ambient because a surface loses heat to the sky by radiation. Sky temperature is 6 ^{0}C below than ambient.

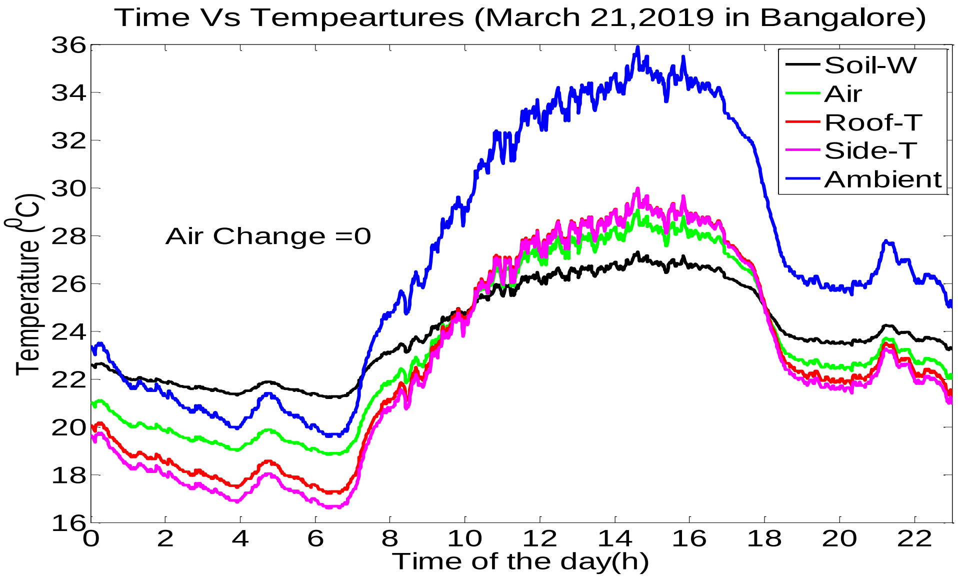

Figure 14: Variation of soil (White-W), inside air, roof (transparent-T), sidewall (transparent -T) and ambient temperature with time

3.3 Surface energy balance for the different components of greenhouse in steady state

In this section, energy incoming and outgoing from the each surface are identified and calculated. As no energy is stored by the any component of greenhouse in steady state, incoming energy must be equal to outgoing. This analysis also gives details of the amounts of energy transfer that takes place by different modes of heat transfer.

Measured ambient data on 21st March,2019, total solar radiation (on roof) , diffuse radiation (on side wall),ambient temperature , humidity and air change, greenhouse dimension(16mx8mx3x) were inputted to the thermal model (MATLAB code) and solution (soil, inside air ,roof side wall temperature, and humidity inside greenhouse) was obtained in steady state .Then surface energy balance was carried out. Energy balance carried out in two different cases. A positive value indicates energy /mass incoming to the surface and negative values indicates energy/mass leaving the surfaces. Table 4 gives the surface energy balance for the different surfaces of the greenhouse, inside air and moisture corresponds to dry soil and 1 kg /s (ACPH =8) mass flow rate of air . Table 5 gives the surface energy balance for the different surfaces of the greenhouse, inside air and moisture corresponds to wet soil and 1 kg /s (ACPH =8) mass flow rate of air.

Table 4 Surface energy balance of differeent surfaces of greenhouse ,inside air and moisture corresponding to dry soil condition , solar 600 W/m^2 and 1kg/s air exchange between ambient and greenhouse

Input to the MALTAB code					**Output from the MATLAB code**				
Total Solar (W/m^2)	Mass Flow rate of air(kg/s)	Ambient Temp(^{0}C)	Ambient Humidity (kg/kgda)	Ambient RH (%)	Dry Soil Temp(^{0}C)	Inside air Temp(^{0}C)	Roof Temp(^{0}C)	Side wall Temp(^{0}C)	Inside air Humidity (kg/kgda)
600.00	1.00 (ACPH=8)	32	0.0177	60.00	54.16	39.67	39.07	35.35	0.0177
Surface energy balance (Watts)									
Surfaces	Total Radiation	Reflected radiation	Transmitted radiation	Radiation exchange Roof-Sky	Radiation exchange Roof-Soil	Radiation Roof -Side	Convection Roof – Ambient	Convection Roof-Inside air	Sum
Roof	76800.00	-7680.00	-61440.00	-9752.93	6956.19	-1047.46	-4141.52	294.53	-11.19
	Transmitted radiation from roof	Reflected radiation	Transmitted radiation	Radiation exchange Roof-Soil	Radiation exchange Soil-side	Convection Soil-inside air	Evaporation Soil	Conduction Soil-Soil	
Dry Soil	61440.00	-12288.00	0.00	-6956.19	-5684.92	-9131.52	0.00	-27380.91	-1.54
	Convection Roof-Inside air	Convection-Soil-Inside air	Convection Side-Inside air	Evaporation Soil	Greenhouse out				
Inside air	-294.53	9131.52	-1125.96	0.00	-7708.35				2.68
	Diffuse radiation	Reflected radiation	Transmitted radiation	Radiation-Roof-Sky	Radiation Soil-Side	Radiation-Soil-Side	Convection Side-Inside air	Convection-Roof-Amb	
Side wall	7200.00	-720.00	-5760.00	-7698.72	1047.46	5684.92	1125.96	-873.14	6.48
	Ambient	Evaporation-Soil	Greenhouse -Out						
Water mass(kg/s)	0.0177	0.00	-0.0177						0.00

Table 5 Surface energy balance of different surfaces of greenhouse, inside air and moisture (Wet soil, total solar 600W/m^2) with air exchange between ambient and greenhouse

Input to the MALTAB code					**Output from the MATLAB code**				
Total Solar (W/m^2)	Mass Flow rate of air(kg/s)	Ambient Temp(K)	Ambient Humidity (kg/kgda)	Ambient RH (%)	Wet Soil Temp(K)	Inside air Temp(K)	Roof Temp(K)	Side wall Temp(K)	Inside air Humidity (kg/kgda)
600.00	1.00(ACPH=8)	32	0.0177	60.00	39.12	34.44	34.95	31.61	0.030588
Surface energy balance(Watts)									
Surfaces	Total Radiation	Reflected radiation	Transmitted radiation	Radiation exchange - Roof-Sky	Radiation exchange Roof-Soil	Radiation Roof -Side	Convection Roof – Ambient	Convection Roof-Inside air	Sum
Roof	76800.00	-7680.00	-61440.00	-6545.11	1749.38	-905.44	-1731.48	-254.59	-7.24
	Transmitted radiation from roof	Reflected radiation	Transmitted radiation	Radiation exchange Roof-Soil	Radiation exchange Soil-side	Convection Soil-inside air	Evaporation Soil	Conduction Soil-Soil	
Dry Soil	61440.00	-12288.00	0.00	-1749.38	-2071.70	-2940.98	-13253.97	-29116.97	19.00
	Convection Roof-Inside air	Convection-Soil-Inside air	Convection Side-Inside air	Evaporation Soil	Greenhouse out				
Inside air	254.59	2940.98	-740.22	13253.97	-15709.32				-6.90
	Diffuse radiation	Reflected radiation	Transmitted radiation	Radiation-Roof-Side	Radiation Soil-Side	Radiation-Side-Sky	Convection Side-Inside air	Convection-Roof-Amb	
Side wall	7200.00	-720.00	-5760.00	- 4533.74	905.44	2071.70	740.22	101.65	5.27
	Ambient	Evaporation-Soil	Greenhouse -Out						
Water mass(kg/s)	0.01	0.01	-0.02						0.00

4 Results and discussions

4.1 Introduction

In this chapter, first the input parameters used for calculation - ambient condition, greenhouse dimension, greenhouse material properties, mass of greenhouse components, view factors, air and water properties are given. These inputs are used to run the simulation. Simulation results are obtained for steady and unsteady state cases in three different conditions.

1. Empty greenhouse with dry soil
2. Empty greenhouse with wet soil
3. Greenhouse with plantation

In all cases, variation of soil, inside air, roof and sidewall temperatures are plotted with time and discussed. In the wet soil case variation of moisture content in the greenhouse air with time is plotted. Effects of ventilation rate on the soil, inside air, roof sidewalls and plant temperatures have been studied and results are presented in this chapter. Results for variation of plants temperature with time for steady state are also given.

4.2 Input parameters used for calculation

For the simulations, the dimensions correspond to the greenhouse located at Gandhi Krishi Vignana Kendra (GKVK), Bangalore has been used. Greenhouse is 16 m length by 8 m width with a maximum height of 3 m. The greenhouse house is covered with 200 µm polyethylene plastic sheet. Overall dimension and material properties and mass are given in the Table **6**.

Figure 15 shows variations of total solar; diffuse radiation, temperature, relative humidity and specific humidity of outside air in Bangalore on 21st March 2019. The data was measured by Centre for Atmospheric and Oceanic Sciences department of IISc. These data are used as input for thermal model. Most of the results are for one full day (24Hrs) ambient data on 21st March. Some results are also for 4 days data (March 20-24) to get longer period results.

Roof of the greenhouse receives total solar radiation (varies with time) that normally falls on it. A constant diffuse radiation (50W/m^2) is assumed to fall normally on all four side walls of the greenhouse.

View factors between different surfaces are calculated and tabulated along with the other input parameters used for simulation (Table 7)

Ventilation i.e. air exchange between outside and greenhouse is an important input parameters of the model. Analysis is carried out for the mass flow rate of air change rate ranging 0 to 10 kg/s (0 to 80 ACPH).

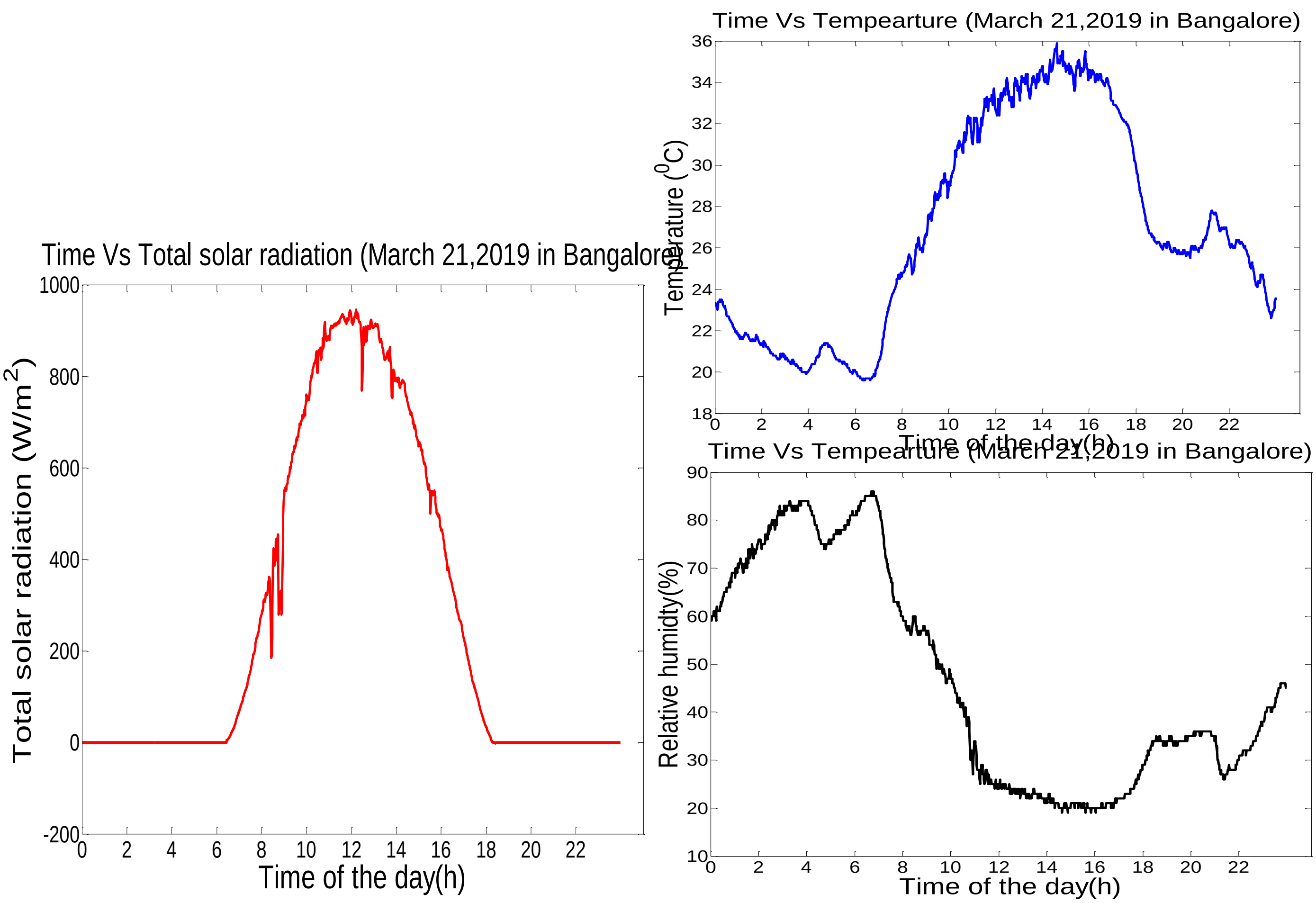

Figure 15: Ambient conditions of Bangalore on March 21, 2019

Ambient conditions of Bangalore on March 21, 2019 are shown in Figure 15 .It can be seen that temperature varies from 19 to 35 ºC. Temperature is highest at 1PM (13 Hrs) when solar radiation intensity is at peak value 950 W/m^2. Relative humidity is lowest at 2 PM day time and highest at night 4 AM. Diffuse radiation is approximately 50 W/m^2.

Table 6 Greenhouse dimensions, plants and materials properties

Greenhouse Surfaces	Dimensions (m)	Area (m^2)	Material	Emissivity (ε)	Transmissivity (τ)	Reflectivity (ρ)	Density ($\frac{kg}{m^3}$)	Mass (kg)	Specific heat capacity ($\frac{J}{kg^0C}$)
Roof	16m x 8m x 200µm	128	Polyfilm	0.9	0.8	0.1	900	23.04	1250
Side wall	16m x 8m x 200µm (2Nos) 8m x 3m x 200µm (2Nos)	144	Polyfilm	0.9	0.8	0.1	900	34.56	1250
Soil	16m x8m x 0.15m (depth)	128	Sand	0.7	0	0.2	1500	28800	800(Dry) 1480(Wet)
Plants leaf	16m x8mx0.005m (assumed values)	128	Biomass	0.9	0.4	0.4	600	96	3500 (Jayalakshmi, 2010)

Table 7: Value of view factors between different surfaces and other input parameters used for calculations

View factors	Values	
Roof –Soil (F_{tb})	0.6	Sky Temperature (T_{sky}) = T_0-6 ^{0}C Diffuse radiation =50 W/m^2 Wet soil and plants RH = 100 % (Saturated with water) Air change= 0 to 10 kg/s (0 to 80 ACPH). Emissivity of sky (ϵ_{sk}) =1 ,Soil temperature at 0.15m depth =298 K Ambient air and water properties : $P_{atm} = 101.325\ kPa, C_{pa} = 1.004 \frac{kJ}{kgK}$, $C_{pw} = 1.84 \frac{kj}{kgK}$, $\nu = 26.54X10^{-6}\ \frac{m^2}{s}, k_f = 2.624X10^{-3} \frac{W}{mk}, h_{fg} = 2260 \frac{kJ}{kg}$,
Roof–Side s (F_{ts})	0.4	
Soil –Roof (F_{bt})	0.6	
Soil –Side (F_{bs})	0.4	
Roof –Sky (F_{tsk})	1	
Side –Sky (F_{ssk})	1	

4.3 Steady state results

Steady state analysis for variation of soil, inside air, roof temperature sidewalls .plants and specific humidity of inside air with time were carried out for dry soil and wet soil conditions. Effects of ventilation rate are plotted and analyzed.

4.3.1 Dry soil and no air exchange between greenhouse and outside

Figure 16 shows variation of soil, inside air, roof, side walls and ambient temperature with time in dry soil condition in absence of ventilation between greenhouse and outside. During night time from 18 Hrs to 6 Hrs. it is observed that roof, side wall and inside air are at lower temperatures than ambient temperature. This is due to the fact that roof, side walls and inside air lose heat. Outside of side wall and roof loose heat to sky by radiation because sky temperature is 6^0C lower then ambient. Inside air gets cooled because side wall and roof is at lower temperature. Soil temperature is lower than ambient in first half of night i.e.18 Hrs -00:00 Hrs and higher in second half of night i.e. 00:00 Hrs to 6Hrs. This is because soil may gain heat or loose depending upon temperature difference between upper surface of the soil and soil at depth of 0.15m in thickness through which conduction takes place. Therefore during first half of the night soil loses heat and thus temperature is lower than ambient, while in second half of the night the soil surface temperature receives heat from the bottom of the soil. During day time (6Hrs - 18Hrs) as solar radiation falls on the roof and is transmitted to the soil surface both surfaces get heated and thus all surface temperature and inside air temperature rise. Due to high transmissivity of roof and high absorpitivity of soil, temperature of soil achieves a highest value 75 ^{0}C (approximately) at 12 noon. The maximum air temperature is 60 ^{0}C at 12 PM.

4.3.2 Effect of air exchange on temperature of different surfaces of greenhouse in dry soil condition

Figure 17 shows variations of the temperatures in the presence of ventilation. Mass flow rate of inside air is 1kg/s between outside and inside of greenhouse, other conditions remains same as explained in no ventilation case (Figure 16). Inside air temperature drops and come closer to roof temperature, this is because some heat is carried out by the outgoing air, correspondingly other surface temperatures also reduces as seen in Figure 17.

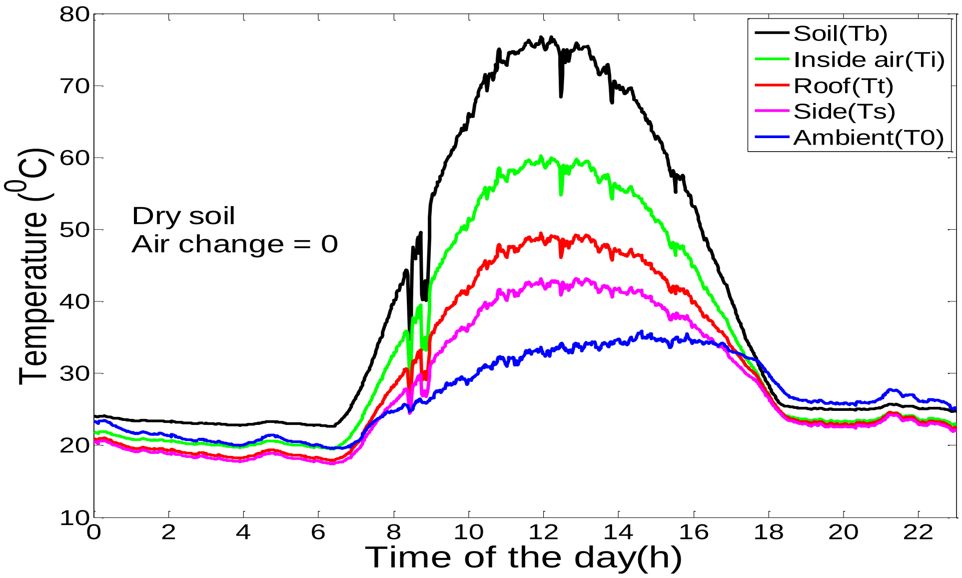

Figure 16: Variation of soil, inside air, roof, sidewalls and ambient temperature with time in Dry soil and no air change condition on 21st March, 2019 Bangalore.

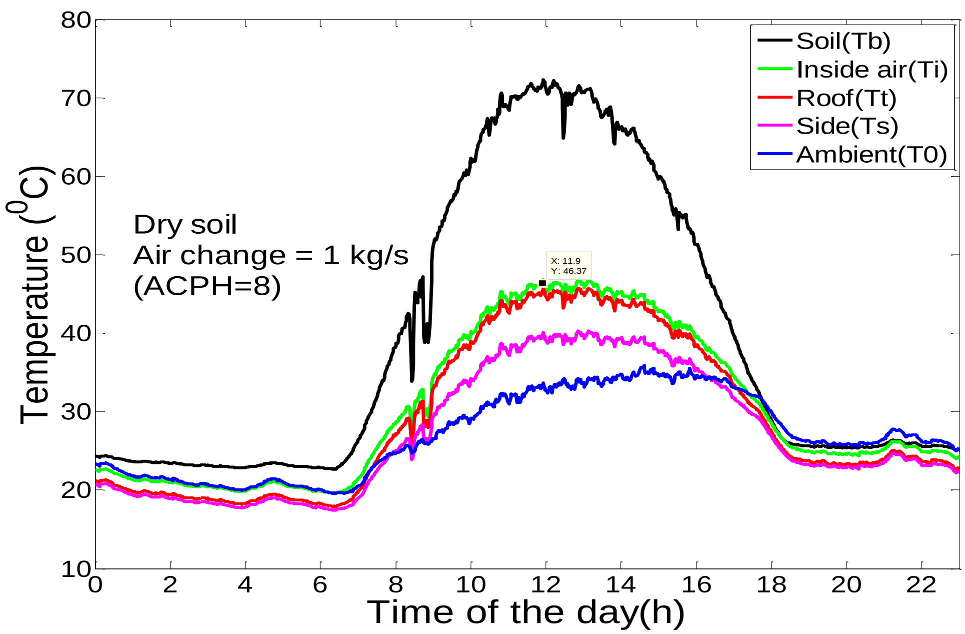

Figure 17: Variation of soil, inside air, roof, sidewalls and ambient temperature with time in dry soil condition and air change 1 kg/s on 21St March, 2019 Bangalore

4.3.3 Effect of ventilation on different surfaces of greenhouse at fixed solar intensity in dry soil condition

Figure 18 shows effect of mass flow rate of air on greenhouse in dry soil, inside air, roof and side wall temperature for 200, 400, 600 and 800 W/m^2 radiation intensities, these radiation intensities correspond to ambient temperatures of 19, 25, 32 and 35^{0}C respectively. As mass flow rate of air increases temperatures start to drop. Initially variation up to 3-4 kg/s (24 - 32 ACPH) is very high, thereafter it becomes nearly constant and effect of air flow is almost negligible. Variation in inside air temperature (green color line) is highest in all cases. When solar .intensity is 800 W/m^2 to maintain inside air temperature 40 ^{0}C, 6 kg/s ventilation will be required, but in case when solar intensity is 600W/m^2, air flow rate of 1kg/s is sufficient.

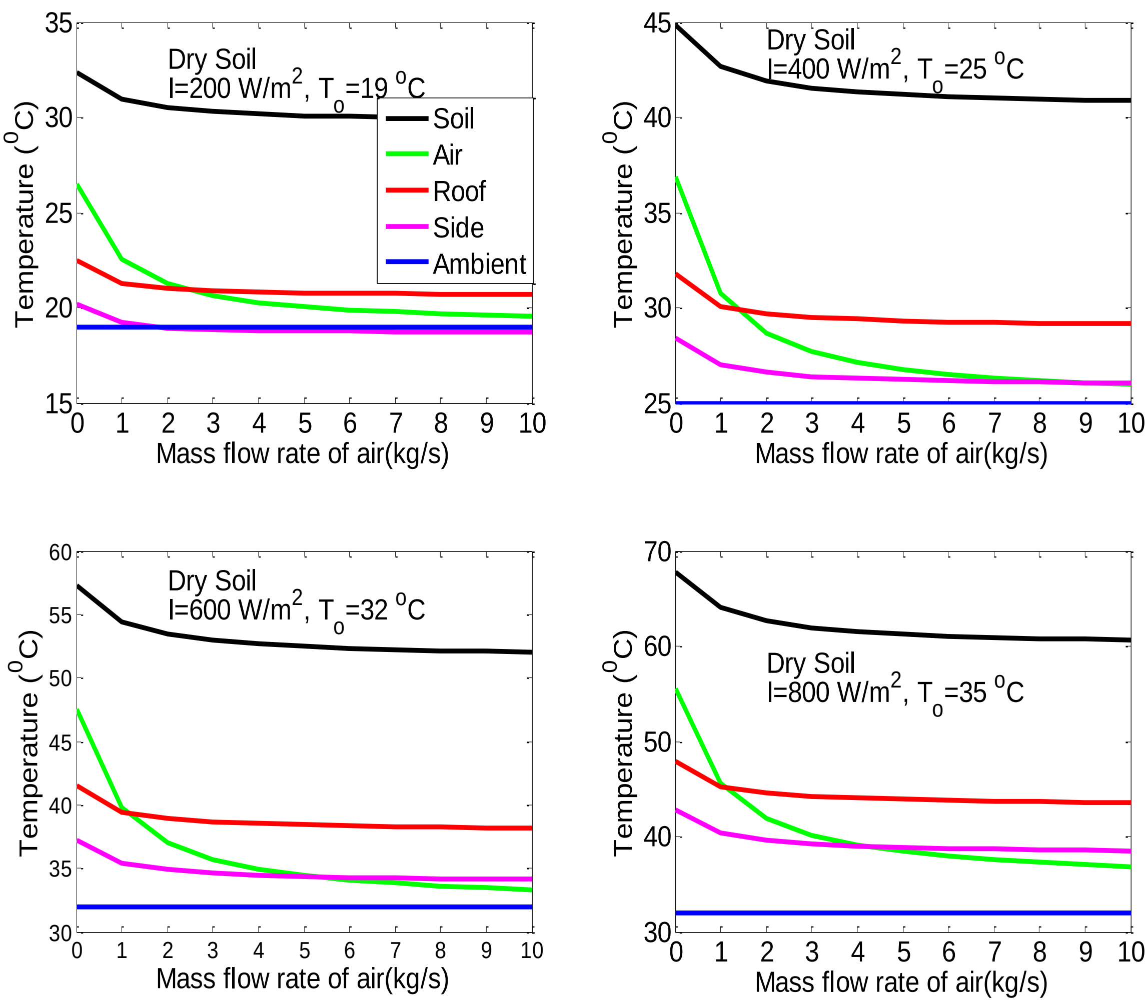

Figure 18: Effect of ventilation on soil, inside air, roof, and side wall temperature in different solar load and ambient temperature for dry soil condition of greenhouse

4.3.4 Effect of air exchange on soil, inside air and roof temperature in dry soil condition

Figure 19, Figure 20 and Figure 21 show respectively the variations of inside air, soil and roof temperature with time for different air change rate (1kg/s =8 ACPH) in dry soil condition on 21st March ,2019 in Bangalore. It is clear from all the three figures that effect of ventilation is highest on inside air compared to roof and soil temperature. If we compare temperatures with and without ventilation, it is seen that when ventilation is increased from 0 to 8 ACPH at 12 noon, inside air temperature drops from 60 ^{0}C to 45 ^{0}C, while soil temperature drops from 75 ^{0}C to 70 ^{0}C and roof temperature drops from 50 to 44 ^{0}C. When air change is 80 ACPH, inside air temperature drops to almost ambient temperature (Figure 19). Soil and roof temperatures are not reduced further after 80 ACPH (Figure 20 and Figure 21).

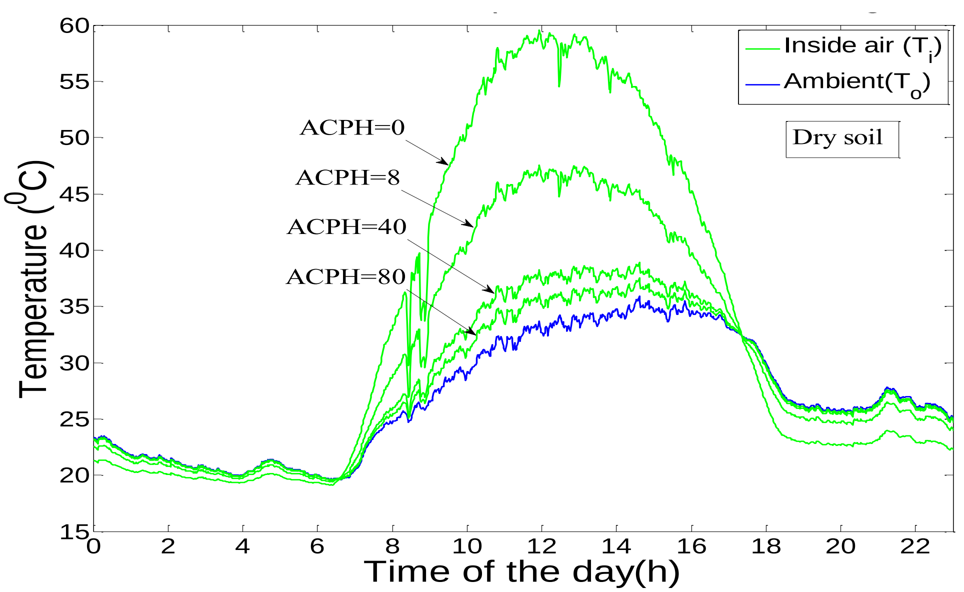

Figure 19: Variation of inside air temperature with time for different air change rate on 21st March, 2019, Bangalore

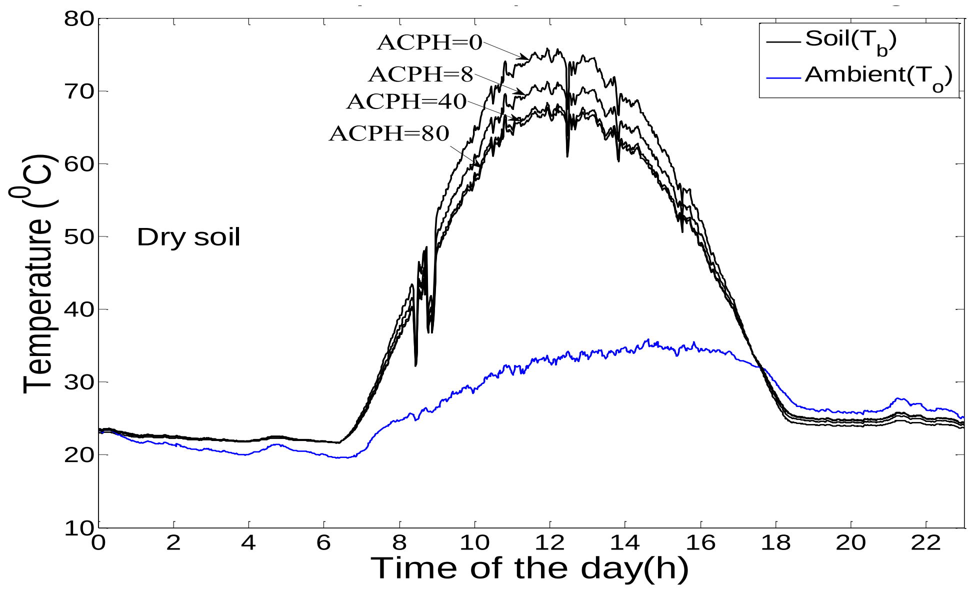

Figure 20: Variation of soil temperature with time dry soil condition time for different air change rate on 21st March, 2019

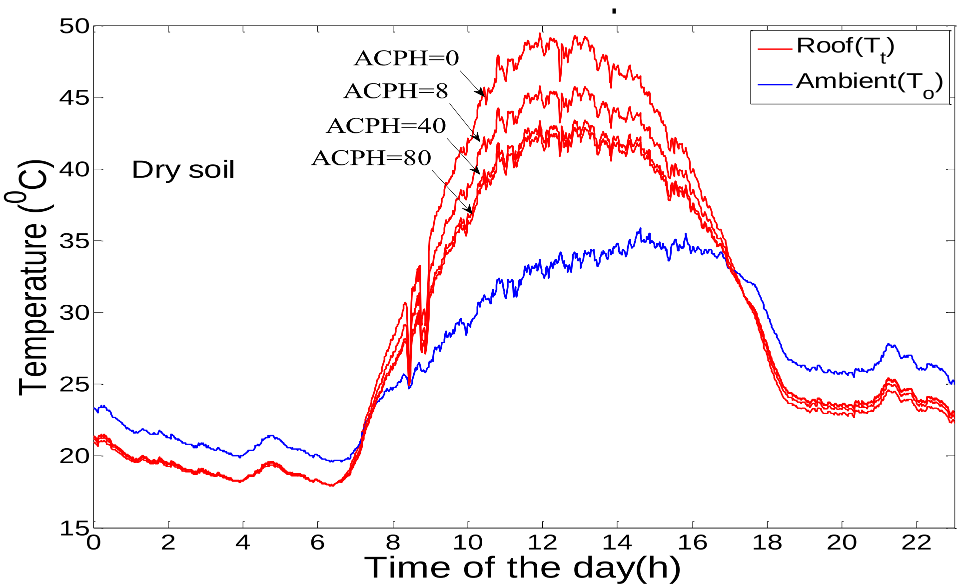

Figure 21 Variation of roof temperature with time for different air change rate on 21st March, 2019

4.4 Dry soil and air exchange between greenhouse and outside – No sky radiation exchange

Figure 22 shows variations of temperatures of different surfaces of greenhouse when radiation between outside of roof/sidewalls and sky are absent. In this case, there no heat is lost to the sky. All surfaces have higher than ambient through the day and night as shown in Figure 22.

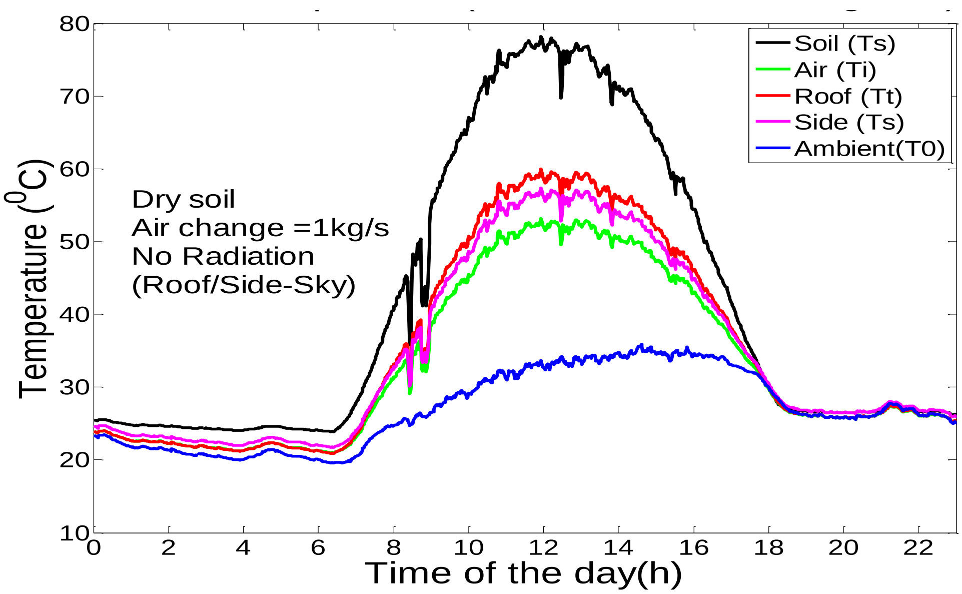

Figure 22: Variation of soil, greenhouse air, roof and ambient temperature with time (when no radiation exchange between roof/side and sky)

4.5 Effect of air exchange on temperature of different surfaces of greenhouse in wet soil condition

Figure 23 shows the variation of soil, inside air, roof, side wall and ambient temperatures with time for the wet soil condition corresponding to ambient conditions obtained on 21st March 2019, Bangalore. The main difference between dry soil and wet soil case is evaporation term. Wet soil is treated as saturated with water (RH 100%). Maximum temperature achieved by soil at 1 PM is 45^0C. This value is 20 ^{0}C less than the soil temperature in dry soil condition (absence of evaporation). This is because wet soil evaporates and loses heat to inside air. Comparing Figure 23 with Figure 17 we found that temperatures of soil, roof, inside air and side wall are significantly lower throughout the day. At night, all greenhouse components temperatures are lower than ambient temperature. However in dry soil condition, soil temperature is higher during first half of the night and lower in the second half of the night as discussed in the dry soil condition case.

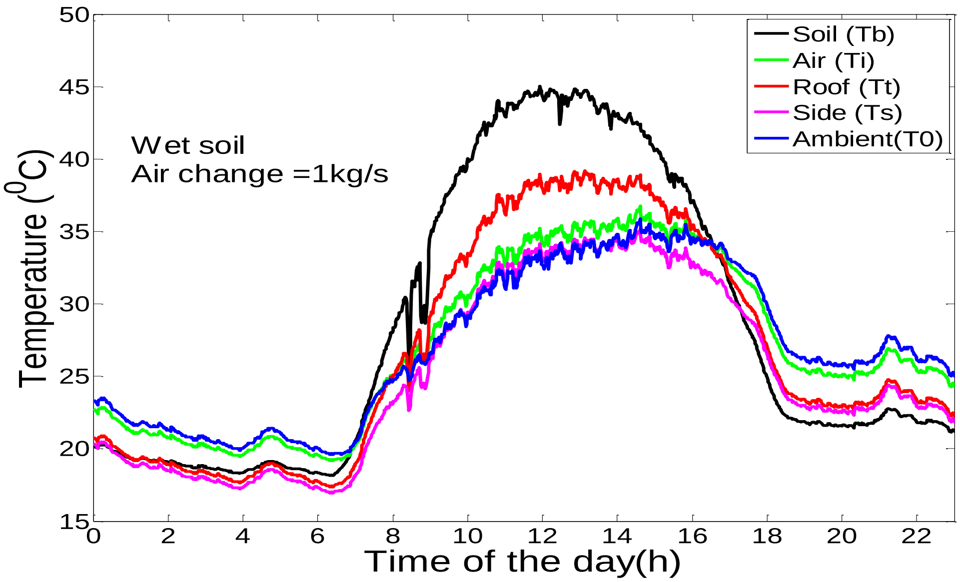

Figure 23: Variation of soil, inside air, roof, side wall and ambient temperature with time (Wet soil and air change 1 kg/s)

4.6 Effect of ventilation on different surfaces of greenhouse at fixed solar intensity in wet soil condition

Figure 24 shows that variation of soil, inside air, roof, side wall and ambient temperature with ventilation for solar intensity 600 W/m^2 and corresponding ambient temperature 35^{0}C. Nature of variation is same as seen in dry soil condition but here maximum temperature of soil, roof, and side wall and inside air are lower than the corresponding values in dry soil cases as shown in Figure 18 Side wall temperature is lower than the ambient because side wall loses heat by radiation to sky. Maximum variation is seen in inside air and temperature drops from 36.5 to 33^{0}C when mass flow rate of air changes from 0 to 3 kg/s. Very small variation is seen in roof and soil temperature with ventilation. After 3 kg/s (24 ACPH) little variation on all surface temperatures are noticed. So, we can conclude that ventilation rate has almost no effect after 24 ACPH.

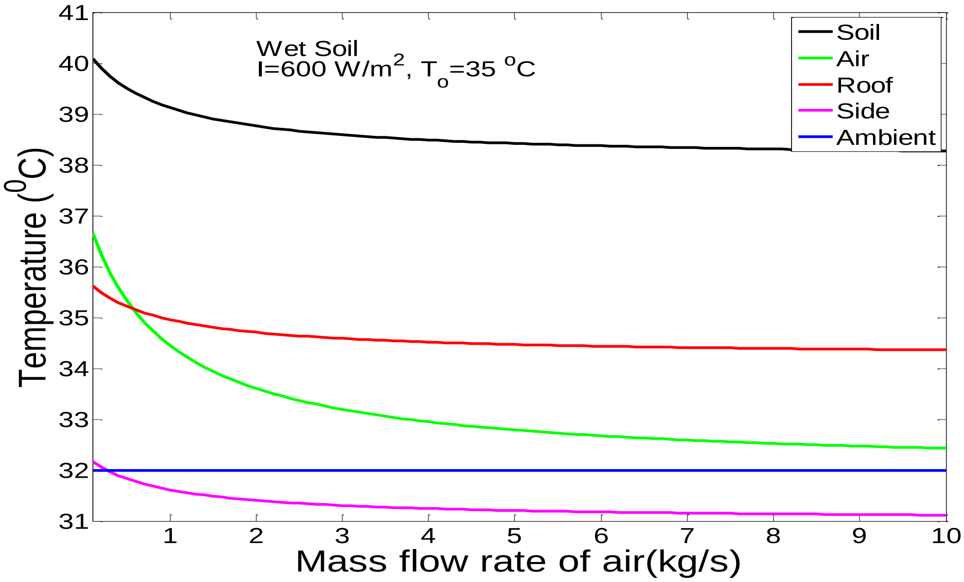

Figure 24: Effect of ventilation on greenhouse soil, air and roof temperature in wet soil condition with Solar Intensity = 600W/m^2 and Ambient=35^{0}C

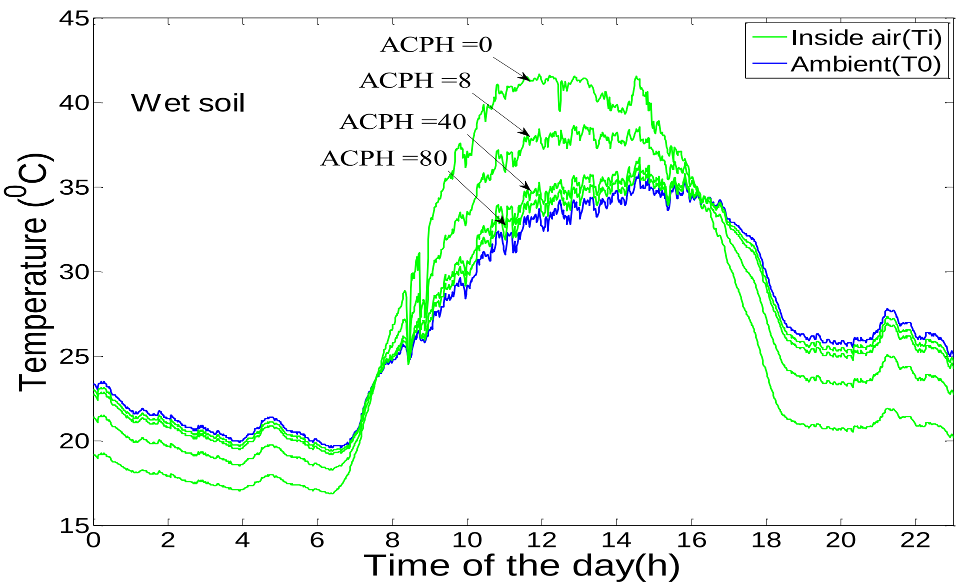

Figure 25: Variation of inside air temperature with time for wet soil condition for different air change rate

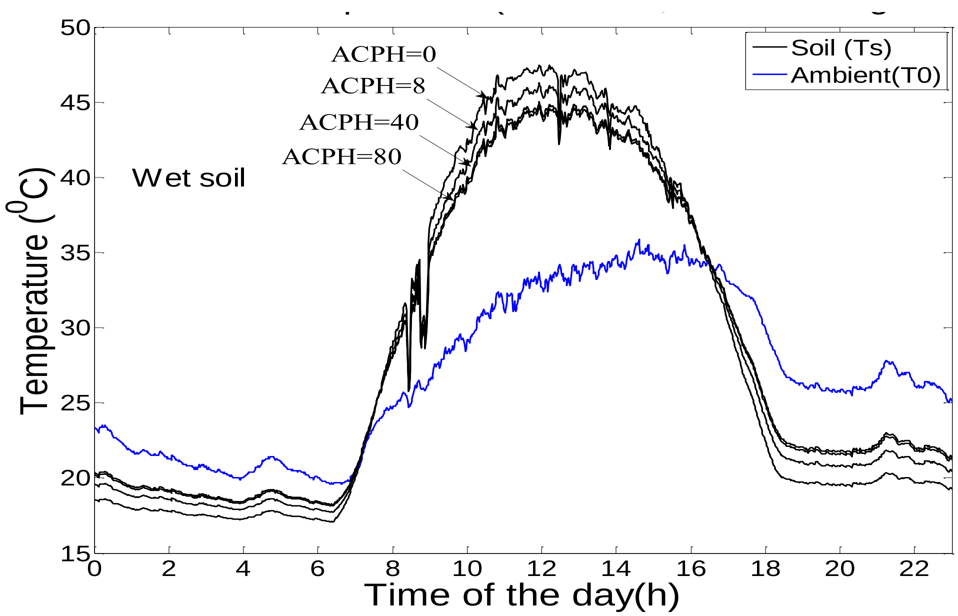

Figure 26: Variation of soil temperature with time in wet soil condition for different air change rate on 21st March, 2019 Bangalore

Figure 27 shows variations of moisture content in the inside air with time for wet soil condition on March 21, 2019 for different air change per hours i.e. 8, 16 and 40. Blue color line is specific humidity of ambient air. Ambient specific humidity is estimated entering measured value of relative humidity and temperature of ambient for March 21(data details in chapter 2). Saturation specific humidity at inside air temperature is also shown in Figure 27. Saturation specific humidity varies between 15g/kgda at 12 night and is maximum value of 43 g/kgda at 2 PM day time. Inside air specific humidity is higher than the ambient during entire day and night period. This is because there is always evaporation from wet soil. At 8 ACPH the moisture content significantly drops and varies between 16 g/kgda at night 12 to a maximum of 22 g/kgda at 12 PM. At higher ACPH 80 moisture content in inside air drops to ambient specific humidity. It is evident from the plot that moisture content never reaches saturated condition in presence of ACPH more than 1.

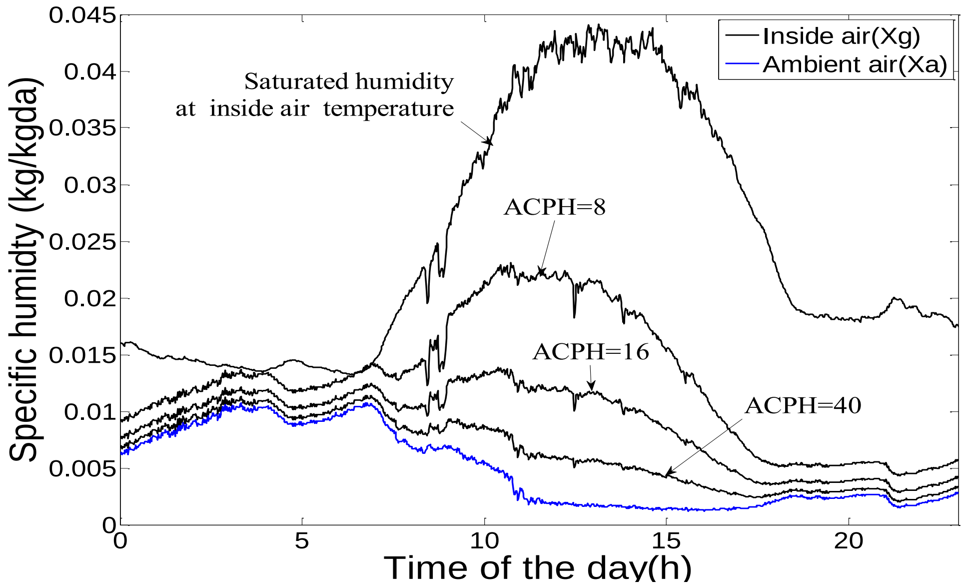

Figure 27: Variation of inside air specific humidity with time in wet soil condition with different air change rate on 21st March , 2019 Bangalore

4.7 Effect of relative humidity of inside air on wet soil temperature and comparison with dry soil condition

As shown in Figure 28 when relative humidity of inside air increases from 30% (red line) to 90% (magenta) wet soil temperature increases but is lower than the dry soil temperature (black line). Temperature of inside air and ambient is 298 K.

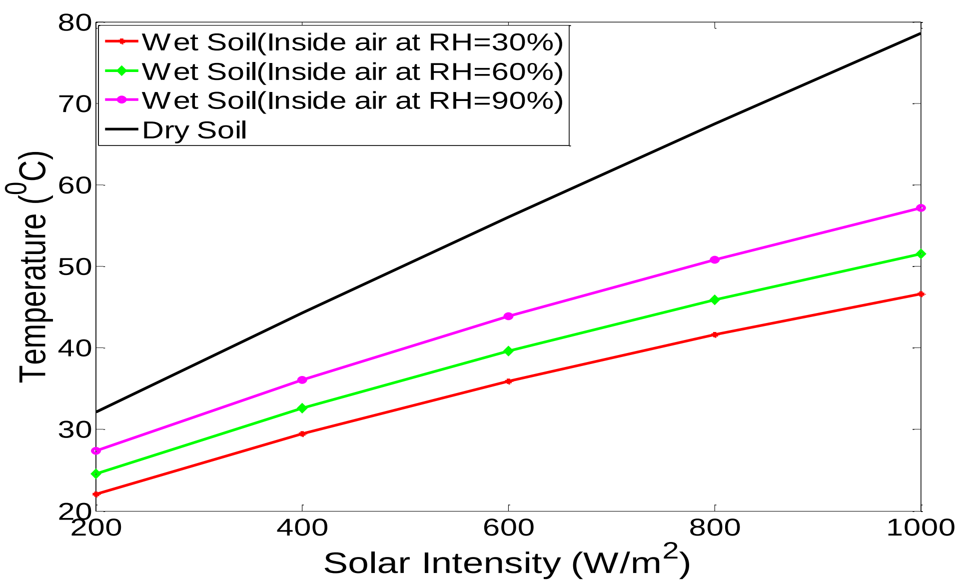

Figure 28: Effect of relative humidity of inside air on wet soil temperature and comparison with dry soil condition in steady state

4.8 Plants and inside air temperature variation with time in steady state

Figure 29 shows variations of the temperatures of the plants, inside air and ambient with time on 21st March 2019 in Bangalore. The total mass of the plants are 96 kg and area covered by the plant is entire bottom surface of the greenhouse, i.e.128 m^2. Plants are assumed 100% saturated with water like wet soil. Average transmissivity and reflectivity of plants are taken 40%. It is seen that during entire day and night, temperature of plant is always lower than inside air and the ambient. This is because plants evaporate. Also, reflectivity and transmissivity of the plant's surface is higher than dry soil and wet soil condition. Average temperature difference between plants and ambient is 4°C in night. We observe minor difference in temperature from 6 AM to12 PM. After 12 PM temperature difference between the ambient and plants is 6°C approximately.

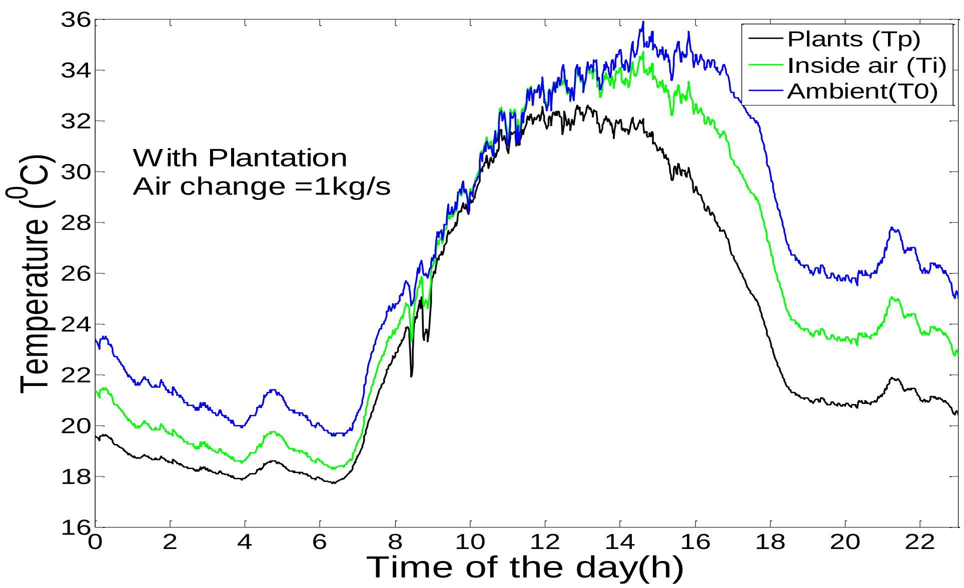

Figure 29: Variation of plants, inside air and ambient temperature with time

Figure 30 shows the variation of soil, inside air, roof, side wall and ambient temperature with time from 21st to 25th March, 2019 at Bangalore. Simulation is carried out for a longer period of four days and the result validate the same observations taken for one day. The air change rate for the simulation is 1 kg/s. It can be concluded that obtained result will also be valid throughout the year.

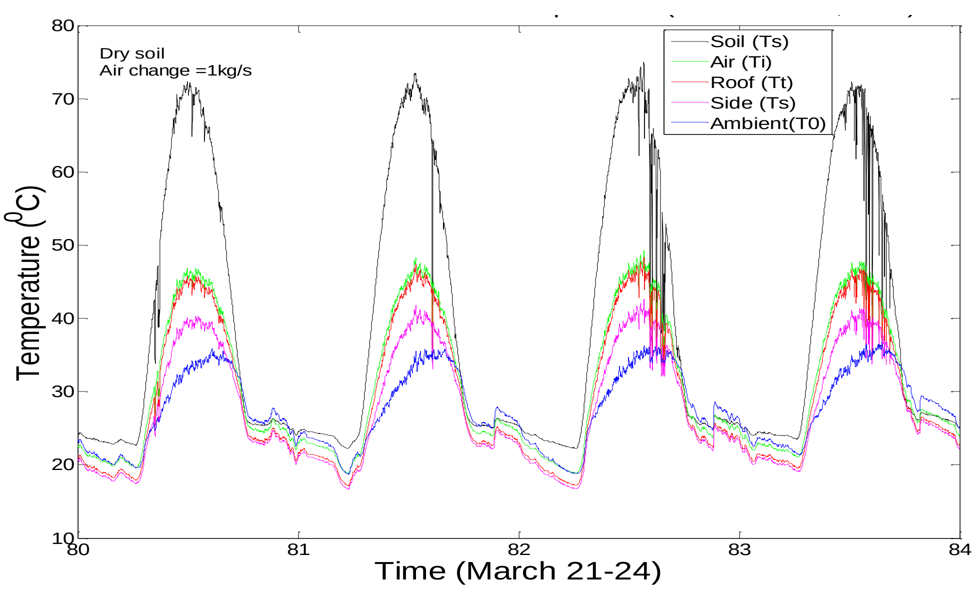

Figure 30: Variation of soil, inside air, side and roof temperature with time in dry soil condition (March 20-24, 2019), Bangalore

4.9 Unsteady state analysis of greenhouse

For unsteady state simulations initial conditions needed are given as below. First simulations are done for a 'test' case.

At $t = 0\,, T_t = T_b = T_i = T_t = T_o = 298K, X_g = 0.0078\; kg/kgda$

At first, unsteady state analysis of greenhouse is carried out at solar radiation of 600W/m^2 and at the ventilation rate of 1 kg/s. Ambient temperature is taken 32 ^{0}C. Later solutions and results are obtained for 24 Hrs. Figure 31 shows the variation of soil, inside air, roof, sidewalls and ambient temperature with time in unsteady state corresponding to solar radiation load of 600 W/m^2 at roof and 50 W/m^2 on sidewalls. Mass of different components of greenhouse and material properties are given in the Table 6 and Table **7**. Figure 31 shows that for the unsteady state conditions, soil takes approximately 10 hours (36000 sec) to reach steady state because its soil mass is very high i.e. 28800 kg. As compared to soil, greenhouse roof and side wall takes less time (few min) to reach steady state. When these components of greenhouse reach steady state, temperature of the soil, inside air, roof and side wall are 55 ^{0}C, 40^{0}C, and 35 ^{0}C respectively. These values closely match with the steady state solutions in similar condition of greenhouse parameters.

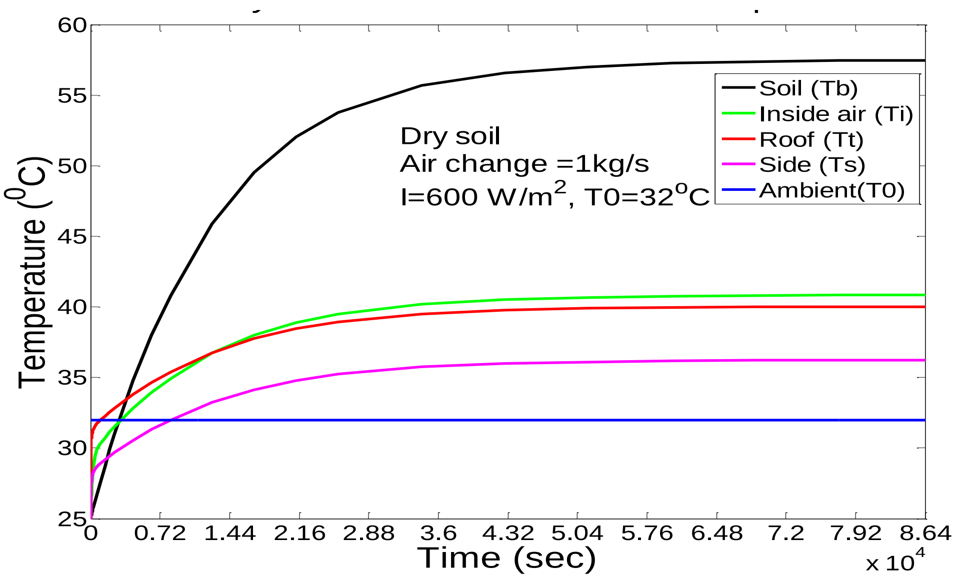

Figure 31: Unsteady state - Variation of soil, inside air, roof, side wall and ambient temperature with time (Dry soil, solar =600W/m^2 and air change =1 kg/s)

Figure 32 shows the unsteady state temperature variations of the various components of the greenhouse with time on 21st March, 2019 at Bangalore. We observed that the highest temperatures achieved are lower compared to the steady state solution values. Also, it is observed that maximum temperature is found at 3 PM in unsteady state however maximum temperature is achieved by the quasi steady state at 1 PM in same conditions. This is due to the thermal inertia of the various components like soil.

Figure **33** shows the variation of temperature of different components of greenhouse in unsteady state in wet soil condition for solar intensity value of 600W/m^2 and ambient temperature at 35 ^{0}C. Initial conditions of temperature are 298 K for all components of greenhouse. Unsteady state temperature of soil at 10 AM (3.6 x 10^4 sec), when solar intensity is approx. 600 W/m^2 and air change rate of 1 kg/s, is 43 ^{0}C and it matches with steady state solution. Similarly inside air temperature is 36 ^{0}C at 10 AM in unsteady state.

Figure 34 shows the variation of temperature of different components of greenhouse in unsteady state for wet soil condition and 1 kg/s air change on 21st March, 2019 at Bangalore. Figure 32 is for dry soil case. Major difference between these two cases is evaporation from soil. In our analysis a constant evaporation heat transfer at 200 W/m^2 is assumed throughout the day and night. However, this varies with time. Soil temperature reduces significantly during night time as shown by the black colored line.

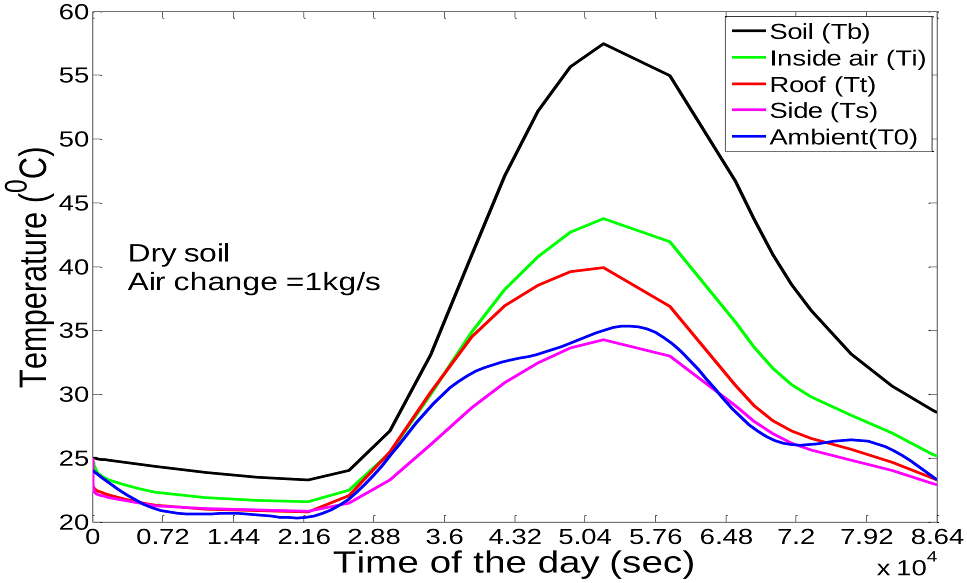

Figure 32: Unsteady state variation of soil, inside air, roof, side wall and ambient temperature with time in Dry soil and air change rate of 1 kg/s

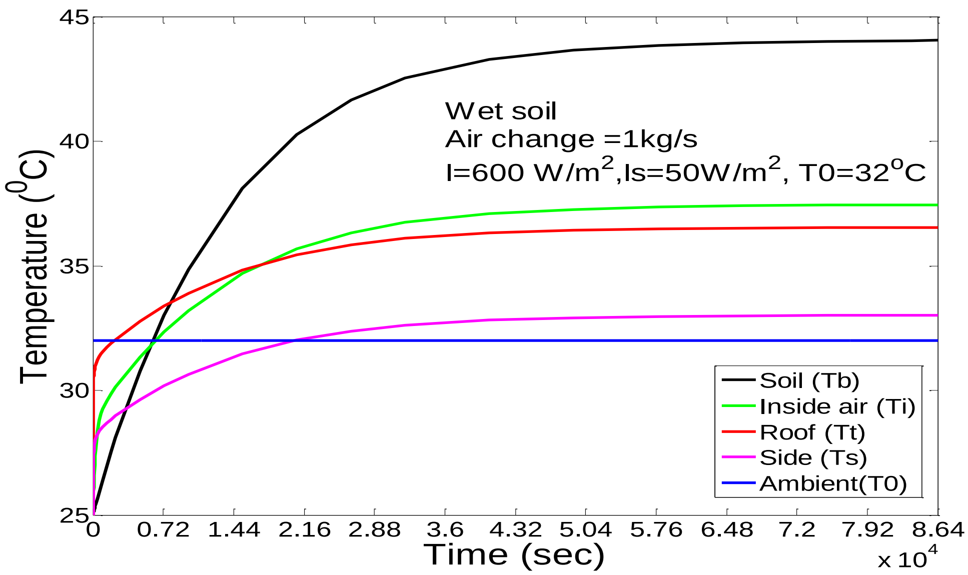

Figure 33: Unsteady state - Variation of soil, inside air, roof, side and ambient temperature with time (Wet soil, solar =600W/m2 and air change =1 kg/s)

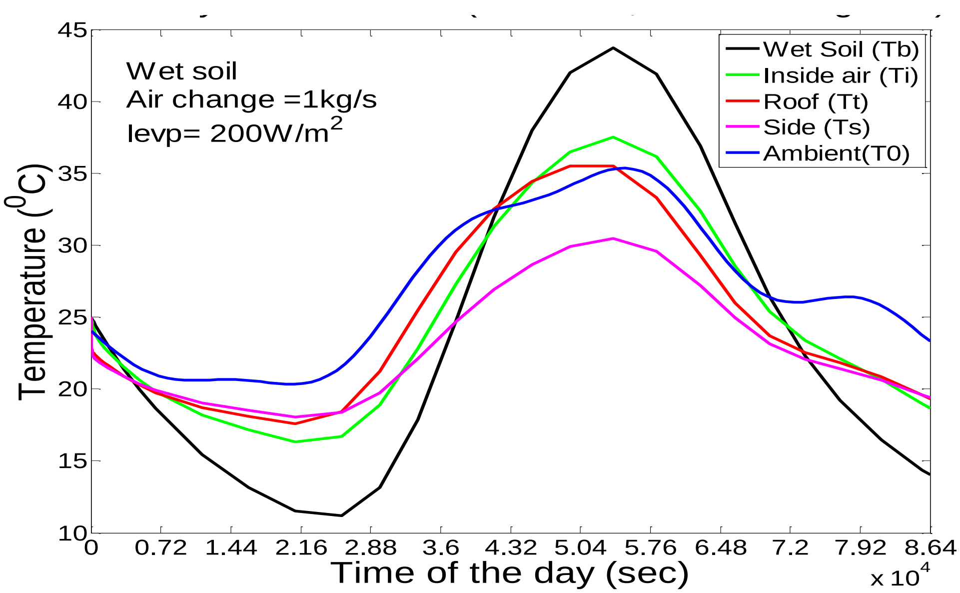

Figure 34: Unsteady state variation of soil, inside air, roof, side wall and ambient temperature with time in wet soil and air change rate of 1 kg/s

4.10 Sensitivity analysis

Important parameters that influences performance of greenhouse are as follows -

4.10.1 Transmissivity of covering material

Transmissivity of greenhouse covering material like roof and side wall are material properties that allow radiation into the greenhouse. Radiation is very important for the photosynthesis of plants, a small change in transmissivity value results in blocking or allowing radiation and hence it is an important parameter. Transmissivity value reduces due to deposition of dirt over the roof with time.

Figure 35 shows that variation of soil temperature and roof temperature is very high with transmissivity. Side wall transmissivity is kept constant i.e. 0.9 and it receives diffused radiation of 50 W/m^2 only. Roof temperature decreases linearly and soil temperature increases linearly as shown by the red color line and black color line respectively. When transmissivity of the roof is changed from 0.7 to 0.8 then temperature of the roof drops approx. 2.75 ^{0}C while soil temperature increases from 52.26 to 54.37^{0}C i.e. 2.11 ^{0}C. However, inside air and side wall did not show much variation. Inside air temperature increases very little.

4.10.2 Reflectivity of soil

Figure 36 shows the variations of temperatures of different components of greenhouse with reflectivity of soil in steady state condition and at solar intensity 600 W/m^2. All surface temperature decreases with reflectivity of the soil linearly. Highest variation is seen in soil temperature. It is to note that multiple reflections are not considered and hence reflected radiation is lost to the surroundings. It can be observed that when soil reflectivity increases from 10% to 20% ,temperature of the soil drops from 57.35 to 54.37 ^{0}C while inside air temperature decreases from 41.10 to 39.35 ^{0}C. In overall analysis we have taken 20% of the soil in both wet and dry condition.

4.10.3 Ventilation rate

Ventilation rate is very important parameter, a small change in ventilation rate changes climatic condition of greenhouse. Detailed analysis has been carried out in previous discussion.

4.10.4 Soil type

Wet or dry soil plays significant role in the prediction of greenhouse inside climate as wet soil evaporates and cools. Hence greenhouse soil temperature is greatly affected by percentage of water content in soil.

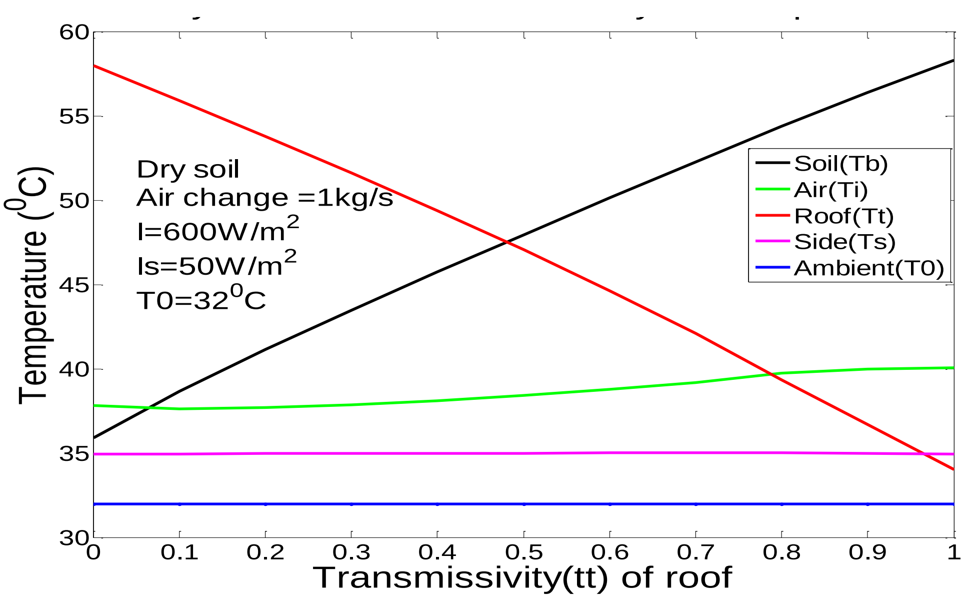

Figure 35: Variation of soil, roof, inside air, side wall temperature with transmissivity of the roof in dry soil, solar intensity 600W/m^2 and ambient temperature 32 ^{0}C in steady state

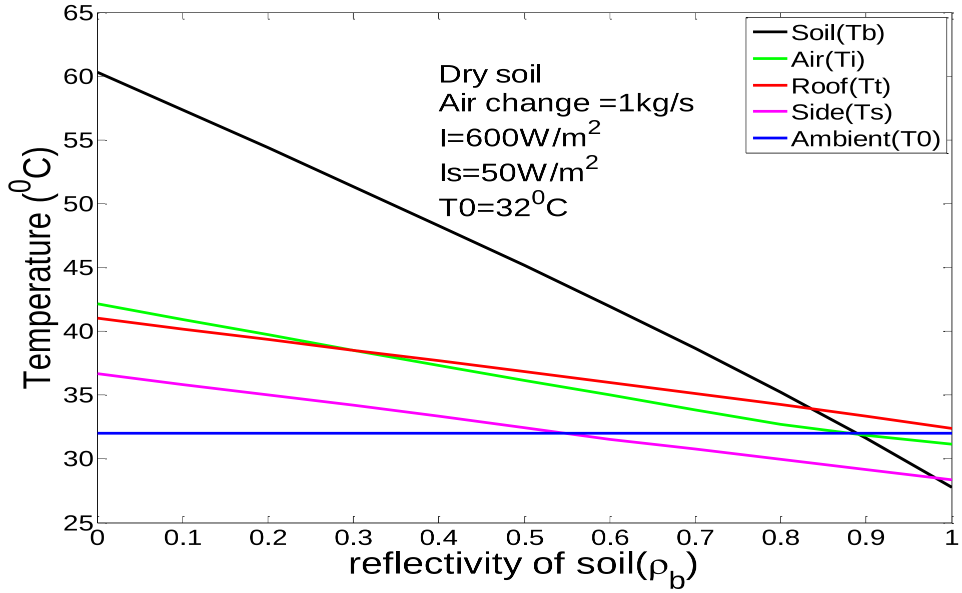

Figure 36: Variation of soil, roof, inside air, side wall temperature with reflectivity of soil in dry soil, solar intensity 600W/m^2 and ambient temperature 32 ^{0}C in steady state.

5 Conclusion

We have shown that greenhouse can be modeled using surface energy balance of different components of greenhouse and inside climate condition can be predicted in varying rate of ventilation.

We carried study and unsteady state analysis and matched the solutions and shown that unsteady solution matches with steady state. Time constant were found out in steady state

Variations of temperature of greenhouse surfaces with time were analyzed for different air change in dry and wet condition of soil.

Sensible parameters were studied and effects on output parameters analyzed.

6 Future works

At present, we have assumed the plants are saturated with water but in real situations, they are definitely not. Also reflectivity and transmissivity are function of wavelength of the incidence radiation. And evaporation rate depends on stomatal opening.

Greenhouse surfaces are assumed flat but in reality it is inclined and hence inclination of solar radiation can be considered.

MATLAB code can be easily modified and used for fan pad system.

Plants covered area can be changed and new simulation can be carried out.

Natural convection inside greenhouse is considered in present analysis, but in reality it mixed and therefore mixed convection correlations can be used in future studies.

Temperature of soil at depth 0.15m is average temperature of greenhouse air for a day that is 298 K. But this is periodic and heat conduction through soil is to be modified solving 1D heat conduction

Location of ventilation is not identified it was assumed outside air enters from one side (16 m x3m) and leaves from the other side. In future analysis exact location of ventilation can be incorporated.

Evaporation from side walls and roof can also be considered in future studies.

Temperature gradient is not considered inside greenhouse and within poly film material. This can also be taken into consideration in future analysis.

7 Appendix - I

MATLAB Codes

```
%MATLAB Code to find Variation of Soil,Inside air,Roof and Side Tempertaure with time in Dry
soil-dry soil steday Equation only
function [F] = eqn(x);
global I IS T0 ma et tt rt eb tb rb es ts rs xa;
% greenhouse dimensions and Shape factors
At=128;             %Top surface(m^2)
Ab=128;             %Bottom Surface(m^2)
As=144;             %Side surface(m^2)
V=384;              %Volume(m^2)
cl=2.66;            %Characteristic length(m)
ftsk=1;             %top to sky
fssk=1;             %side to sky
esk=1;              %emmisvity of sky
ftb=0.6;            %top to bottom
fbt=0.6;            %bottom to top
fts=0.4;            %top to side
fbs=0.4;            %bottom to side
fst=(At/As)*ftb;    %side to top
fsb=(Ab/As)*fbs;    %side to bottom
%Air properties and water properties
den=1.22;           %Density(kg/m^3)
cpa=1005 ;          %Specific heat capacity of air (J/kgK)
kinv=1.56*10^-5;    %Kinamatic viscosity(m^2/s)
tdv=18.5*10^-6;     %Thermal diffusivity(m^2/s)
beta=1/310;         %Bulk moduls(1/K)
ka=0.0267;          %Thermal conductivity(W/mK)
hfg=2260*1000;      %Latant heat of water(J/kg)
cpv=1.84*1000;      %Specific heat capacity of vapor(J/kgK)
R=8315;             %Universal gas constant(J/kmol/K)
M=18;               %Molecular weight of water(g/mol)
%soil properties
ks=1.1;             %Thermal conductivity(W/mK)
L=0.15;             %Depth of soil(m)
TL=298;
%Constants
sigm=5.670373*10^-8;    %Stefen boltzman(W/m^2/K^4)
g=9.81;                 %Gravity(m/s^2)
%Convective heat tranfer cofficent (W/m^2/K)
ht=4.57;
hb=4.92;
hi=3.9;
hs=1.81;
%Convective heat tranfer cofficent
% ht=real((0.15*ka/cl)*(g*beta*(x(3)-T0)*cl^3/(kinv*tdv))^(1/3));      % top surface(Outside)
% hb=real((0.15*ka/cl)*(g*beta*(x(1)-x(2))*cl^3/(kinv*tdv))^(1/3));    % Bottom surface(Inside)
% hi=real((0.15*ka/cl)*(g*beta*(x(2)-x(3))*cl^3/(kinv*tdv))^(1/3));    % top surface(Inside)
```

```
% hs=real((0.504*ka/cl)*(g*beta*(x(4)-T0)*cl^3/(kinv*tdv))^(1/4));     % side surface(Inside)
xa=0.017;

% Equations
F1=(I-I*rt-I*tt)*At- sigm*At*ftsk*et*esk*(x(3)^4-(T0-6)^4)-sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-
sigm*At*fts*et*es*(x(3)^4-x(4)^4)-ht*At*(x(3)-T0)-hi*At*(x(3)-x(2));

F2=(I*tt-I*tt*rb-I*tt*tb)*Ab+sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-
hb*Ab*(x(1)-x(2))-ks*Ab*(x(1)-TL)/L;

F3=hi*At*(x(3)-x(2))+hb*At*(x(1)-x(2))+ hs*As*(x(4)-x(2))+ma*cpa*(T0-(x(2)));

F4=(IS-IS*rs-IS*ts)*As-sigm*As*fssk*es*esk*(x(4)^4-(T0-6)^4)+sigm*At*fts*et*es*(x(3)^4-
x(4)^4)+sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-hs*As*(x(4)-x(2))-hs*As*(x(4)-T0);

F5=ma*xa-ma*x(5);

F = [F1; F2; F3; F4; F5];
```

```
%MATLAB Code to find Variation of Soil,Inside air,Roof and Side Tempertaure with time in Dry Soil
condition-solver
clear all,clc;
global I IS T0 ma et tt rt eb tb rb es ts rs;
%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.7;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity
IS=50;
ma=1;
load('temp.mat');           % data for 80 to 81 ,1 day data
load('rh.mat');
load('rtime.mat');
load('Solar.mat');
load('IST.mat');

for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298 0];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x;
```

```
end

plot(IST,X(1,:)-272,'k','LineWidth',3);
hold on
% plot(IST,X(2,:)-273,'g','LineWidth',3);
% plot(IST,X(3,:)-273,'r','LineWidth',3);
% plot(IST,X(4,:)-273,'m','LineWidth',3);
% plot(IST,Temp,'b','LineWidth',3);
% legend('Soil(Tb)','Inside air(Ti)','Roof(Tt)', 'Side(Ts)','Ambient(T0)');
% xlim([0  23]);
% str = {'Dry soil','Air change = 1 kg/s','(ACPH=8)'};
% text(1,50,str,'FontSize',28)
% xlabel('Time of the day(h)','FontSize',34);
% ylabel('Temperature (^0C)','FontSize',34);
% set(gca,'FontSize',24 ,'XTick',0:2:23);
% % title('Time Vs Tempearture (March 21,2019 in Bangalore)','FontSize',32);
%
```

```
clear all;
%MATLAB Code for Unsteady state Temperature Calculation for a Radiation load (Particular time )
Equation nad solution

%Mass and specific heat of greenhouse material
mt=23.04;    %Mass of roof (200 micron polyfilm)
cpt=1250;    %Specific heat capacity of polyfilm(J/kg/K)
mb=28800;    %Mass of soil(kg)
cpb=800;     %Heat capacity of dry soil(J/kg/K)
ms=51.84;    %Mass of side wall(kg)
cps=1250;    %Specific heat capacity of side wall(J/kg/K)
mag=468;     %Mass of air(kg)

%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity

%Shape factors and greenhouse dimensions
At=128;             %Top surface(m^2)
Ab=128;             %Bottom Surface(m^2)
As=144;             %Side surface(m^2)
v=384;              %Volume(m^3)
cl=2.66;            %Characteristic length(m)
```

```
ftsk=1;             %top to sky
fssk=1;             %side to sky
esk=1;              %emmisvity of sky
ftb=0.6;            %top to bottom
fbt=0.6;            %bottom to top
fts=0.4;            %top to side
fbs=0.4;            %bottom to side
fst=(At/As)*ftb;    %side to top
fsb=(Ab/As)*fbs;    %side to bottom

%%Air  and water properties
den=1.22;           %Density(kg/m^3)
cpa=1005;           %Specific heat capacity of moist air(J/kg/K)
kinv=1.56*10^-5;    %Kinamatic viscosity(m^2/s)
tdv=18.5*10^-6;     %Thermal diffusivity(m^2/s)
beta=1/310;         %Bulk moduls(1/K)
ka=0.0267;          %Thermal conductivity(W/mK)
hfg=2260*1000;      %Latant heat of water(J/kg)
cpv=1840;      %Specific heat capacity of vapor(J/kg/K)
M=18;               %Molecular weight of water(g/mole)
%soil properties
ks=1.1;             %Thermal conductivity (W/mK)
L=0.15;             %Depth of soil(m)
TL=298;             %Soil Temperature depth 0.15cm
%Constants
sigm=5.670*10^-8;    %Stefen boltzman
g=9.81;              %Gravity
R=8315;              %Universal gas constant(J/kmol/K)
%Convective heat tranfer cofficent (W/m^2/K)
ht=4.57;
hb=4.92;
hi=3.9;
hs=1.81;
%radiation load
I=600;  %diffuse radiation
IS=50;  %total radiation
ma=1;      %air chnage
T0=305;
Tsk=299;
%Equation Cofficents
%top surfcae
k1=1/(mt*cpt);
k2=I*(1-rt-tt)*At;
k3= sigm*At*ftsk*et*esk;
k4=sigm*At*ftb*et*eb;
k5=sigm*At*fts*et*es;
k6=ht*At;
k7=hi*At;
% Soil
k8=1/(mb*cpb);
k9=(I*tt-I*tt*rb-I*tt*tb)*Ab;
k10=sigm*At*ftb*et*eb;
k11=sigm*Ab*fbs*eb*es;
```

```
k12=hb*Ab;
k13=ks*Ab/L;

%Side wall
k14=1/(ms*cps);
k15=(IS-IS*rs-IS*ts)*As;
k16=sigm*fssk*es*esk*As;
k5=sigm*At*fts*et*es;
k11=sigm*Ab*fbs*eb*es;
k19=hs*As;
k20=hs*As;
%greenhouse air
k21=1/(mag*cpa);
k22=hi*At;
k23=hb*Ab;
k24=hs*As;
k25=ma*cpa;


f = @(t,x)[
k8*(k9+k10*(x(3)^4-x(1)^4)-k11*(x(1)^4-x(4)^4)-k12*(x(1)-x(2))- k13*(x(1)-T0)); %soil

k21*(k22*(x(3)-x(2))+k23*(x(1)-x(2))+k24*(x(4)-x(2))+k25*(T0-x(2))); %air

k1*(k2-k3*(x(3)^4-Tsk^4)-k4*(x(3)^4-x(1)^4 )-k5*(x(3)^4-x(4)^4)-k6*(x(3)-T0)-k7*(x(3)-x(2)));
%roof

k14*(k15+k5*(x(3)^4-x(4)^4)+k11*(x(1)^4-x(4)^4)-k16*(x(4)^4-Tsk^4)-k19*(x(4)-x(2) )-k20*(x(4)-
T0))]; %side


[t,x] = ode15s(f,[0 86400],[298 298 298 298]);
figure
plot(t,x(:,1)-273,'k','LineWidth',3)
hold on
plot(t,x(:,2)-273,'g','LineWidth',3)
plot(t,x(:,3)-273,'r','LineWidth',3)
plot(t,x(:,4)-273,'m','LineWidth',3)
xlim([0  86400]);
str = {'Dry soil','Air change =1kg/s','I=600 W/m^2, T0=32^oC'};
text(32000,50,str,'FontSize',28)
xlabel('Time (sec)','FontSize',34);
ylabel('Temperature (^0C)','FontSize',34);
set(gca,'FontSize',24 ,'XTick',0:7200:86400);
title('Unsteady state solution -Time Vs Temeperature ','FontSize',32);
hold on
t=0:86400;
plot(t,zeros(86401,1)+32,'b','LineWidth',3);
legend('Soil (Tb)','Inside air (Ti)','Roof (Tt)', 'Side (Ts)','Ambient(T0)');
```

```
clear all;
%MATLAB Code for Unsteady  Time Vs Temeperature(All Surfaces) Plot for any duration- 24Hrs/Any No
of Days

%Mass and specific heat of elements of greenhouse
mt=23.04;    %Mass of roof (200 micron polyfilm)
cpt=1250;    %Specific heat capacity of polyfilm(J/kg/K)
mb=28800;    %Mass of soil(kg)
cpb=800;     %Heat capacity of dry soil(J/kg/K)
ms=51.84;    %Mass of side wall(kg)
cps=1250;    %Specific heat capacity of side wall(J/kg/K)
mag=468;     %Mass of air(kg)

%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity

%Shape factors and greenhouse dimensions
At=128;             %Top surface(m^2)
Ab=128;             %Bottom Surface(m^2)
As=144;             %Side surface(m^2)
v=384;              %Volume(m^3)
cl=2.66;            %Characteristic length(m)
ftsk=1;             %top to sky
fssk=1;             %side to sky
esk=1;              %emmisvity of sky
ftb=0.6;            %top to bottom
fbt=0.6;            %bottom to top
fts=0.4;            %top to side
fbs=0.4;            %bottom to side
fst=(At/As)*ftb;    %side to top
fsb=(Ab/As)*fbs;    %side to bottom
%Air  and water properties
den=1.22;           %Density(kg/m^3)
cpa=1005;           %Specific heat capacity of moist air(J/kg/K)
kinv=1.56*10^-5;    %Kinamatic viscosity(m^2/s)
tdv=18.5*10^-6;     %Thermal diffusivity(m^2/s)
beta=1/310;         %Bulk moduls(1/K)
ka=0.0267;          %Thermal conductivity(W/mK)
hfg=2260*1000;      %Latant heat of water(J/kg)
cpv=1.84*1000;      %Specific heat capacity of vapor(J/kg/K)
M=18;               %Molecular weight of water(g/mole)
%soil properties
```

```
ks=1.1;             %Thermal conductivity (W/mK)
L=0.15;             %Depth of soil(m)
TL=298;             %Soil Temperature depth 0.15cm
%Constants
sigm=5.670*10^-8;    %Stefen boltzman
g=9.81;              %Gravity
R=8315;             %Universal gas constant(J/kmol/K)
%Convective heat tranfer cofficent (W/m^2/K)
ht=4.57;
hb=4.92;
hi=3.9;
hs=1.81;
%Diffuse radiation load and Sky Temperature
IS=50;      %Diffuse radiation(W/m^2)
Tsk=292;    %Sky temperature(K)
%Air chnage
ma=1;       %(kg/s)

%Equation Cofficents
%top surfcae
k1=1/(mt*cpt);
% k2=I*(1-rt-tt)*At;
k3=sigm*At*ftsk*et*esk;
k4=sigm*At*ftb*et*eb;
k5=sigm*At*fts*et*es;
k6=ht*At;
k7=hi*At;
% Soil
k8=1/(mb*cpb);
% k9=I*(tt-tt*rb-tt*tb)*Ab;
k10=sigm*At*ftb*et*eb;
k11=sigm*Ab*fbs*eb*es;
k12=hb*Ab;
k13=ks*Ab/L;

%Side wall
k14=1/(ms*cps);
k15=(IS-IS*rs-IS*ts)*As;
k16=sigm*fssk*es*esk*As;
k5=sigm*At*fts*et*es;
k11=sigm*Ab*fbs*eb*es;
k19=hs*As;
k20=hs*As;
%greenhouse air
k21=1/(mag*cpa);
k22=hi*At;
k23=hb*Ab;
k24=hs*As;
k25=mag;

%Total radiation estimation
%Curve Fit For Total Radiation
t=linspace(0,86400);
       a0 =       322.8;
```

```
       a1 =        -351;
       b1 =      -327.5;
       a2 =       17.38;
       b2 =       161.1;
       a3 =      -24.71;
       b3 =       7.258;
       a4 =       28.21;
       b4 =       8.456;
       w =   8.745e-05 ;
   I=a0 + a1*cos(t*w) + b1*sin(t*w) + a2*cos(2*t*w) + b2*sin(2*t*w) + a3*cos(3*t*w) +
b3*sin(3*t*w)+ a4*cos(4*t*w) + b4*sin(4*t*w);
%    plot(t,I,'kd')
% %End

% % Curve Fit For Ambient Temperature
 t=linspace(0,86400);
a01 = 26.97;
a11 =-4.812;
b11 = -4.985;
a21 =1.513;
b21 =0.7722;
a31 =0.5001;
b31 =-0.0241;
a41 =-0.1668;
b41 =-1.054;
w1 =7.377e-05;
T0 = 273+a01 + a11*cos(t*w1) + b11*sin(t*w1) + a21*cos(2*t*w1) + b21*sin(2*t*w1) +
a31*cos(3*t*w1) + b31*sin(3*t*w1)+ a41*cos(4*t*w1) + b41*sin(4*t*w1);
%  plot(t,T0-273)
% % End



%MainCode-Solution by ODE Solver 15s

f = @(t,x)[k8*((a0 + a1*cos(t*w) + b1*sin(t*w) + a2*cos(2*t*w) + b2*sin(2*t*w) + a3*cos(3*t*w) +
b3*sin(3*t*w)+ a4*cos(4*t*w) + b4*sin(4*t*w))*(tt-tt*rb-tt*tb)*Ab+k10*(x(3)^4-x(1)^4)-
k11*(x(1)^4-x(4)^4)-k12*(x(1)-x(2))- k13*(x(1)-TL)); %soil

k21*(k22*(x(3)-x(2))+k23*(x(1)-x(2))+k24*(x(4)-x(2))+k25*((273+a01 + a11*cos(t*w1) +
b11*sin(t*w1) + a21*cos(2*t*w1) + b21*sin(2*t*w1) + a31*cos(3*t*w1) + b31*sin(3*t*w1)+
a41*cos(4*t*w1) + b41*sin(4*t*w1))-x(2))); %air

k1*((a0 + a1*cos(t*w) + b1*sin(t*w) + a2*cos(2*t*w) + b2*sin(2*t*w) + a3*cos(3*t*w) +
b3*sin(3*t*w)+ a4*cos(4*t*w) + b4*sin(4*t*w))*(1-rt-tt)*At-k3*(x(3)^4-Tsk^4)-k4*(x(3)^4-x(1)^4 )-
k5*(x(3)^4-x(4)^4)-k6*(x(3)-(273+a01 + a11*cos(t*w1) + b11*sin(t*w1) + a21*cos(2*t*w1) +
b21*sin(2*t*w1) + a31*cos(3*t*w1) + b31*sin(3*t*w1)+ a41*cos(4*t*w1) + b41*sin(4*t*w1) ))-
k7*(x(3)-x(2)));  %roof

k14*(k15+k5*(x(3)^4-x(4)^4)+k11*(x(1)^4-x(4)^4)-k16*(x(4)^4-Tsk^4)-k19*(x(4)-x(2) )-k20*(x(4)-
(273+a01 + a11*cos(t*w1) + b11*sin(t*w1) + a21*cos(2*t*w1) + b21*sin(2*t*w1) + a31*cos(3*t*w1) +
b31*sin(3*t*w1)+ a41*cos(4*t*w1) + b41*sin(4*t*w1))))]; %side

[t,x] = ode15s(f,t,[292 292 292 292]);
```

```
[t,x] = ode15s(f,[0 86400],[298 298 298 298]);
figure
plot(t,x(:,1)-273,'k','LineWidth',3)
hold on
plot(t,x(:,2)-273,'g','LineWidth',3)
plot(t,x(:,3)-273,'r','LineWidth',3)
plot(t,x(:,4)-273,'m','LineWidth',3)
xlim([0  86400]);
str = {'Dry soil','Air change =1kg/s'};
text(3600,40,str,'FontSize',28)
xlabel('Time of the day (sec)','FontSize',34);
ylabel('Temperature (^0C)','FontSize',34);
set(gca,'FontSize',24 ,'XTick',0:7200:86400);
title('Unsteady state solution -(March 21,2019 in Bangalore) ','FontSize',32);
hold on
t=linspace(0,86400);
T0 = 273+a01 + a11*cos(t*w1) + b11*sin(t*w1) + a21*cos(2*t*w1) + b21*sin(2*t*w1) +
a31*cos(3*t*w1) + b31*sin(3*t*w1)+ a41*cos(4*t*w1) + b41*sin(4*t*w1);


plot(t,T0-273,'b','LineWidth',3)

legend('Soil (Tb)','Inside air (Ti)','Roof (Tt)', 'Side (Ts)','Ambient(T0)');
```

```
%MATLAB Code for steady state energy balance  in Dry Soil condition , No Air exchange

clear all;clc;
x(1)=329.8601;
x(2)=320.5845;
x(3)=314.3032;
x(4)=310.2032;

%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity

I=600;          %Total Rdaiation(on roof)(W/m^2)
IS=50;          %Diffuse radiation(on side surface) (W/m^2)
T0=305;         %Ambient Tempearture(K)
ma=0;           %Air exchnage rate(kg/s)
% greenhouse dimensions and Shape factors
At=1;             %Top surface(m^2)
Ab=1;             %Bottom Surface(m^2)
```

```
As=1.125;              %Side surface(m^2)
V=384;                %Volume(m^2)
cl=2.66;              %Characteristic length(m)
ftsk=1;               %top to sky
fssk=1;               %side to sky
esk=1;                %emmisvity of sky
ftb=0.6;              %top to bottom
fbt=0.6;              %bottom to top
fts=0.4;              %top to side
fbs=0.4;              %bottom to side
fst=(At/As)*ftb;      %side to top
fsb=(Ab/As)*fbs;      %side to bottom
%Air properties and water properties
den=1.22;             %Density(kg/m^3)
cpa=1005 ;            %Specific heat capacity of air (J/kgK)
kinv=1.56*10^-5;      %Kinamatic viscosity(m^2/s)
tdv=18.5*10^-6;       %Thermal diffusivity(m^2/s)
beta=1/310;           %Bulk moduls(1/K)
ka=0.0267;            %Thermal conductivity(W/mK)
hfg=2260*1000;        %Latant heat of water(J/kg)
cpv=1.84*1000;        %Specific heat capacity of vapor(J/kgK)
R=8315;               %Universal gas constant(J/kmol/K)
M=18;                 %Molecular weight of water(g/mol)
%soil properties
ks=1.1;               %Thermal conductivity(W/mK)
L=0.15;               %Depth of soil(m)
TL=298;
%Constants
sigm=5.670373*10^-8;    %Stefen boltzman(W/m^2/K^4)
g=9.81;                 %Gravity(m/s^2)
%Convective heat tranfer cofficent (W/m^2/K)
ht=4.57;
hb=4.92;
hi=3.9;
hs=1.81;


F1=(I-I*rt-I*tt)*At- sigm*At*ftsk*et*esk*(x(3)^4-(T0-6)^4)-sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-
sigm*At*fts*et*es*(x(3)^4-x(4)^4)-ht*At*(x(3)-T0)-hi*At*(x(3)-x(2));

F2=(I*tt-I*tt*rb-I*tt*tb)*Ab+sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-
hb*Ab*(x(1)-x(2))-ks*Ab*(x(1)-TL)/L;

F3=hi*At*(x(3)-x(2))+hb*At*(x(1)-x(2))+ hs*As*(x(4)-x(2))+ma*cpa*(T0-(x(2)));

F4=(IS-IS*rs-IS*ts)*As-sigm*As*fssk*es*esk*(x(4)^4-(T0-6)^4)+sigm*At*fts*et*es*(x(3)^4-
x(4)^4)+sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-hs*As*(x(4)-x(2))-hs*As*(x(4)-T0);

F = [F1; F2; F3; F4]
F11=I*At;
F12=-I*rt*At;
F13=-I*tt*At;
F14=- sigm*At*ftsk*et*esk*(x(3)^4-(T0-6)^4);
F15=-sigm*At*ftb*et*eb*(x(3)^4-x(1)^4);
```

```
F16=-sigm*At*fts*et*es*(x(3)^4-x(4)^4);
F17=-ht*At*(x(3)-T0);
F18=-hi*At*(x(3)-x(2));

F21=I*tt*Ab;
F22=-I*tt*rb*Ab;
F23=-I*tt*tb*Ab;
F24=+sigm*At*ftb*et*eb*(x(3)^4-x(1)^4);
F25=-sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4);
F26=-hb*Ab*(x(1)-x(2));
F27=-ks*Ab*(x(1)-TL)/L;


F31=hi*At*(x(3)-x(2));
F32=+hb*At*(x(1)-x(2));
F33=hs*As*(x(4)-x(2));
F34=ma*cpa*(T0-x(2));

F41=IS;
F42=-IS*rs;
F43=-IS*ts;
F44=-sigm*fssk*es*esk*(x(4)^4-(T0-6)^4);
F45=+sigm*(At/1.125)*fts*et*es*(x(3)^4-x(4)^4);
F46=+sigm*(Ab/1.125)*fbs*eb*es*(x(1)^4-x(4)^4);
F47=-hs*(x(4)-x(2));
F48=-hs*(x(4)-T0);


RSAS=[F11 F12 F13 F14 F15 F16 F17 F18; F21 F22 F23 F24 F25 F26 F27 0; F31 F32 F33 F34 0 0 0 0;F41
F42 F43 F44 F45 F46 F47 F48;];
```

```
%MATLAB Code for evaporation calculation
```

```
clear all;clc;
Ta=30;Tb=40; Ab=128;                  % air temperature
R=8314;M=18;Rh2o=R/M;
pw=exp(25.317-5144/(273+Tb));   % presure of vapur at surfcae (satuaration pressure ) wet surface
tem(Pa)
pa=exp(25.317-5144/(273+Ta));   % partial presure of water vapur in the air (saturation pressure
)at air temp(Pa)
h=4;ro=1.212;cp=1004;r=0.7;     % air propertie
hfg=2256*1000;                  %latant heat of vaporisation(kj/kg or 1000*j/kg)
k=h/(ro*cp)
cb=(pw)/(Rh2o*(Tb+273))         %concentraion of vapor in wet surface ( kg/m^3)
ca=(r*pa)/(Rh2o*(Ta+273))       %concentraion of vapor in air ( kg/m^3)
mw=(cb-ca)*k                    %evaporation(kg/m^2/s)
qe=k*(cb-ca)*hfg                %Evapotaive Heat tranfer(W/m^2)
```

```
Transmissivity variation clear all,clc;
format shortg
global I IS T0 ma et tt rt eb tb rb es ts rs xa;
%Surface emision properties
%Top surface
```

```
et=0.9;          %emmisivity
% tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity
xa=0.01;
I=600;          %Total Rdaiation(on roof)(W/m^2)
IS=0;          %Diffuse radiation(on side surface) (W/m^2)
T0=305;         %Ambient Tempearture(K)
ma=1;
TT =0:0.1:1;    %Air exchnage rate(kg/s)
for i=1:length(TT);
    tt =TT(i);
   x0 = [298 298 298 298 0];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x;
end
plot(TT,X(1,:)-273,'k','LineWidth',3);
hold on
plot(TT,X(2,:)-273,'g','LineWidth',3);
plot(TT,X(3,:)-273,'r','LineWidth',3);
plot(TT,X(4,:)-273,'m','LineWidth',3);
plot(TT,(T0-273),'b','LineWidth',3);
legend('Soil(Tb)','Air(Ti)','Roof(Tt)', 'Side(Ts)','Ambient(T0)');
xlabel('Transmissivity(tt) of roof','FontSize',34);
ylabel('Temperature (^0C)','FontSize',34);
set(gca,'FontSize',24 ,'XTick',0:0.1:1);
str = {'Dry soil','Air change =1kg/s', 'I=600W/m^2','Is=50W/m^2','T0=32^0C'};
text(0.05,48,str,'FontSize',28)
title('Steady state -Roof Transmissivity Vs Temperatures','FontSize',32);
plot(TT,zeros(11,1)+32,'b','LineWidth',3);
```

```
%MATLAB Code to find Variation of Soil,Air,Roof and Side Tempertaure with time in Dry Soil
condition
clear all,clc;
global I IS T0 ma et tt rt eb tb rb es ts rs;
%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.7;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
```

```
rs=0.1;          %reflectivity
IS=50;
load('temp.mat');           % data for 80 to 81 ,1 day data
load('rh.mat');
load('rtime.mat');
load('Solar.mat');
load('IST.mat');

ma=0;
for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298 0];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x;
end
plot(IST,X(1,:)-273,'k','LineWidth',2);
hold on
plot(IST,Temp,'LineWidth',2);
legend('Soil(T_b)','Ambient(T_o)')
xlim([0  23]);
xlabel('Time of the day(h)','FontSize',34);
ylabel('Temperature (^0C)','FontSize',34);
set(gca,'FontSize',24 ,'XTick',0:2:23);
title('Time Vs Soil Temperature (March 21,2019 in Bangalore)','FontSize',32);
str = {'Dry soil'};
text(1,50,str,'FontSize',28)
hold on

ma=1;
for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298 0];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x;
end
plot(IST,X(1,:)-273,'k','LineWidth',2);
hold on

ma=5;
for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298 0];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x;
end
plot(IST,X(1,:)-273,'k','LineWidth',2);
hold on

ma=10;
for i=1:length(Solar);
    I =Solar(i);
```

```
    T0=273+Temp(i);
   x0 = [298 298 298 298 0];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x;
end
plot(IST,X(1,:)-273,'k','LineWidth',2);
hold on
```

```
%MATLAB code for validation of model by slecting White,Black and Transparent surfaces
clear all; clc;
global I IS T0 ma et tt rt eb tb rb es ts rs;
%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=1;          %transmissivity
rt=0;          %reflectivity
%Bottom surface
eb=1;          %emmisivity
tb=0;            %transmissivity
rb=0;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=1;          %transmissivity
rs=0;          %reflectivity
IS=50;
ma=0;
load('temp.mat');           % data for 80 to 81 ,1 day data
load('rh.mat');
load('rtime.mat');
load('Solar.mat');
load('IST.mat');

for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x-273;
end

% subplot(2,2,1)
plot(IST,X(1,:),'k','LineWidth',3);
hold on
plot(IST,X(2,:),'g','LineWidth',3);
plot(IST,X(3,:),'r','LineWidth',3);
plot(IST,X(4,:),'m','LineWidth',3);
plot(IST,Temp,'LineWidth',3);
xlim([0  23]);
legend('Soil-B','Inside air', 'Roof-T', 'Side-T','Ambient');
xlabel('Time of the day(h)','FontSize',28);
ylabel('Temperature (^0C)','FontSize',28);
set(gca,'FontSize',28 ,'XTick',0:2:23);
title('Time Vs Tempeartures (March 21,2019 in Bangalore)','FontSize',30);
str = {'Air Change =0'};
```

```
text(2,60,str,'FontSize',28)
hold on

%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=1;          %transmissivity
rt=0;          %reflectivity
%Bottom surface
eb=1;          %emmisivity
tb=0;            %transmissivity
rb=1;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=1;          %transmissivity
rs=0;          %reflectivity

IS=50;
ma=0;
load('temp.mat');           % data for 80 to 81 ,1 day data
load('rh.mat');
load('rtime.mat');
load('Solar.mat');
load('IST.mat');

for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x-273;
end
% subplot(2,2,2)
plot(IST,X(1,:),'k','LineWidth',3);
hold on
plot(IST,X(2,:),'g','LineWidth',3);
plot(IST,X(3,:),'r','LineWidth',3);
plot(IST,X(4,:),'m','LineWidth',3);
plot(IST,Temp,'LineWidth',3);
xlim([0  23]);
legend('Soil-W','Air', 'Roof-T', 'Side-T','Ambient');
xlabel('Time of the day(h)','FontSize',28);
ylabel('Temperature (^0C)','FontSize',28);
set(gca,'FontSize',28 ,'XTick',0:2:23);
title('Time Vs Tempeartures (March 21,2019 in Bangalore)','FontSize',30);
str = {'Air Change =0'};
text(2,28,str,'FontSize',28)
hold on

%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0;          %transmissivity
rt=0;          %reflectivity
```

```
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=1;           %reflectivity
%side wall
es=0.9;          %emmisivity
ts=1;           %transmissivity
rs=0;           %reflectivity

IS=50;
ma=0;
load('temp.mat');           % data for 80 to 81 ,1 day data
load('rh.mat');
load('rtime.mat');
load('Solar.mat');
load('IST.mat');
for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x-273;
end

% subplot(2,2,3)
plot(IST,X(1,:),'k','LineWidth',3);
hold on
plot(IST,X(2,:),'g','LineWidth',3);
plot(IST,X(3,:),'r','LineWidth',3);
plot(IST,X(4,:),'m','LineWidth',3);
plot(IST,Temp,'LineWidth',3);
xlim([0  23]);
xlabel('Time of the day(h)','FontSize',28);
ylabel('Temperature (^0C)','FontSize',28);
set(gca,'FontSize',28 ,'XTick',0:2:23);
title('Time Vs Tempeartures (March 21,2019 in Bangalore)','FontSize',30);
str = {'Air Change =0'};
text(2,50,str,'FontSize',28)
legend('Soil-W','Air', 'Roof-B', 'Side-T','Ambient');
hold on

%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=1;            %transmissivity
rt=0;            %reflectivity
%Bottom surface
eb=1;           %emmisivity
tb=0;           %transmissivity
rb=1;           %reflectivity
%side wall
es=0.9;         %emmisivity
ts=0;           %transmissivity
rs=0;           %reflectivity
```

```
IS=50;
ma=0;
load('temp.mat');            % data for 80 to 81 ,1 day data
load('rh.mat');
load('rtime.mat');
load('Solar.mat');
load('IST.mat');

for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
   x0 = [298 298 298 298];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x-273;
end
plot(IST,X(1,:),'k','LineWidth',3);
hold on
plot(IST,X(2,:),'g','LineWidth',3);
plot(IST,X(3,:),'r','LineWidth',3);
plot(IST,X(4,:),'m','LineWidth',3);
plot(IST,Temp,'LineWidth',3);
xlim([0  23]);
xlabel('Time of the day(h)','FontSize',28);
ylabel('Temperature (^0C)','FontSize',28);
set(gca,'FontSize',28 ,'XTick',0:2:23);
title('Time Vs Tempeartures (March 21,2019 in Bangalore)','FontSize',30);
str = {'Air Change =0'};
text(2,28,str,'FontSize',28)
legend('Soil-W','Air','Roof-T', 'Side-B','Ambient');
```

```
%MATLAB Code for RH variation clear all,clc;
global I IS T0 ma et tt rt eb tb rb es ts rs xa RH;
%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity
IS=50;          %Diffuse radiation(on side surface) (W/m^2)
ma=0;
Solar=[200 400 600 800 1000];          %Total Rdaiation(on roof)(W/m^2)
IS=50;          %Diffuse radiation(on side surface) (W/m^2)
Temp=[308 308 308 308 308];         %Ambient Tempearture(K)
```

```
ma=0.01;           %Air exchnage rate(kg/s)

 RH=0.3; xa =0.001;;

 for i=1:length(Solar);
    I =Solar(i);
    T0=Temp(i);
    x0 = [298 298 298 298  0];
[x,fval,exitflag] = fsolve(@WetSoilSteadyEqn,x0);
X(:,i) = x;
end
plot(Solar,X(1,:)-273,'-*r','LineWidth',3);
hold on

 RH=0.6; xa =0.001;;

 for i=1:length(Solar);
    I =Solar(i);
    T0=Temp(i);
    x0 = [298 298 298 298  0];
[x,fval,exitflag] = fsolve(@WetSoilSteadyEqn,x0);
X(:,i) = x;
end
plot(Solar,X(1,:)-273,'-dg','LineWidth',3);
hold on

 RH=0.9; xa =0.001;

 for i=1:length(Solar);
    I =Solar(i);
    T0=Temp(i);
    x0 = [298 298 298 298  0];
[x,fval,exitflag] = fsolve(@WetSoilSteadyEqn,x0);
X(:,i) = x;
end
plot(Solar,X(1,:)-273,'-om','LineWidth',3);
hold on



for i=1:length(Solar);
    I =Solar(i);
    T0=Temp(i);
   x0 = [298 298 298 298 0];
[x,fval,exitflag] = fsolve(@DrySoilSteadyEqn,x0);
X(:,i) = x;
end
plot(Solar,X(1,:)-273,'k','LineWidth',3);
hold on
xlim([200  1000]);
xlabel('Solar Intensity (W/m^2)','FontSize',34);
ylabel('Temperature (^0C)','FontSize',34);
set(gca,'FontSize',28)
```

```
legend('Wet Soil(Inside air at RH=30%)','Wet Soil(Inside air at RH=60%)','Wet Soil(Inside air at
RH=90%)', 'Dry Soil');
```

```
%MATLAB Code for steady state energy balance of surfaces of greenhouse in Dry Soil condition with
air exchange

clear all;clc;
x(1)=327.17;
x(2)=312.67;
x(3)=312.08;
x(4)=308.35;
x(5)=0.0170;
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity

I=600;          %Total Rdaiation(on roof)(W/m^2)
IS=50;          %Diffuse radiation(on side surface) (W/m^2)
T0=305;         %Ambient Tempearture(K)
ma=1;           %Air exchnage rate(kg/s)
xa=0.017;
% greenhouse dimensions and Shape factors
At=128;             %Top surface(m^2)
Ab=128;             %Bottom Surface(m^2)
As=144;             %Side surface(m^2)
V=384;              %Volume(m^2)
cl=2.66;            %Characteristic length(m)
ftsk=1;             %top to sky
fssk=1;             %side to sky
esk=1;              %emmisvity of sky
ftb=0.6;            %top to bottom
fbt=0.6;            %bottom to top
fts=0.4;            %top to side
fbs=0.4;            %bottom to side
fst=(At/As)*ftb;    %side to top
fsb=(Ab/As)*fbs;    %side to bottom
%Air properties and water properties
den=1.22;           %Density(kg/m^3)
cpa=1005 ;          %Specific heat capacity of air (J/kgK)
kinv=1.56*10^-5;    %Kinamatic viscosity(m^2/s)
tdv=18.5*10^-6;     %Thermal diffusivity(m^2/s)
```

```
beta=1/310;          %Bulk moduls(1/K)
ka=0.0267;           %Thermal conductivity(W/mK)
hfg=2260*1000;       %Latant heat of water(J/kg)
cpv=1.84*1000;       %Specific heat capacity of vapor(J/kgK)
R=8315;              %Universal gas constant(J/kmol/K)
M=18;                %Molecular weight of water(g/mol)
%soil properties
ks=1.1;              %Thermal conductivity(W/mK)
L=0.15;              %Depth of soil(m)
TL=298;
%Constants
sigm=5.670373*10^-8;    %Stefen boltzman(W/m^2/K^4)
g=9.81;                 %Gravity(m/s^2)
%Convective heat tranfer cofficent (W/m^2/K)
ht=4.57;
hb=4.92;
hi=3.9;
hs=1.81;


% Equations
F1=(I-I*rt-I*tt)*At- sigm*At*ftsk*et*esk*(x(3)^4-(T0-6)^4)-sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-
sigm*At*fts*et*es*(x(3)^4-x(4)^4)-ht*At*(x(3)-T0)-hi*At*(x(3)-x(2));

F2=(I*tt-I*tt*rb-I*tt*tb)*Ab+sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-
hb*Ab*(x(1)-x(2))-ks*Ab*(x(1)-TL)/L;

F3=hi*At*(x(3)-x(2))+hb*At*(x(1)-x(2))+ hs*As*(x(4)-x(2))+ma*cpa*(T0-(x(2)));

F4=(IS-IS*rs-IS*ts)*As-sigm*As*fssk*es*esk*(x(4)^4-(T0-6)^4)+sigm*At*fts*et*es*(x(3)^4-
x(4)^4)+sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-hs*As*(x(4)-x(2))-hs*As*(x(4)-T0);

F5=ma*xa-ma*x(5);

F = [F1; F2; F3; F4; F5]

F11=I*At;
F12=-I*rt*At;
F13=-I*tt*At;
F14=- sigm*At*ftsk*et*esk*(x(3)^4-(T0-6)^4);
F15=-sigm*At*ftb*et*eb*(x(3)^4-x(1)^4);
F16=-sigm*At*fts*et*es*(x(3)^4-x(4)^4);
F17=-ht*At*(x(3)-T0);
F18=-hi*At*(x(3)-x(2));

F21=I*tt*Ab;
F22=-I*tt*rb*Ab;
F23=-I*tt*tb*Ab;
F24=+sigm*At*ftb*et*eb*(x(3)^4-x(1)^4);
F25=-sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4);
F26=-hb*Ab*(x(1)-x(2));
F27=-ks*Ab*(x(1)-TL)/L;
```

```
F31=hi*At*(x(3)-x(2));
F32=+hb*At*(x(1)-x(2));
F33=hs*As*(x(4)-x(2));
F34=ma*cpa*(T0-(x(2)));


F41=IS*As;
F42=-IS*rs*As;
F43=-IS*ts*As;
F44=-sigm*fssk*es*esk*As*(x(4)^4-(T0-6)^4);
F45= sigm*fts*At*et*es*(x(3)^4-x(4)^4);
F46= sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4);
F47=-hs*As*(x(4)-x(2));
F48=-hs*As*(x(4)-T0);


RSAS=[F11 F12 F13 F14 F15 F16 F17 F18; F21 F22 F23 F24 F25 F26 F27 0; F31 F32 F33 F34 0 0 0 0;F41
F42 F43 F44 F45 F46 F47 F48;];
```

```
%Energy Balance wet soil condition
clear all;clc;
x(1)=312.12;
x(2)=307.45;
x(3)=307.96;
x(4)= 304.61;
x(5)=0.022888;

%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%Bottom surface
eb=0.9;          %emmisivity
tb=0;            %transmissivity
rb=0.2;          %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity

I=600;          %Total Rdaiation(on roof)(W/m^2)
IS=50;          %Diffuse radiation(on side surface) (W/m^2)
T0=305;         %Ambient Tempearture(K)
ma=1;
xa=0.010;       %Specific Humidityt (kg/kgda)At 32 degree and RH 50%

% greenhouse dimensions and Shape factors
At=128;             %Top surface(m^2)
Ab=128;             %Bottom Surface(m^2)
As=144;             %Side surface(m^2)
V=384;              %Volume(m^2)
cl=2.66;            %Characteristic length(m)
ftsk=1;             %top to sky
```

```
fssk=1;             %side to sky
esk=1;              %emmisvity of sky
ftb=0.6;            %top to bottom
fbt=0.6;            %bottom to top
fts=0.4;            %top to side
fbs=0.4;            %bottom to side
fst=(At/As)*ftb;    %side to top
fsb=(Ab/As)*fbs;    %side to bottom
%Air properties and water properties
den=1.22;           %Density(kg/m^3)
cpa=1005 ;          %Specific heat capacity of air (J/kgK)
kinv=1.56*10^-5;    %Kinamatic viscosity(m^2/s)
tdv=18.5*10^-6;     %Thermal diffusivity(m^2/s)
beta=1/310;         %Bulk moduls(1/K)
ka=0.0267;          %Thermal conductivity(W/mK)
hfg=2260*1000;      %Latant heat of water(J/kg)
cpv=1.84*1000;      %Specific heat capacity of vapor(J/kgK)
R=8315;             %Universal gas constant(J/kmol/K)
M=18;               %Molecular weight of water(g/mol)
%soil properties
ks=1.1;             %Thermal conductivity(W/mK)
L=0.15;             %Depth of soil(m)
TL=298;
%Constants
sigm=5.670373*10^-8;    %Stefen boltzman(W/m^2/K^4)
g=9.81;                 %Gravity(m/s^2)
%Convective heat tranfer cofficent (W/m^2/K)
ht=4.57;
hb=4.92;
hi=3.9;
hs=1.81;
% %Convective heat tranfer cofficent
% ht=real((0.15*ka/cl)*(g*beta*(x(3)-T0)*cl^3/(kinv*tdv))^(1/3));    % top surface(Outside)
% hb=real((0.15*ka/cl)*(g*beta*(x(1)-x(2))*cl^3/(kinv*tdv))^(1/3));       % Bottom
surface(Inside)
% hi=real((0.15*ka/cl)*(g*beta*(x(2)-x(3))*cl^3/(kinv*tdv))^(1/3));       % top surface(Inside)
% hs=real((0.504*ka/cl)*(g*beta*(x(4)-T0)*cl^3/(kinv*tdv))^(1/4));   % side surface(Inside)
%hm=0; (To check with Dry soil Result)
RH=0.6;
hm=hb/(den*cpa);                  %mass tranfer cofficent(soil-greenhouse air)
pw=exp(25.317-5144/(x(1)));       %Saturation presures of water vapor at tho soil surface
pi=exp(25.317-5144/x(2));         %Saturation presures of water vapor in the greenhouse air
cb=(1*pw*M)/(R*(x(1)));             %concentration of water  at the soil
ca=(RH*pi*M)/(R*x(2));            %concentration of water  in the greenhouise air

% Equations
F1=(I-I*rt-I*tt)*At- sigm*At*ftsk*et*esk*(x(3)^4-(T0-6)^4)-sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-
sigm*At*fts*et*es*(x(3)^4-x(4)^4)-ht*At*(x(3)-T0)-hi*At*(x(3)-x(2));

F2=(I*tt-I*tt*rb-I*tt*tb)*Ab+sigm*At*ftb*et*eb*(x(3)^4-x(1)^4)-sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-
hb*Ab*(x(1)-x(2))-ks*Ab*(x(1)-TL)/L-Ab*hm*(cb-ca)*hfg;

F3=hi*At*(x(3)-x(2))+hb*At*(x(1)-x(2))+ hs*As*(x(4)-x(2))+ma*cpa*(T0-x(2));
```

```
F4=(IS-IS*rs-IS*ts)*As-sigm*As*fssk*es*esk*(x(4)^4-(T0-6)^4)+sigm*At*fts*et*es*(x(3)^4-
x(4)^4)+sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4)-hs*As*(x(4)-x(2))-hs*As*(x(4)-T0);

F5=ma*xa+hm*Ab*(cb-ca)-ma*x(5);

F = [F1; F2; F3; F4; F5];


F11=I*At;
F12=-I*rt*At;
F13=-I*tt*At;
F14=- sigm*At*ftsk*et*esk*(x(3)^4-(T0-6)^4);
F15=-sigm*At*ftb*et*eb*(x(3)^4-x(1)^4);
F16=-sigm*At*fts*et*es*(x(3)^4-x(4)^4);
F17=-ht*At*(x(3)-T0);
F18=-hi*At*(x(3)-x(2));

F21=I*tt*Ab;
F22=-I*tt*rb*Ab;
F23=-I*tt*tb*Ab;
F24=+sigm*At*ftb*et*eb*(x(3)^4-x(1)^4);
F25=-sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4);
F26=-hb*Ab*(x(1)-x(2));
F27=-ks*Ab*(x(1)-TL)/L;
F28=-hm*Ab*(cb-ca)*hfg;


F31=hi*At*(x(3)-x(2));
F32=hb*At*(x(1)-x(2));
F33=hs*As*(x(4)-x(2));
F34=ma*cpa*(T0-x(2))


F41=IS*As;
F42=-IS*rs*As;;
F43=-IS*ts*As;;
F44=-sigm*fssk*As*es*esk*(x(4)^4-(T0-6)^4);
F45=+sigm*At*fts*et*es*(x(3)^4-x(4)^4);
F46=+sigm*Ab*fbs*eb*es*(x(1)^4-x(4)^4);
F47=-hs*As*(x(4)-x(2));
F48=-hs*As*(x(4)-T0);

F51=ma*xa;
F52=hm*Ab*(cb-ca);
F53=-ma*x(5);

RSAS=[F11 F12 F13 F14 F15 F16 F17 F18; F21 F22 F23 F24 F25 F26 F27 F28; F31 F32 F33 F34 0 0 0
0;F41 F42 F43 F44 F45 F46 F47 F48; F51 F52 F53 0 0 0 0 0 ];
```

```
% Calculation of specic humidity and saturation specific humidity of amabient air

clear all;clc;
load('Temp.mat');
load('rh.mat');
```

```
load('rtime.mat');
load('Solar.mat');
load('IST.mat');
Tamb=Temp;

for i=1:length(Tamb);
    patm=101325;
pvs=exp(25.317-5144/(273+Tamb(i)));
pv=0.01*eRH(i)*pvs;
xa(i)=0.622*((0.01*eRH(i)*pv)/(patm-0.01*eRH(i)*pv));
end

plot(IST,xa*1000,'g','LineWidth', 1);
hold on
```

```
%Plants  tempertaures clear all,clc;
global I IS T0 ma et tt rt eb tb rb es ts rs xa;
%Surface emision properties
%Top surface
et=0.9;          %emmisivity
tt=0.8;          %transmissivity
rt=0.1;          %reflectivity
%plants
eb=0.95;           %emmisivity
tb=0.4;            %transmissivity
rb=0.4;            %reflectivity
%side wall
es=0.9;          %emmisivity
ts=0.8;          %transmissivity
rs=0.1;          %reflectivity
IS=50;          %Diffuse radiation(on side surface) (W/m^2)
ma=1;
% data for 80 to 81 ,1 day data
load('temp.mat');      %Ambient Tempearture(degreeC)
load('rh.mat');        %Relative Humidity
load('rtime.mat');     %day step
load('Solar.mat');     %Total Rdaiation(on roof)(W/m^2)
load('IST.mat');       %Time step

for i=1:length(Temp);
     patm=101325;
pvs=exp(25.317-5144/(273+Temp(i)));
pv=0.01*eRH(i)*pvs;
xair(i)=0.622*((0.01*eRH(i)*pv)/(patm-0.01*eRH(i)*pv));
end


for i=1:length(Solar);
    I =Solar(i);
    T0=273+Temp(i);
    xa=xair(i);
   x0 = [298 298 298 298  0];
[x,fval,exitflag] = fsolve(@SteadyPlantsEqn,x0);
```

```
X(:,i) = x;
end
figure
plot(IST,X(1,:)-273,'k','LineWidth',2);
hold on
plot(IST,X(2,:)-273,'g','LineWidth',2);
plot(IST,Temp,'LineWidth',2);
legend('Plants (Tp)','Inside air (Ti)','Ambient(T0)');
xlim([0  23]);
str = {'With Plantation','Air change =1kg/s'};
text(1,30,str,'FontSize',28)
xlabel('Time of the day(h)','FontSize',34);
```

8 Appendix - II

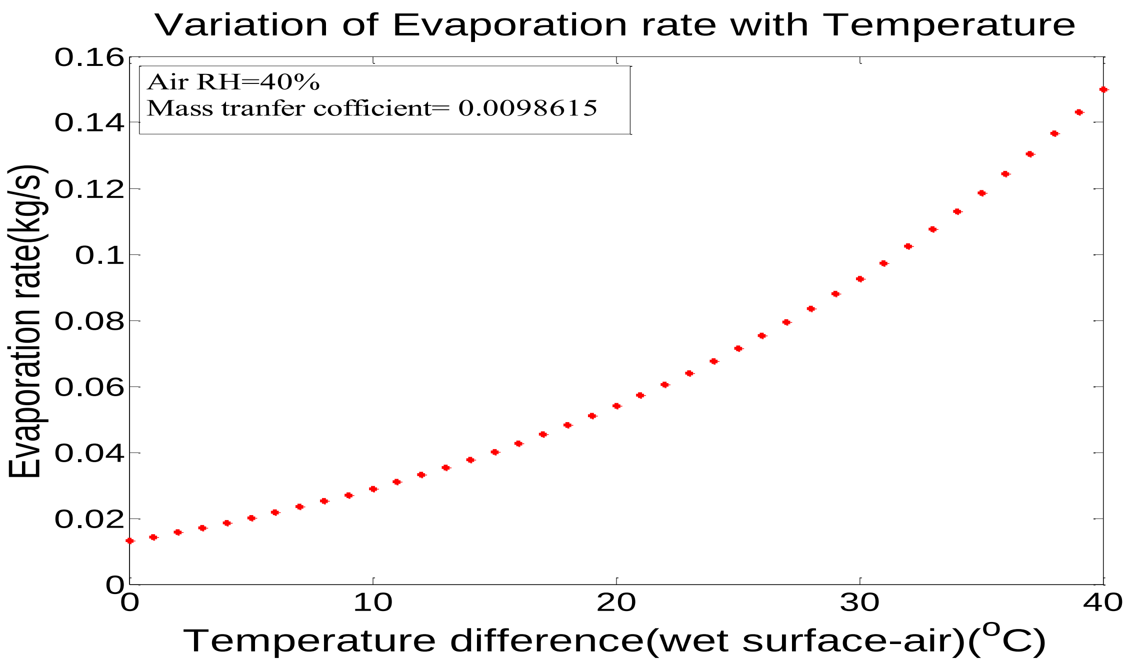

Figure 37: Variation of evaporation rate with Temperature difference between surface and ambient

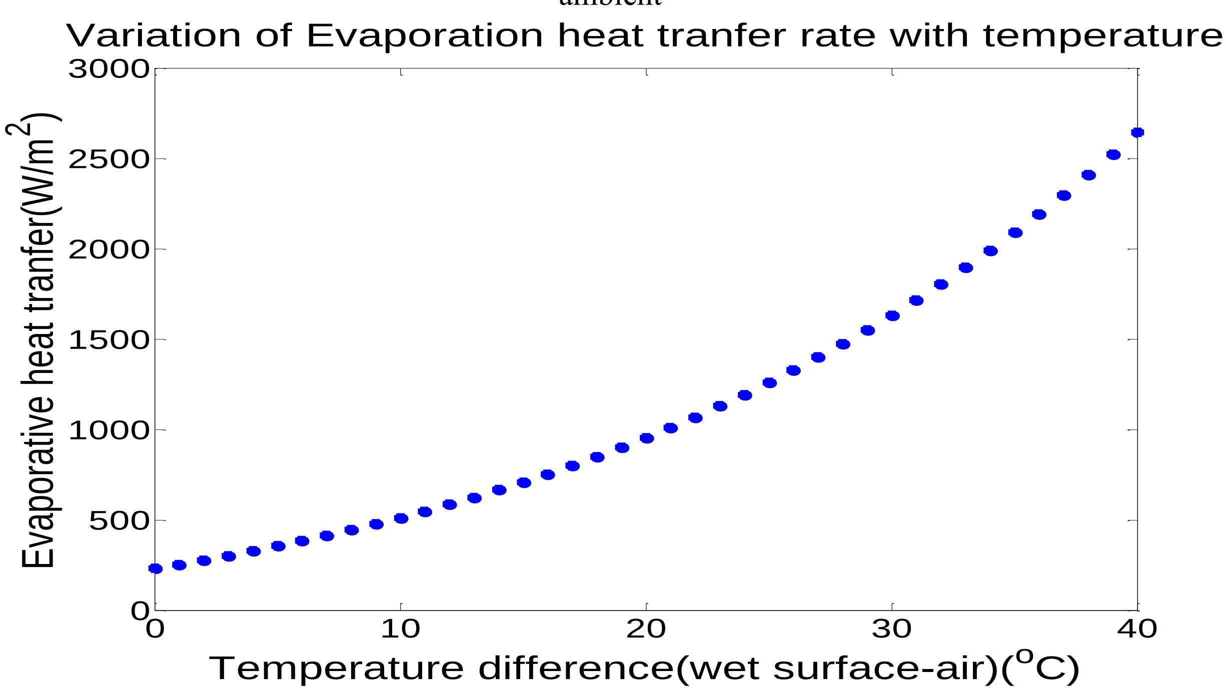

Figure 38: Variation of evaporation heat with Temperature difference between surface and ambient

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