International Journal of Systems Science and Applied Mathematics
2023; 8(3): 31-44
http://www.sciencepublishinggroup.com/j/ijssam
doi: 10.11648/j.ijssam.20230803.11
ISSN: 2575-5838 (Print); ISSN: 2575-5803 (Online)

Numerical Model for the Convective Heat and Mass Flow for the Internal Climate of Greenhouse

Dickson Kande, Titus Rotich, Fredrick Nyamwala

Department of Mathematics, Physics and Computing, Moi University, Eldoret, Kenya

Email address:
kandesnr@gmail.com (Dickson Kande), drrotich@mu.ac.ke (Titus Rotich), foluoch2000@yahoo.com (Fredrick Nyamwala)

To cite this article:
Dickson Kande, Titus Rotich, Fredrick Nyamwala. Numerical Model for the Convective Heat and Mass Flow for the Internal Climate of Greenhouse. *International Journal of Systems Science and Applied Mathematics*. Vol. 8, No. 3, 2023, pp. 31-44.
doi: 10.11648/j.ijssam.20230803.11

Received: May 20, 2023; **Accepted**: June 12, 2023; **Published**: October 9, 2023

Abstract: In the last three decades, sub-division of farming land for settlement coupled with climatic variability and changes has presented a threat to food security by affecting the annual rainfall cycles, soil moisture and production. This called for responsive strategies in terms in order to deal with the threats posed where one of them is greenhouse farming where more favorable temperatures are obtained by applying the appropriate control methods. With this in mind, researchers of this paper aimed to improve the current and increase greenhouse farming in the Central Kenya region which has been one of the country's food baskets and has been greatly affected. In a greenhouse, heat and mass transfer, is mainly through convection where convection is used to refer to the sum of advection and diffusion transfer. Ventilation is one of the most important components for the success of a greenhouse as it regulates the temperature, humidity and vapor pressure deficit to the required levels. To achieve this, controlled ventilation was adopted to provide right amount of dry air to sustain the evaporative cooling rate, without causing an unwanted rise in vapor pressure deficit and air temperature. The greenhouse is a dynamic controllable system implemented in either cold or hot regions to provide a specific climate conditions for the plants, where they will not grow optimally. The micro-climate parameters in a greenhouse are mainly the air temperature and the relative humidity which can be predicted by conducting experiments or by simulation. In relation to convection heat and mass transfer inside a greenhouse, this is required for two reasons: to regulate the greenhouse temperature and to remove water vapor transpired by the plants. A mathematical model which is a mathematical description of properties and interactions in the system is developed for the greenhouse under study. This paper implemented an RKM4 model of convective heat and mass transfer for ventilation and cooling systems inside a greenhouse based on the governing equations of fluid dynamics.

Keywords: Greenhouse, Model, Ventilation, Systems, Runge-Kutta Methods, Heat Transfer, Mass Transfer

1. Introduction

Agriculture has continued to be the mainstay of the Kenyan economy with an estimated gross domestic product share of 25.9% making it an important contributor to both employment and food security of rural households. Climate change has significantly affected global agriculture in the twenty-first century and the Inter-Governmental Panel on Climate Change assessment report indicates that most countries will experience an increase in average temperature, more frequent heat waves, more stressed water resources, desertification, and periods of heavy precipitation. These climatic variability and change have also posed a threat to food security in Kenya by effecting the rainfall patterns, temperature variations and crop production which in turn affect agricultural production and food security given that most of the population in Kenya lives in the rural areas and relies on agriculture for its livelihoods. This is made worse by the fact that agriculture is predominantly rain-dependent with the smallholder farmers, being the hardly hit by the climatic and environmental hazards as their options for diversifying their resources and income sources are limited. This calls for clear response strategies in terms of mitigation and adaptation in order to deal with the threats posed by climate change. In order to counter the above mentioned challenges, National Climate Change Response Strategy has proposed the adaptation such as irrigation systems and dykes and greenhouse farming [1].

Inside greenhouses more favorable temperatures are attained by applying the appropriate control methods. It is with this idea that the researchers of this paper use to improve the current and increase greenhouse farming in the Central Kenya region which has been the food basket for Kenya in the past but in recent decades it has been affected by temperature changes. The greenhouses are built to gather light and to trap the considerable heat contained in sunshine. They are so efficient at retaining some solar energy, that without specialized ventilation and cooling equipment, they will quickly fry a crop during high light periods. The actual temperature of any given leaf in the greenhouse depends upon the surrounding air temperature, the relative moisture content of the air, and whether or not it is in the direct rays of the sun. The cooling effect of evapotranspiration is central to the ability of plants to regulate their tissue temperatures. When plants evaporate water into the surrounding air, they modify the properties of the air and an exchange with outside air regulates the internal temperature and moisture content, [3-5].

However, one can often strike a balance between the need for sufficient light for plant growth and the need to control potentially damaging temperatures by blocking, filtering, and reflecting incoming light on the outside of the greenhouse covering, or by using fixed or retractable shade materials inside the greenhouse, Figure 1. Extremely high light levels can actually stop or slow down photosynthesis if plants are forced to restrict air and moisture exchange from the leaves to conserve water and avoid wilting. Therefore, shading of the greenhouse is beneficial, resulting in a net gain in photosynthesis and continued healthy plant growth. The ventilation of the greenhouse is required to remove heated air and to introduce drier air for evaporative cooling. The ventilation system applied should be designed to remove heat evenly from all parts of the greenhouse. In areas with extremely high temperatures and very dry air, it may be possible to maintain cooler air temperatures than outdoors by taking advantage of the combined effects of evaporative cooling equipment and crop transpiration, [3, 4].

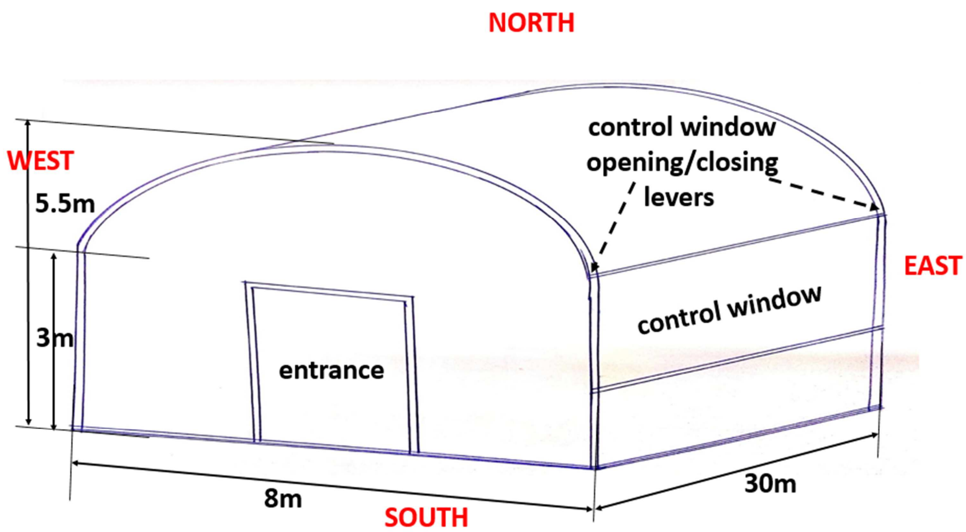

Figure 1. *Dimensions of the greenhouse under study.*

Heat transfer is thermal energy in transit due to a spatial temperature difference while mass transfer is the flow of molecules from one body to another when these bodies are in contact or within a system consisting of two components when the distribution of materials is not uniform mainly due to concentration difference. In a greenhouse, HMT, mainly occur through convection which is the movement of groups of molecules within fluid either by diffusion or by advection. Inside the greenhouse, heat fluxes supplied are due to condensation of water vapor on the cover, from solar radiation and heat fluxes exchanged during ventilation, and as a result of plant transpiration. Most of convective heat fluxes exchanging between different parts of the greenhouse and the air inside the greenhouse depend on the heat transfer coefficients and the temperature difference between the elements surface and the air. Mass transfer due to ventilation can take place in both directions depending on the conditions inside and outside the greenhouse, [2, 5, 6].

When the modeling has been done, the equations governing the mathematical model are then solved to obtain the required solution. For highly detailed models, computer programs are required to determine the solutions. Simulation is the application of a model with the objective to derive strategies that help solve a problem or answer a question pertaining to a system. In the analysis, assumptions are usually made to simplify the model which usually affects the accuracy of the response of the model. Model of a system can be divided into number of blocks as shown by Figure 2, which in itself are complete systems where the blocks have some relevance to main system and each block should be accurate and tested independently before they are integrated together. In mathematics, a dynamic system is a system in which a function describes the time dependence of a point in a geometrical space. At any given time, proper control system design is one of the most important objectives of system dynamics, [7, 9].

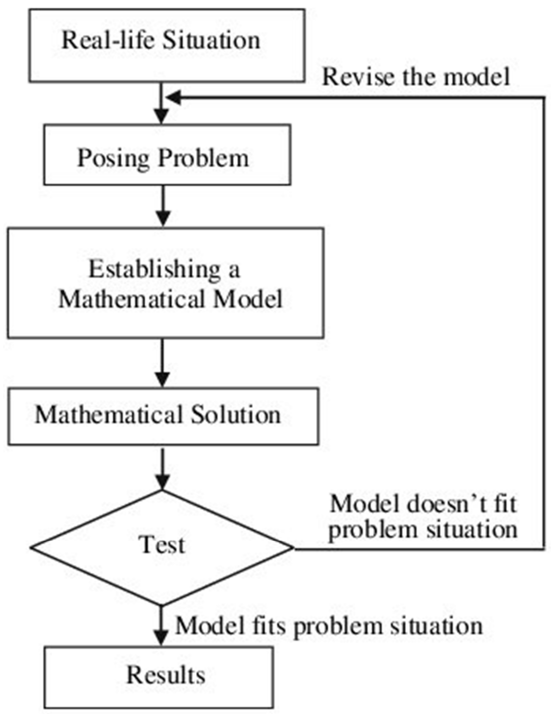

Figure 2. *Schematic representation of the Modeling process.*

Micro-climate in the greenhouse is due to combination of complex mechanisms involving HMT processes occurring inside the greenhouse and between the interior and the surroundings. The formulation of mathematical models for the heat and mass balances in the greenhouse are dynamic systems where inputs can be controlled to produce the intended outputs. The model was tested for many indoor climate conditions that could be simulated before the greenhouse were constructed guided by the authors [10, 12].

The study aimed to develop an RKM4 model for the internal temperature and humidity in a greenhouse and then determine the numerical solutions of the CHMT inside the greenhouse that would favor maximum yields of some selected crops. During the formulation of a mathematical model of these processes, equations of heat and mass balances for the air inside the greenhouse should be formulated [9, 10, 12, 17]. Micro-climate in the greenhouse was the result of combination of complex mechanisms involving processes of CHMT which produced highly non-linear equations. To simplify the model, the following simplifying assumptions were made: the flow of the gases and vapors inside the greenhouse is assumed to be incompressible and lamina, due to the lack of empirical data no effect of energy loses was neglected, the impact of the ground on the HMT was neglected, and the evaporation from the greenhouse cover and crops was neglected, because in modern greenhouses a condensate is drained from the cover.

2. Literature Review

The dynamic behavior of the micro-climate inside a greenhouse is a combination of physical processes involving energy transfer and mass balance. The internal processes depend on the outside environmental conditions, structure of the greenhouse, type and state of the crop, and on the effect of the control actuators. The internal greenhouse climate is a function of air temperature, water content in the air, carbon dioxide concentration in the air, temperatures of the outer and inner surface of the cover, crop temperature, soil surface temperature, and temperature of each of the layers in which the soil is divided. Besides the climatical variables, in modeling greenhouse climate one has to consider the presence or absence of installed actuators that constitute the inputs to the system and that can be artificially manipulated. In models of the greenhouse, principle of continuity between its elements applies, so that the HMT processes in each can be studied using mass and energy equations, [3, 7, 10].

Agricultural greenhouse aims to create a favorable micro-climate to the requirements of growth and development of culture, from the surrounding weather conditions, produce according to the cropping calendars fruits, vegetables and flower species out of season and widely available along the year. The greenhouse is a very confined environment, where multiple components are exchanged between key stakeholders and those factors are light, temperature and relative humidity. So, there is a necessity to carry out in deep investigation on the design aspects of greenhouse and its functional characteristics influence on micro-climate. This information is useful for the researchers' work on the engineering aspects of greenhouse technology [9, 13, 19].

The advancement of technology has allowed the development of greenhouses so that they become increasingly sophisticated and of an industrial nature. As a result, the greenhouse growers prefer these new technologies while optimizing the investment in the field to effectively meet the supply and demand of these fresh products cheaply and widely available throughout the year. These were the observations made by the research [11] while Druma, A. M. [23] presented a dynamic model of a greenhouse in order to predict the air temperature and the relative humidity. In a different paper, in order to maintain a steady climate [15] used intelligent greenhouse climate controller designed using fuzzy logic programming. In order to visualize the evolution of climatic parameters in real time, an analysis of boundary conditions for greenhouse climate was done by Dwyer, D. [16] while Rodríguez, F., et al. [20] performed a greenhouse simulation by Dymola and Baptista, F. et al. [22] performed a validation of dynamic model.

In another research, the author [21] performed a temperature model of greenhouse and the research [18] developed CFD model for HMT in greenhouse for a wide range of climate condition. According to the Inter-Governmental Panel on Climate Change, climate change has resulted to increased frequency and intensity of natural disasters and extreme weather conditions. This climate change has consequently affected food security in several respects. With this in mind, this research work by the author [1] targeted increased greenhouse farming in Kenya as one of the remedies.

2.1. Energy and Mass Balances

2.1.1. Convective Heat Transfer

Convective heat transfer, often referred to simply as convection, is the transfer of heat from one place to another by the movement of fluids. Although often discussed as a distinct method of heat transfer, convective heat transfer involves the combined processes of unknown conduction and advection. In addition to energy transfer due to specific molecular motion, energy is transferred by bulk, or macroscopic, motion of the fluid. This motion is associated with the fact that, at any instant, large numbers of molecules are moving collectively or as aggregates. Such motion, in the presence of a temperature gradient, contributes to heat transfer. Because the molecules in aggregate retain their random motion, the total heat transfer is then due to the superposition of energy transport by random motion of the molecules and by the bulk motion of the fluid. It is customary to use the term convection when referring to this cumulative transport and the term advection when referring to the transport due to bulk fluid motion, shown in Figure 3, [7, 15, 19, 23].

2.1.2. Convective Mass Transfer

Mass transfer between a moving fluid and a surface or between immiscible moving fluids separated by a mobile interface is often aided by the dynamic characteristics of the moving fluid. This mode of transfer is called convective mas s transfer, with the transfer always going from a higher to a lower concentration of the species being transferred. Convective transfer depends s on both the transport properties and the dynamic characteristics of the flowing fluid. As in the case of convective heat transfer, a distinction must be made between two types of flow. When an external pump or similar device causes the fluid motion, the process is called forced convection. If the fluid motion is due to a density difference, the process is called free or natural convection shown in Figure 3, [7, 17, 23].

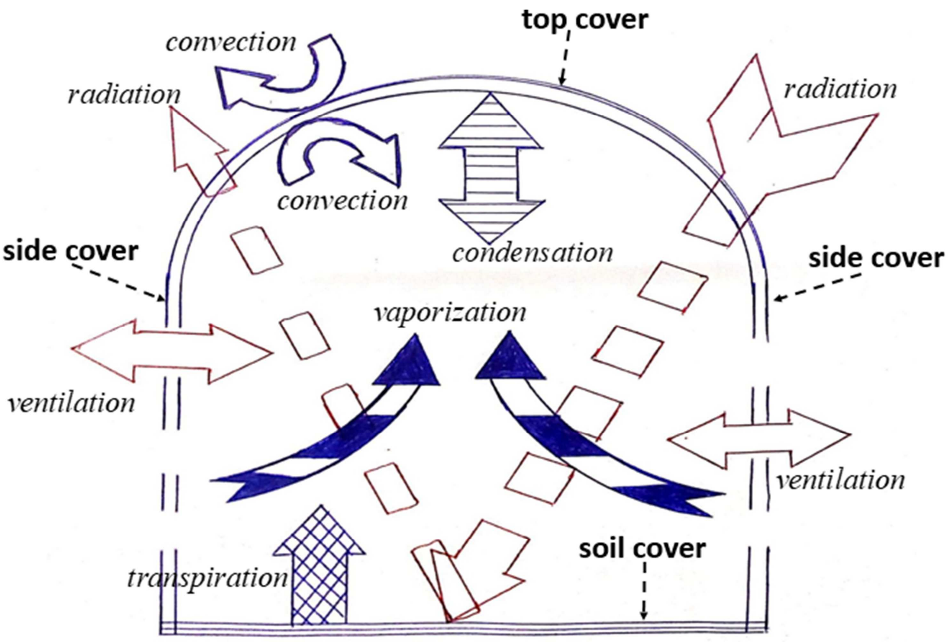

Figure 3. *Modes of heat and mass exchange inside and outside a greenhouse.*

2.2. Structural Requirements

Greenhouse ventilation is required to regulate temperature and moisture levels and provide carbon dioxide for good crop production. There are two basic ventilation systems used in greenhouse production systems, natural and mechanical ventilation systems. Natural ventilation depends upon normal air movement created by wind pressures or by gradients induced by differences in air temperature between the growing area and the outside environment. Mechanical ventilation is defined as air movement created by fans that bring air into the growing area through controllable openings built into the greenhouse walls and exhaust it through the fan assembly. The ability to change the size of inlets is important for proper design of mechanical ventilation systems. Fan ventilation is normally controlled by thermostats and in some cases by humidity sensing devices when relative humidity is the control parameter, [6, 13, 17].

There are two primary reasons airflow is necessary in greenhouses: to remove excess heat through ventilation as the temperature rises, replacing hot air with cooler air, and to control relative humidity and carbon dioxide within the plant canopy. A single system can serve both needs in smaller greenhouses, while separate exhaust and circulation systems are common in larger-sized greenhouses. Separate systems need to be carefully coordinated and adjusted to work together instead of counteracting each other Air movement systems range from simple, do-it-yourself arrangements to professionally designed, installed and integrated computer controlled systems, [13, 16, 19].

2.3. Mathematical Modeling of Greenhouses

The micro-climate in the greenhouse is mainly controlled to achieve maximum plant production and should be monitored closely. The intrinsic greenhouse features are complex, thus, the setting and tuning of greenhouse climate controllers is a very difficult procedure. A large number of greenhouse controller settings make it difficult to foresee its influence on the results and the costs involved. The dynamic behavior of the greenhouse micro-climate is a combination of HMT balance. These processes depend on the environmental conditions, structure of the greenhouse, type and state of the crop, and on the effect of the control actuators, [20, 21, 23].

3. Materials and Methods

To promote good growth of plants, greenhouses, require either heating or cooling depending with the climatic conditions of the region they are, but equally important they require ventilation during hot days. In relation to CHMT inside a greenhouse, this is required for two reasons: to regulate the internal temperature and to remove water vapor transpired by the plants which are done through ventilation, caused by pressure differences or natural buoyancy forces through ventilators located either on top, on the sides, or both. Air movement and mixing within the greenhouse has a direct influence on the energy exchange of the vegetation. Therefore, it is important that the ventilators are designed correctly and the rate of ventilation controlled adequately. Cultivation technologies are developing with time aiming to lower the cost of production as they gain widespread acceptance and this drives the needs for a knowledge-rich information technology as we move from the information age to a knowledge-driven society. This have increased the efforts based on modern communication technologies to provide the missing bridge from the expert teams or knowledge bases to the low-level controllers of the production side, [7, 10, 24, 27, 28, 33].

In this thesis, the understanding of transport mechanisms leading to the estimation of energy and mass balances of the greenhouse system was very important. The study involved the solar radiation, exchange by convection between the plants, structural parts and the internal and external air, latent heat produced by condensation and vaporization of the water inside and the exchange through evapotranspiration process of the plants inside. The processes of thermal energy exchange among the greenhouse, the surroundings, and the greenhouse components are illustrated in Figure 3, [2, 5, 7, 10, 25].

3.1. Modes of CHMT Gases and Vapor Inside the Greenhouse

The dynamic behaviour of the micro-climate inside greenhouses is a combination of physical processes involving energy transfer and water vapour fluxes. These processes depend on the outside environmental conditions, structure of the greenhouse, type and state of the crop and on the effect of the control actuators, [2, 12, 16, 33].

For successful growing of plants inside greenhouses, climate variables like temperature, humidity and carbon dioxide concentration need to be studied carefully. These environmental factors are not possible to change but their effects can be altered. The idea behind greenhouses farming is to alter these environmental factors of a small enclosed region to favor growth of plants that can otherwise not be grown in the original state of these factors. The Table 1 shows some plants and the environmental factors that favors their optimum yields.

Table 1. *Plants and the environmental factors that favor their optimum yields.*

Plant	Temperature range	Relative humidity range
Tomato	17 – 22°C	65 - 75%
Kale	17 – 22°C	70 - 80%
Cabbage	15 - 20°C	70 - 80%
Strawberries	15 - 23°C	64 - 77%
Grapes	15 - 30°C	60 - 70%
Peas	12 - 24°C	70 - 80%

3.1.1. Temperature

Air temperature influences the energy balance of the plant canopy through the convective heat transfer to the plant leaves and bodies and this affect air movement in the greenhouse. The optimal level of the air temperature in the greenhouse depends on the photosynthetical activity of the plant in question, under the influence of the intensity of solar radiation on disposal, that is, for each light intensity, there is an optimal air temperature, enabling maximum photosynthetical activity, Figure 4, [7, 22, 27].

3.1.2. Humidity

Water transport between the plant canopy and the environment is one of the most important parameters of the photosynthetical activity. The water vapour transport depends mainly on light intensity at disposal, temperature of the environment, and root characteristics of the plant in question in combination with the ability of the cultivation base to offer the necessary water quantity, but also on the air humidity of the plant environment. The air humidity influences the greenhouse climate characteristics and transpiration of the plant leaves. The intensity of the water transport of the plants depends directly on the temperature inside the greenhouse, Figure 5, [4, 25, 28].

3.2. Numerical Model

As internal air diffuses from one point to another inside the greenhouse, it moves with the energy it possesses resulting to heat flow rate which constitute the CHMT. The Figures 7 and 8 show the convective heat and mass flow of a mixture of components making the greenhouse air, while figure 1 represent a diagrammatic view of the sample greenhouse under study, [6, 7, 17].

3.2.1. Heat Transfer Equation

The amount of heat balance in the greenhouse is a multidimensional quantity consisting of heat transfer and mass exchange to and from the greenhouse environment. The parameters involved in the physical process of the greenhouse are in an energy balance with the environment and, all together, are in an energy balance with the greenhouse environment. The heat balance according to Figure 7 can be expressed as equation (1), [6, 7, 33].

$$\rho C_p V \frac{dT_{in}}{dt} = Q_{total} = \left(Q_{rad}+Q_{trp}\right) - \left(Q_{cnv}+Q_{cond}+Q_{ven}+Q_{vap}\right) \quad (1)$$

Where, Q_{total} net heat flux supplied into the greenhouse in Js^{-1}, Q_{in} total heat flux entering into the greenhouse from the outside in Js^{-1}, Q_{out} total heat flux leaving the greenhouse to the outside in Js^{-1}, Q_{rad} heat flux supplied from solar radiation in Js^{-1}, Q_{trp} heat flux of transpiration in Js^{-1}, Q_{cnv} heat flux exchanged between interior air and greenhouse cover in Js^{-1}, Q_{cond} heat flux supplied by condensation in Js^{-1}, Q_{ven} heat flux exchanged through the ventilation in Js^{-1} and Q_{vap} heat flux exchanged through the ventilation in Js^{-1}.

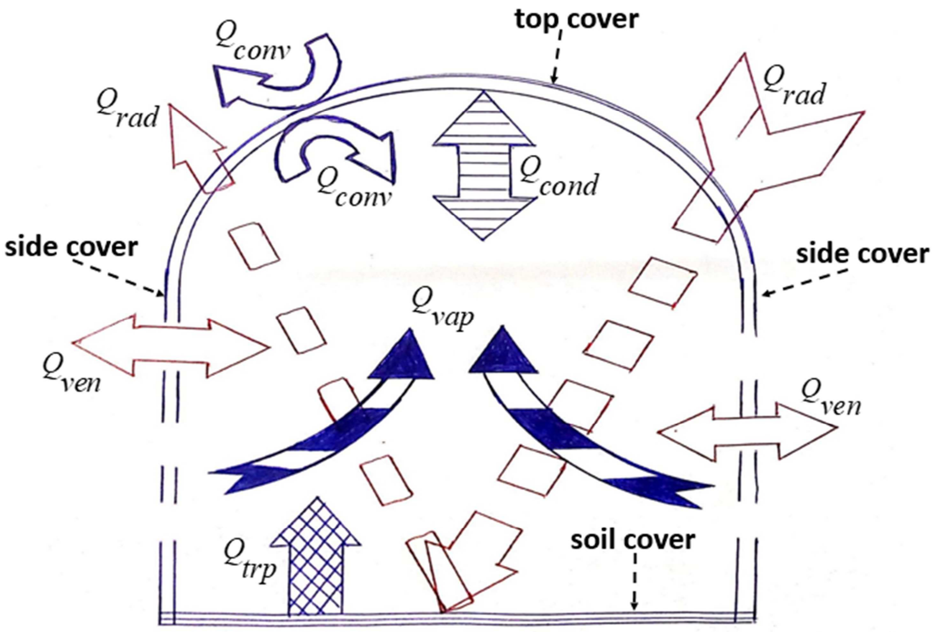

Figure 4. *Heat transfer fluxes with the internal air in a greenhouse.*

Solar radiation is one of the most important environmental factors for plant growth and is received at the earth's surface depending on the season because of the geographical relationship between the sun and the earth. For calculation, the following simplified equation (2) was derived by the authors:

$$Q_{rad} = \tau_{air} I_{air} A_{gh} \quad (2)$$

Where, I_{air} solar radiation density in Wm^2, τ_{air} transmissivity of the greenhouse covering materials for solar radiation and A_{gh} area of the cover of the greenhouse in m^2.

Transpiration is assumed to occur from sub-stomatal cavities in the leaves of vegetation and or from below the soil surface. The heat exchange due to it can be estimated by equation (3), [6, 7, 33]:

$$Q_{trp} = \frac{\lambda\alpha}{L_{air}(\lambda+\gamma)}\left[(1-\alpha)\tau_{air}I_{air}A_{gh} - \left(\frac{0.16\kappa\rho C_p (T_{in}-T_{out})}{r}\right)\right] \quad (3)$$

Where, λ is slope of saturation vapor pressure curve at air temperature in PaK^{-1}, α is Priestley-Taylor coefficient, ρ is air density inside the greenhouse in kgm^{-3}, γ is Psychrometric constant in PaK^{-1}, C_p *is s*pecific heat of air inside the greenhouse in $Jkg^{-1}K^{-1}$, L_{air} is latent heat of vaporization in Jkg^{-1}, T_{in} *and* T_{out} are air temperature inside and outside the greenhouse in K respectively, r is radiative resistance, *K is u*nit conversion

Equation (4) estimated the convective heat exchange between the air inside the greenhouse and the cover, [6, 7, 33]:

$$Q_{conv} = H_{conv} A_{gh} \left(T_{in}-T_{out}\right) \quad (4)$$

Where, H_{conv} is heat transfer coefficient of the internal air between the floor and the cover in $Wm^{-2}K^{-1}$

The heat given off by the condensed water vapor inside the greenhouse was calculated using the equation (5), [6, 7, 33]:

$$Q_{cond} = \rho_{wat} L_{sat} m_{cond} \left(H_{in}-H_{out}\right)\left(T_{in}-T_{out}\right) \quad (5)$$

Where, ρ_{wat} is density of water in kgm^{-3}, L_{sat} is latent heat of saturation water in Jkg^{-1}, m_{cond} is mass heat transfer coefficient at the surface of the greenhouse in ms^{-1}, H_{in} and H_{out} are humidities of the air inside and outside the greenhouse in % respectively.

The heat exchange through ventilation is a method of balancing the temperature and humidity of the greenhouse to that of the outside by opening part of the cover either manually or electronically. For this study heat exchange was determined using equation (6) below, [6, 7, 33]:

$$Q_{ven} = G\rho C_p \left(T_{in} - T_{out}\right) \quad (6)$$

Where, G is indoor and outdoor ventilation rate in m^3s^{-1}

Equation to determine amount of heat in vaporization of the internal water content, equation (7), which was a function of pressure and temperature at which the transformation occur, was calculated using the first law of thermodynamics, that is, (Authors):

$$Q_{vap} = C_{vap} A_{floor} u\left(\rho - \rho_{wat}\right)\left(T_{in} - T_{out}\right) \quad (7)$$

Where C_{vap} is specific heat of water vapour inside the greenhouse in $Jkg^{-1}K^{-1}$, u is rate at which the irrigated water leave the soil surface in ms^{-1} and A_{floor} is area of the floor of the greenhouse plants in m^2.

The convection heat transfer model for greenhouse was represented by an air temperature sub-model of the internal air as the parameters of the convection process between the cover, the greenhouse air and the floor. The inside temperature was thus calculated using equation (8), [6, 7, 33]:

$$\rho C_p V \frac{dT_{in}}{dt} = \tau_{air} I_{air} A_{gh} + \left[\begin{array}{l} \frac{\alpha\lambda(1-\alpha)}{L_{air}(\lambda+\gamma)} \tau_{air} I_{air} A_{gh} - \\ \frac{0.16\kappa\lambda\alpha\rho C_p}{rL_{air}(\lambda+\gamma)}\left(T_{in} - T_{out}\right) \end{array}\right] - H_{conv} A_{gh}\left(T_{in} - T_{out}\right) G\rho C_p \left(T_{in} - T_{out}\right) - \quad (8)$$
$$-\rho_{wat} L_{sat} m_{cond}\left(H_{in} - H_{out}\right)\left(T_{in} - T_{out}\right) - C_{vap} A_{pipe} u\left[\rho - \rho_{wat}\right]\left(T_{in} - T_{out}\right)$$

Which was further simplified as,

$$\frac{dT_{in}}{dt} = A_1\left(T_{in} - T_{out}\right) + A_3\left(H_{in} - H_{out}\right)\left(T_{in} - T_{out}\right) + A_4 \quad (9)$$

Where, V is greenhouse volume in m^3, $A_1 = \frac{1}{\rho C_p V}\left[-\frac{0.16\kappa\lambda\alpha\rho C_p}{rL_{air}(\lambda+\gamma)} - H_{conv} A_{gh} - G\rho C_p - C_{vap} A_{pipe} u\left(\rho - \rho_{wat}\right)\right]$, $A_3 = -\frac{1}{\rho C_p V}\rho_{wat} L_{sat} m_{cond}$ and

$$A_4 = \frac{1}{\rho C_p V}\left[1 + \frac{\alpha\lambda(1-\alpha)}{L_{air}(\lambda+\gamma)}\right]\tau_{air} I_{air} A_{gh}$$

3.2.2. Mass Transfer Equation

Convective mass balance for the internal relative humidity a given ventilation rate and a rate of moisture production for the considered greenhouse was performed. As Figure 5 shows the main sources of vapor in a greenhouse are crop transpiration, evaporation of the soil surface and pools, and water influx by fogging or cooling, [6, 7, 33].

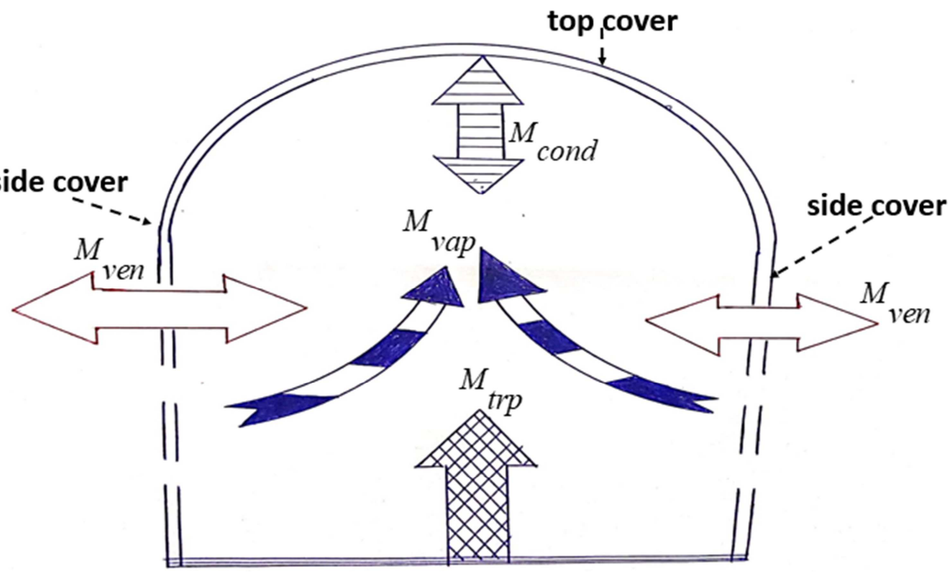

Figure 5. *Mass transfer fluxes with the internal air in a greenhouse.*

The model describing the changes in the water vapor content of the air inside the greenhouse is based on the mass balance equation, equation (10). To evaluate the inside relative humidity, a mass balance calculation was performed using the equation, [6, 7, 33]:

$$V\frac{dH_{in}}{dt} = M_{total} = M_{trp} + M_{vap} - M_{cond} - M_{ven} \quad (10)$$

Where, M_{total} net mass flux content of inside the greenhouse in $kgm^{-2}s^{-1}$, M_{trp} mass flux due to transpiration process in $kgm^{-2}s^{-1}$, M_{vap} mass flux of water vapour from irrigated water in $kgm^{-2}s^{-1}$, M_{cond} mass flux due to condensation process in $kgm^{-2}s^{-1}$ and M_{ven} mass lost flux due to ventilation in $kgm^{-2}s^{-1}$.

Water use during the mass transfer process between the air and water for the evaporative cooler was evaluated by the transpiration of the plants model where in this study, the water evaporation rate in the evaporative cooling system for a given air flow rate through the greenhouse was evaluated by the equation (11) below adopted from work by, [6, 7, 33]:

$$M_{trp} = \frac{\lambda\alpha}{rA_{gh}(\lambda+\gamma)}\left[(1-\alpha)\tau_{air}I_{air}A_{gh} - \left(\frac{0.16\kappa\rho C_p(T_{in}-T_{out})}{r}\right)\right] \quad (11)$$

The amount of water vapor released due to condensation is estimated using the equation (12) below;

$$M_{cond} = \rho_{wat}L_{sat}m_{cond}\left(H_{in}-H_{out}\right)\left(T_{in}-T_{out}\right) \quad (12)$$

M_{vap} was determined from the first law of thermodynamics just like Q_{vap} to get equation (13) below,

$$M_{vap} = A_{floor}u\left(\rho-\rho_{wat}\right) \quad (13)$$

Regulation of the water vapor content of the air inside the greenhouse was also done through ventilation. Since the evaporative cooling process is an adiabatic exchange of heat, the amount of sensible heat removed from the air equals the amount of heat absorbed by the water evaporated as latent heat of vaporization. The amount of moisture transferred from the inside air to the outside air via ventilation was expressed as shown by equation (14), [6, 7, 33]:

$$M_{ven} = \frac{\rho C_p G}{3.52895PA_{gh}}\left(H_{in}-H_{out}\right) \quad (14)$$

The total mass of gases inside the greenhouse was given by the differential equation 15:

$$V\frac{dH_{in}}{dt} = \frac{\lambda\alpha}{rA_{gh}(\lambda+\gamma)}\left[(1-\alpha)\tau_{air}I_{air}A_{gh} - \left(\frac{0.16\kappa\rho C_p(T_{in}-T_{out})}{r}\right)\right] + A_{floor}u\left[\rho-\rho_{wat}\right] - \rho_{wat}L_{sat}m_{cond}\left(H_{in}-H_{out}\right)\left(T_{in}-T_{out}\right) - \frac{\rho C_p G}{3.52895PA_{gh}}\left(H_{in}-H_{out}\right) \quad (15)$$

Which was further written as,

$$\frac{dH_{in}}{dt} = B_1\left(T_{in}-T_{out}\right) + B_2\left(H_{in}-H_{out}\right) + B_3\left(H_{in}-H_{out}\right)\left(T_{in}-T_{out}\right) + B_4 \quad (16)$$

Where, $B_1 = -\frac{0.16\kappa\rho C_p V\lambda\alpha}{r^2 A_{gh}(\lambda+\gamma)}$, $B_2 = -\frac{V\rho C_p G}{3.52895PA_{gh}}$, $B_3 = -V\rho_{wat}L_{sat}m_{cond}$ and $B_4 = V\left\{\frac{\lambda\left(\alpha-\alpha^2\right)Q_{rad}}{rA_{gh}(\lambda+\gamma)} + A_{floor}u[\rho-\rho_{wat}]\right\}$.

3.3. Numerical Solutions of the CHMT Model Inside the Greenhouse That Would Favor Maximum Yields

The climate produced in a greenhouse is the result of complex mechanisms involving the processes of heat and mass exchange. The internal climate is also strongly dependent on the outside conditions, especially in unheated greenhouses. In greenhouse climate models the parameters of the internal climate such as air, soil and crop temperatures, and air humidity are calculated using energy and water vapor balances for the various components of the system. The dynamic behavior of the microclimate inside a greenhouse is a combination of physical systems involving internal heat transfer and mass balance. The HMT coefficients are functions of the system variables and it is important that they are formulated under relevant conditions of the greenhouse situation. Further, greenhouse climate models are specific for a greenhouse type, crop, region and weather conditions and the models are formulated and validated for those specific conditions and it is not possible to directly extrapolate them to different conditions, since they may produce erroneous predictions; thus the need for a model to be formulated for the current geographical location, the Central Kenya region, shown by the pair of equations (17).

$$\left.\begin{aligned}\frac{dT_{in}}{dt} &= A_1(T_{in}-T_{out}) + A_3(H_{in}-H_{out})(T_{in}-T_{out}) + A_4\\ \frac{dH_{in}}{dt} &= B_1(T_{in}-T_{out}) + B_2(H_{in}-H_{out}) + B_3(H_{in}-H_{out})(T_{in}-T_{out}) + B_4\end{aligned}\right\} \quad (17)$$

Where A_i and B_i for $i=1,2,3,4$ are the air climate parameters inside the greenhouse.

In this part, the RKM4 for solving the systems of the DE for the model was developed. RKM4 was developed by expansion of the Taylor method of order 4 and then rearranging the terms got to get recursive formulas.

3.4. Numerical Solutions of the CHMT Model Inside the Greenhouse

The RKM4 used to solve for the governing DE for the model equations (17) was developed consisting of variables and parameters using the formula (18) and (19) below to give the internal temperatures and the corresponding internal humidity as shown;

$$\left.\begin{array}{l} fT\_in = @(t, T\_in, H\_in) \quad A1*(T\_in - T\_out) + \\ \qquad A3*(T\_in - T\_out)*(H\_in - 0.5) + A4; \\ \\ fH\_in = @(t, T\_in, H\_in) \quad B1*(T\_in - T\_out) + B2*(H\_in - H\_out) + \\ \qquad B3*(T\_in - T\_out)*(H\_in - H\_out) + B4; \end{array}\right\} \quad (18)$$

And the RKM4 recursive formulas to solve the system (18) were developed as represented by formula (19) below;

$$\left.\begin{array}{l} K1T\_in = fT\_in(t(i), T\_in(i), H\_in(i)); \\ L1H\_in = fH\_in(t(i), T\_in(i), H\_in(i)); \\ K2T\_in = fT\_in(t(i)+h/2, T\_in(i)+(h/2)*K1T\_in, H\_in(i)+(h/2)*L1H\_in); \\ L2H\_in = fH\_in(t(i)+h/2, T\_in(i)+(h/2)*K1T\_in, H\_in(i)+(h/2)*L1H\_in); \\ K3T\_in = fT\_in(t(i)+h/2, T\_in(i)+(h/2)*K2T\_in, H\_in(i)+(h/2)*L2H\_in); \\ L3H\_in = fH\_in(t(i)+h/2, T\_in(i)+(h/2)*K2T\_in, H\_in(i)+(h/2)*L2H\_in); \\ K4T\_in = fT\_in(t(i)+h, T\_in(i)+h*K3T\_in, H\_in(i)+h*L3H\_in); \\ L4H\_in = fH\_in(t(i)+h, T\_in(i)+h*K3T\_in, H\_in(i)+h*L3H\_in); \\ \\ T\_in(i+1) = T\_in(i) + (h/6)*(K1T\_in + 2*K2T\_in + 2*K3T\_in + K4T\_in); \\ H\_in(i+1) = H\_in(i) + (h/6)*(L1H\_in + 2*L2H\_in + 2*L3H\_in + L4H\_in); \end{array}\right\} \quad (19)$$

Where *K1, K2, K3* and *K4* were the RKM4 constants to solve for T_in while *L1, L2, L3* and *L4* are the RKM4 constants to solve for H_in and h was the time-step. This was then followed by a MATLAB (Appendix II) code for (18) and (19) was then developed to determine the numerical solution for the model.

4. Results and Discussion

The solution of high temperatures inside the greenhouse was based on decreasing the energy inputs and eliminating their excesses; in cases where heating is used, the artificial energy input is eliminated by turning it off while to decrease natural inputs, solar radiation was minimized by means of shading, inside or outside the greenhouse. The increase in energy losses was achieved with ventilation, natural and forced, as a first step. Every ventilation system is used to regulate the interior air temperature to the value of the outside air if the renewed air has the same humidity which in many cases is not enough to achieve acceptable thermal levels inside the greenhouse when the external air temperature is not excessive. If the interior temperature must be further decreased, active cooling methods are usually applied. At plant level, the first measure to limit high temperatures was to irrigate properly, so that the plants could transpire to the maximum and decrease their temperature, complemented by efficient air renewal through ventilation. Ventilation is the air exchange between the greenhouse and the exterior through the greenhouse openings, vents and slits. The air renewal allows the evacuation of the excess heat and a decrease in the air temperature, modifying the atmospheric humidity, and modifying the gas composition of the atmosphere. If the air leaving the greenhouse is dry, the energy evacuated is very limited due to the low specific heat of dry air, while if it's humid, the temperature decrease will be much higher, as the energy evacuated with the humid greenhouse air is much bigger. Therefore, the humidity difference between the interior and exterior is more important than the temperature difference, for greenhouse cooling purposes, [22, 25, 27].

4.1. Modes of CHMT Gases and Vapor Inside a Greenhouse

With the advent of sophistication in greenhouse technology, their computerization has become a necessity. This has created a new opportunity to manipulate internal climatical parameters, mainly temperature and humidity; which were the target for study in this research work. The designed CHMT model was composed the system of DE, (17) related to the greenhouse temperature and humidity of internal air.

4.1.1. Temperature

The internal temperature is the most important climate parameter inside the greenhouse and it influences all the other parameter under this study. In order to control the internal temperature, temperature sensors and control windows opening and closing auto-levers were used in order to open and close the control windows with temperature variations. This process was assimilated as a single process.

4.1.2. Humidity

The internal humidity on the other hand was controlled by humidity sensors coupled with the control windows opening and closing auto-levers just like the temperature. The internal temperature and humidity were therefore set to be controlled simultaneously with time and the external parameters as the unifying factors.

4.2. Numerical Solutions of the CHMT Model Inside the Greenhouse That Would Favor Maximum Yields

Numerical methods are techniques by which mathematical problems are formulated using DE and then solved with arithmetic operations. Although there are many kinds of numerical methods, they have one common characteristic: they invariably involve large numbers of tedious arithmetic calculations. Numerical computations of the governing equations were performed and a MATLAB code written for proper comparison and validations. The solutions were compared with theoretical parameter values for some selected crops that were intended to be grown in the modeled and simulated greenhouse for the targeted region.

The system of equations (19) was solved by RKM4 to determine values of internal temperature and humidity of the greenhouse subject to the intended crop to be grown and the external climatical conditions and presented by Table 2 below. The numerical values for constants A_i and B_i were calculated using Appendix as follows:

Table 2. *Numerical solutions for internal Temperature and Humidity in the greenhouse.*

Crop to be planted	Average required Temperature	Average required Humidity	Model Calculated T_{in} in °C	Model Calculated H_{in} in %
Tomato	19.5	70.0	19.5004	70.0000
Kale	19.5	75.0	19.5003	75.0000
Cabbage	17.5	70.0	17.5003	70.0000
Strawberry	19.0	70.5	19.0003	75.5000
Grapes	22.5	65.0	22.5004	65.0000
Peas	18.0	75.0	18.0003	75.0000

4.3. Comparisons of Results

In this part, the simulation and numerical model results, were compared to the theoretical climatical values for some crops to identify which ones can be grown in the modeled greenhouse for optimum yields.

4.3.1. Temperature

Proper temperature and humidity management in the greenhouse begin with reliable climate-control systems. It is advisable to check historical climate data regularly to determine whether your control systems are delivering the desired temperature and that the greenhouse is not cycling too frequently between heating and cooling. The threshold temperature to begin operating natural ventilation for majority of the crops grown in the study region was noted to range between 15°C and 30°C, and with maturity age of 3 to 4 months. Table 3 represent comparison of the numerically calculated and the theoretical temperature distribution for the crops targeted to be planted in the region studied using equation (17).

Table 3. *Comparison of the numerically calculated and the theoretical temperature distribution for the crops targeted to be planted in the region studied.*

T_{out} in °C	Average required Temp	Model Calculated T_{in} in °C	Error / Absolute Difference
15	19.5	15.00047792	0.00047792
16	19.5	16.00046088	0.00046088
17	17.5	17.00043748	0.00043748
18	19.0	18.00042315	0.00042315
19	22.5	19.00041634	0.00041634
20	18.0	20.00039715	0.00039715
21	17.5	21.00038531	0.00038531
22	22.5	22.00036882	0.00036882
23	17.5	23.00034890	0.00034890
24	18.0	24.00033533	0.00033533
25	19.5	25.00032685	0.00032685
26	17.5	26.00032277	0.00032277
27	19.0	27.00032277	0.00032277
28	18.0	28.00031879	0.00031879
29	22.5	29.00031879	0.00031879
30	22.5	30.00031879	0.00031879

4.3.2. Humidity Management

The air's moisture-holding capacity is directly related to temperature. When temperature is low, humidity due to transpiration decreases and nutrients that moves via transpiration decreases. The greenhouse air is close to humidity saturation and as the walls are colder, water condenses on them first. Later, condensation will occur in other parts of the greenhouse and even on the coldest parts of the plants such as the stems and fruits. A small opening of the vents will evacuate a large amount of the air saturated with humidity, decreasing this condensation. For the region studied, the air humidity was noted to lie between 65% and 80%, which favored production of majority of the crops. The table 4 below represents comparison of the numerically calculated humidity distribution for the crops targeted to be planted in the region studied using equation (17).

Table 4. *Comparison of the numerically calculated humidity distribution and the theoretical distribution for the crops targeted to be planted in the region studied.*

H_{out} in %	Average required Hum	Model Calculated H_{in} in %	Error / Absolute Difference
54	70.0	53.99994386	5.614E-05
56	75.0	55.99994737	5.263E-05
59	70.0	58.99995047	4.953E-05
61	70.5	60.99995322	4.678E-05
62	65.0	61.99995568	4.432E-05
65	75.0	64.99995791	4.209E-05
67	70.0	66.99995991	4.009E-05
70	65.0	69.99996173	3.827E-05
74	70.0	73.99996339	3.661E-05
77	75.0	76.99996492	3.508E-05
79	75.0	78.99996632	3.368E-05
80	70.0	79.99996762	3.238E-05
80	70.5	79.99996882	3.118E-05
81	75.0	80.99996993	3.007E-05
81	65.0	80.99997097	2.903E-05
81	65.0	80.99997193	2.807E-05

4.3.3. The CHMT Coefficients Gases and Vapor Inside a Greenhouse

The micro-climate inside a greenhouse is described by non-linear and multivariable systems of DE that are highly coupled together making it impossible to accurately control the ventilation processes manually. This research focused on internal temperature and humidity simulation of the greenhouse with the corresponding values and the plant requirements used as base to determine the expected temperature and humidity, [7, 10]. In the study, two greenhouses based in the mountainous cold zone and lowland hot zone of Central Kenya region were studied and their operating greenhouse temperature and relative humidity for two days were measured to error value of 0.1^0C and 5% respectively.

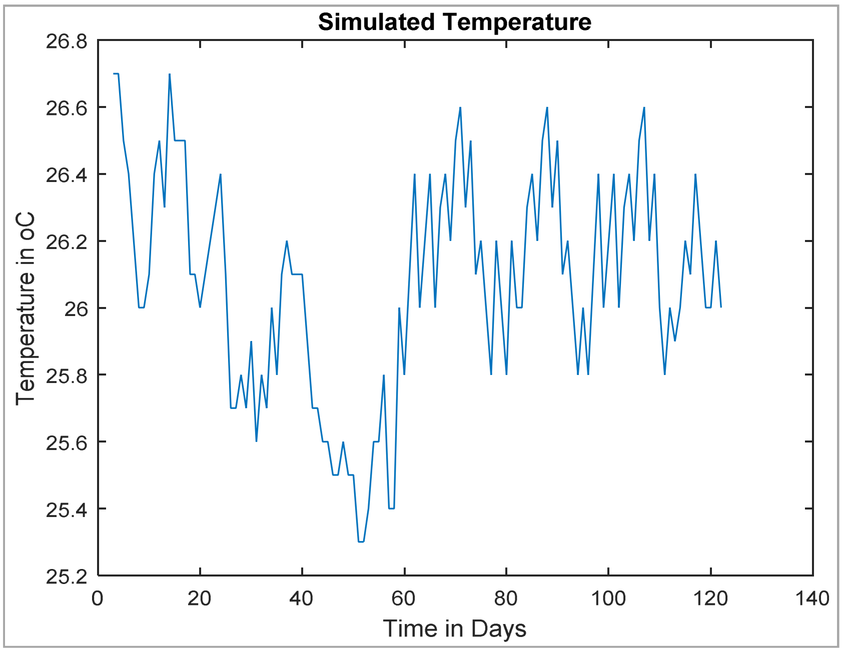

Figure 6. *Graphical representation of the Simulated Temperature.*

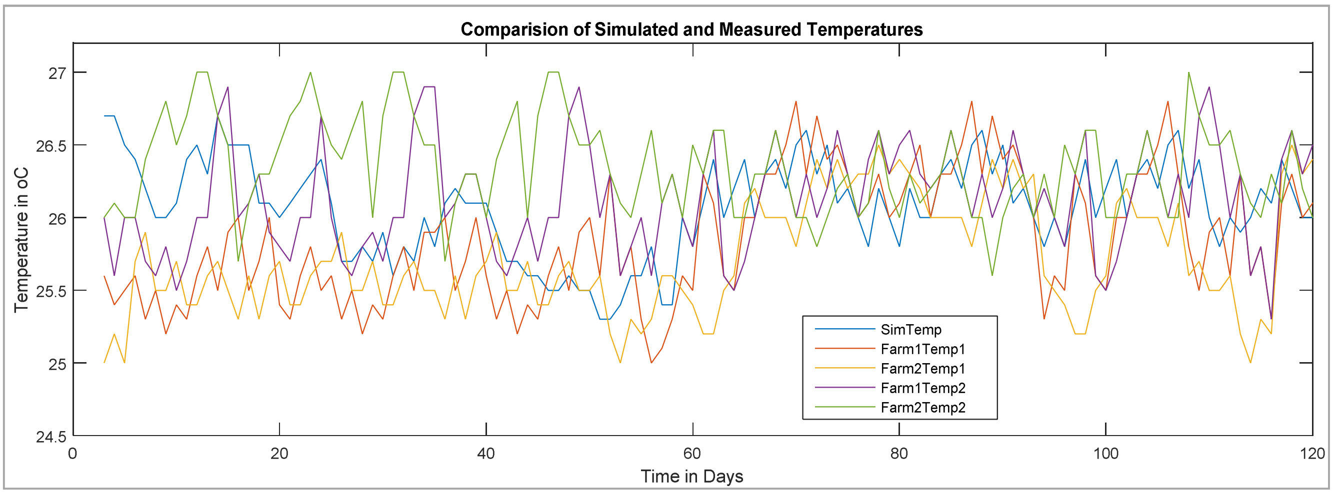

Figure 7. *Comparison of graphs of simulated temperature and temperature for some selected days in two different zones of the region under study.*

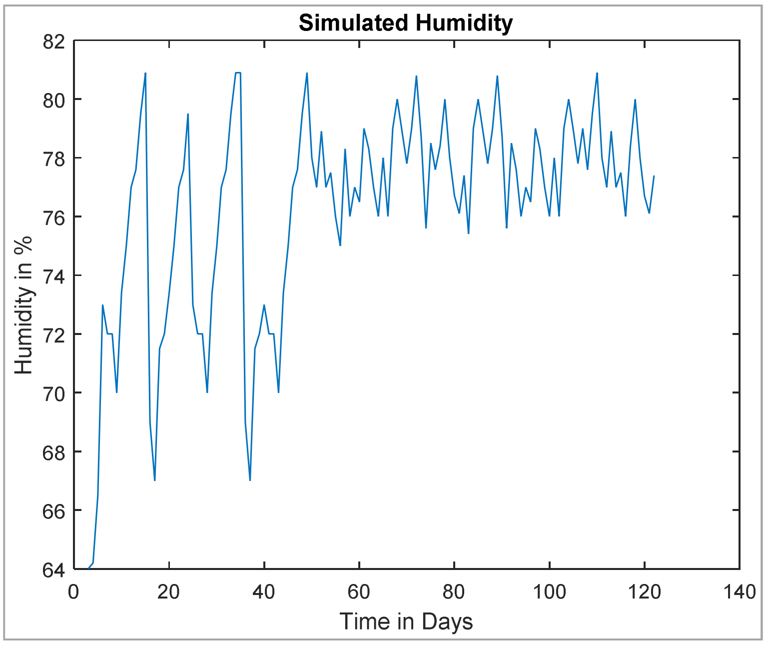

Figure 8. *Graphical representation of the Simulated Humidity.*

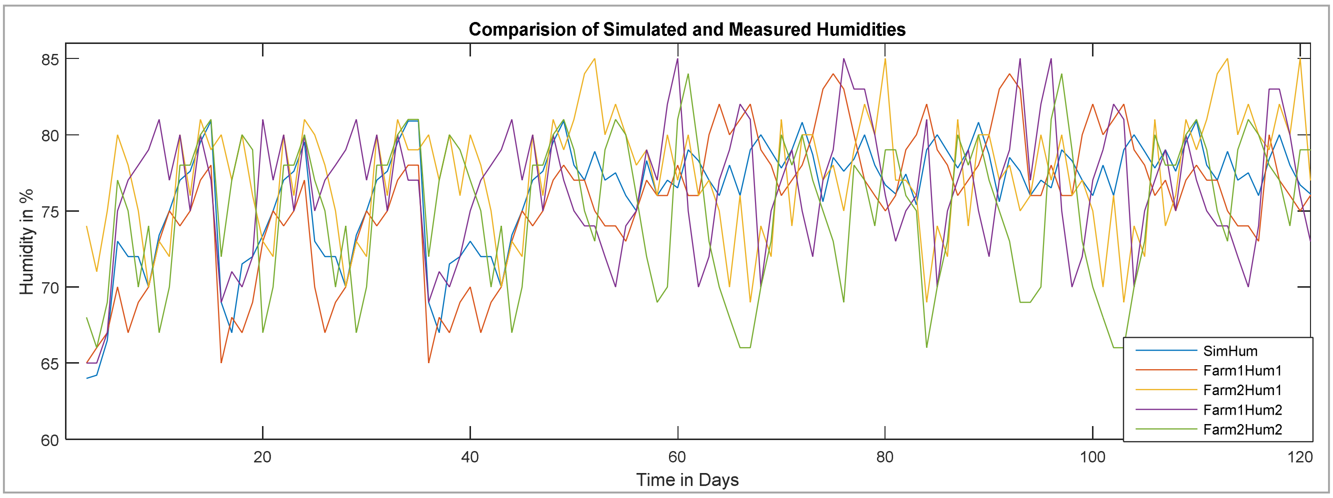

Figure 9. *Comparison of graphs of simulated humidity and humidity for some selected days in two different zones of the region under study.*

5. Conclusions and Recommendations

5.1. Modes of CHMT Gases and Vapour Inside the Greenhouse

The HMT involved in the evaporation of a water fluxes inside the greenhouse and the results were determined numerically and by simulation. The study aimed at analyzing the convective heat and mass transfer that occurred inside the greenhouse. A numerical model was built using a method based on the mass and heat balances and solutions obtained by integration of the mass and energy conservation equations from the conservation equations. The solutions from the two models were compared to the theoretical climate requirements of different crops. Each of the equations for HMT got contained a coefficient of either heat or mass transfer that were determined using the works done by the authors [6, 8, 11] in their separate models. The research work was a great success as the simulated values for ideal temperature and relative humidity were determined. The simulated values did show the need for automated methods for controlled cooling and ventilating systems instead of the manual systems that are applied by most greenhouses owners in the region of research.

5.2. Numerical Solutions of the CHMT Inside the Greenhouse That Would Favor Maximum Yields

Depending on the environmental conditions of both the inside and outside of the greenhouse, the internal microclimate is regulated either by manually closing and opening the ventilations or by use of automated cooling and ventilating machines. The use of automated cooling and ventilating machines has not been so common in the area of study, yet the farmers have also adopted greenhouse farming but control the internal microclimate manually. Further, if the amount of humidity is below expected values, water vapour inside the greenhouse can be increased by irrigation using sprinklers with nozzle jets of the desired size and pressure. Further, the researchers recommend adoption of models building before the real greenhouse as simulation is highly accurate in calculations and enables investigation of climate changes and other parameters on the greenhouse microclimate without the cost of building the greenhouse and testing the plants response within.

Abbreviations

CHMT: convection heat and mass transfer
DE: differential equations
HMT: heat and mass transfer
PID: Proportional-Integral-Derivative
RKM4: Runge-Kutta Method of order 4

Appendix

The Input Parameters for the Greenhouse Variables Used in Simulink Model

Symbol	Numerical Value	Description
τ_{air}	0.89	Transmissivity of the greenhouse covering materials for solar radiation
I_{air}	1.366	Solar radiation density in Wm^2
A_{gh}	529.434	Area of the cover of the greenhouse in m^2
λ	0.2456	Slope of saturation vapor pressure curve at air temperature in $kPaK^{-1}$
α	1.26	Priestley-Taylor coefficient
ρ	1.292	Air density inside the greenhouse in kgm^{-3}
C_p	1.314	Specific heat of air inside the greenhouse in $Jkg^{-1}K^{-1}$
L_{air}	2.45	Latent heat of vaporization in $kJkg^{-1}$
H_{soil}	6.45	Soil heat flux in $MJm^{-2}d^{-1}$
γ	66	Psychrometric constant in $kPaK^{-1}$
r	0.64	Radiative resistance
κ	86400	Unit conversion constant in sd^{-1}
H_{conv}	4.8	Heat transfer coefficient of the internal air between the floor and the cover in $Wm^{-2}K^{-1}$
ρ_{wat}	1006.2	Density of water in kgm^{-3}
L_{sat}	2400	Latent heat of water in $kJkg^{-1}$
m_{cond}	7×10^{-7}	Mass heat transfer coefficient at the surface of the greenhouse in ms^{-1}
G	0.644	Indoor and outdoor ventilation rate in m^3s^{-1}
V	1015.2	Greenhouse volume in m^3
A_{floor}	240	Area of the floor of the greenhouse in m^2
A_{leaf}	3	Area leaf of the plants inside the greenhouse in m^2
P	1.013	Atmospheric pressure in kPa

References

[1] Kabubo-Mariara, J. and M. Kabara, *Environment for Development.*

[2] Defraeye, T., et al., *Convective heat and mass transfer modelling at air–porous material interfaces: Overview of existing methods and relevance.* Chemical Engineering Science, 2012. 74: p. 49-58.

[3] Dickson, K. K., A CFD Analysis of Heat and Mass Transfer in greenhouses: An Introduction. *Mathematical Modeling and Application.* Vol. 2, No. 2, 2017, pp. 17-20.

[4] Rodríguez, F., et al., *Modeling and control of greenhouse crop growth*. 2015: Springer.

[5] Roy, J., et al., *PA—Precision Agriculture: convective and ventilation transfers in greenhouses, Part 1: the greenhouse considered as a perfectly stirred tank.* Biosystems Engineering, 2002. 83 (1): p. 1-20.

[6] Boulard, T. and B. Draoui, *Natural ventilation of a greenhouse with continuous roof vents: measurements and data analysis.* Journal of Agricultural engineering research, 1995. 61 (1): p. 27-35.

[7] Raczek, A. and E. Wachowicz, *Heat and mass exchange model in the air inside a greenhouse.* Agricultural Engineering, 2014. 149: p. 185-195.

[8] Radojević, N., et al., *Microclimate control in greenhouses.* FME Transactions, 2014. 42 (2): p. 167-171.

[9] Velten, K., *Mathematical modeling and simulation: introduction for scientists and engineers*. 2009: John Wiley & Sons.

[10] Leite, E. P., *Matlab: modelling, programming and simulations*. 2010: Sciyo.

[11] Bergman, T. L. and F. P. Incropera, *Fundamentals of heat and mass transfer*. 2011: John Wiley & Sons. Kooli, S., et al. *Modeling and Experimental Studies for Thermal Performance of a Ground Heat Storage System Integrated with a Greenhouse*. in *Ichmt Digital Library Online*. 2009. Begel House Inc.

[12] Ali, R. B., E. Aridhi, and A. Mami. *Dynamic model of an agricultural greenhouse using Matlab-Simulink environment.* in *Sciences and Techniques of Automatic Control and Computer Engineering (STA), 2015 16th International Conference on*. 2015. IEEE.

[13] Castilla, N., *Greenhouse technology and management*. 2013: Cabi.

[14] Alghannam, A. R. O., *Using proportional integral derivative and Fuzzy logic with optimization for greenhouse.* International Journal of Latest Trends in Agriculture and Food Sciences, 2012. 2 (2).

[15] Potdar, S. R., C. B. Patil, and R. R. Mudholkar, *Greenhouse Air-Temperature Modelling and Fuzzy Logic Control.*

[16] Dwyer, D., *Defining ventilation boundary conditions for a greenhouse climate model.* 2014.

[17] Bartzanas, T. and C. Kittas. *Heat and mass transfer in a large evaporative cooled greenhouse equipped with a progressive shading*. in *International Conference on Sustainable Greenhouse Systems-Greensys2004 691*. 2004.

[18] Zanino, R., S. Giors, and L. S. Richard, *CFD model of ITER CICC. Part VI: Heat and mass transfer between cable region and central channel.* Cryogenics, 2010. 50 (3): p. 158-166.

[19] Sharma, P., G. Tiwari, and V. Sorayan, *Temperature distribution in different zones of the micro-climate of a greenhouse: a dynamic model.* Energy conversion and management, 1999. 40 (3): p. 335-348.

[20] Rodríguez, F., et al. *Modelling and simulation of greenhouse climate using Dymola*. in *IFAC 15th Triennial World Congress. Barcelona. Pp*. 2002.

[21] Chao, J., et al., *Simple Model of Temperature in the Pomona College Organic Farm Greenhouse.* 2014.

[22] Baptista, F., et al., *Greenhouses climate modelling. Tests, adaptation and validation of a dynamic climate model.* Spanish Journal of Agricultural Research, 2010. 8 (2): p. 285-298.

[23] Druma, A. M., *Dynamic climate model of a greenhouse*. 1998: United Nations University.