Numerical Modeling of Thermal Radiation Heat Transfers in Agricultural Greenhouse

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Abstract. The effects caused by convection and radiation heat transfer on the distribution of temperature, airflow and heat transfer in a greenhouse containing a heated solid block are studied numerically. Differential governing equations of the system are analyzed by utilized the finite volume method and the coupling of pressure-velocity is handled by the algorithm of SIMPLER. The systems algebraic equations are resolved by the conjugated of the gradient method. The greenhouse is supposed of an aspect ratio of A = 1.5, and the numerical results are presented in terms of streamlines, isotherms and Nusselt number for the range of Rayleigh numbers between $10^3$ and $10^6$. For the case of inlet airflow, the mixed convection of the airflow of in a greenhouse formed by two walls lateral and a roof with two symmetrical slopes were studied. The heating conditions of the walls for the greenhouse was taken as ($T_c$ for the floor and $T_f$ for the roof, with $T_c > T_f$), with openings of the cold air inlet is left-walled and the outlet is so the symmetry of right walls. The Prandtl number is set at 0.702 (for the case of air). Several situations have been considered for Rayleigh number and solid block height at fixed Reynolds number at $Re = 100$. The results showed that the Rayleigh number has important effect on the performance of the flow and thermal structure. Also, the isotherms and current lines is effected by varying the solid block height. In addition the local and medium Nusselt number along the hot wall increased with increasing the Rayleigh number and solid block height.

Keywords: Agricultural Greenhouse, Thermal Radiation, Natural Convection.

Symbols

| Symbol | Description |
|--------|-------------|
| A      | aspect ratio, L / b |
| b      | greenhouse height, m |
| g      | acceleration of gravity, m/s² |
| h      | block greenhouse, m |
| H      | block dimensionless height |
| kf     | thermal conductivity of the fluid, W/m.K |
| Nu     | Nusselt number of solid block |
| Nr     | number of radiation |
| Ns     | number of power lines |
| p      | pressure, Pa |
| P      | dimensional pressure |
| Pr     | Prandtl number, |
| Ra     | Rayleigh number |
| Ri     | dimensionless radiation of Si |
| T      | surface temperature, K |
| T*     | dimensional temperature |
| To     | average temperature, K |
| u, v   | velocities according to x, y, m/s |
U, V dimensional velocities according to x, y
x, y Cartesian coordinates, m
X, Y dimensionless coordinates

Greek Symbols
\( \alpha \) thermal diffusivity, \( m^2/s \)
\( \beta \) coefficient of volume expansion, \( 1/K \)
\( \Delta T \) maximum temperature difference, K
\( \theta_r \) radiation flux density, W/m\(^2\)
\( \theta_i \) dimensionless radiation flux density
\( \theta \) dimensionless temperature
\( \varepsilon_i \) emissivity of the radiation surface

1. Introduction

The designs of the modern greenhouse by using several properties of the cover material in experimental studies have a strong impact on the energy greenhouse. Several experimental and numerical studies have been done on convection natural in rectangular cavities that used in many industry issues such as sensor design solar energy, the cooling of electronic components, and the analysis of agricultural greenhouses [1]. A simple structure and other factors must be considered for low-temperature conditions of the outdoor where the cold air enters the greenhouse by the heat conduction. When the indoor temperature out of control which easily causes frost disaster and chilling injury [2]. Many experimental and numerical studies have been conducted in the case of mixed convection ranging from simple shape cavity rectangular [3] to more complex shapes such as cavities with corrugated walls [4] or trapezoidal cavities [5]. But, the mixed convection heat transfer is often encountered in laminar flows because of their strong viscosities [6].

The heating process in a greenhouse was analyzed by [7]. He studied the convective heat transfer inside a greenhouse containing heating radiators. His results can contribute to the design of a good greenhouse. The temperature inside the greenhouse decreases during the winter and prevents the development of the plant; which is pushing farmers to look for alternatives to heating greenhouses while maintaining a set temperature. The turbulent kinetic energy distribution, temperature distribution and velocity field inside the greenhouse by employed a 3D ANSYS-Fluent model was investigated by [8]. Two geometric models were used in numerical simulations of the model with reduced height and real model. The real model results presented that the turbulent kinetic energy is given between \( 1.27-6 \text{ m}^2/\text{s}^2 \). A roof structure of the greenhouse containing heating radiators was developed by [9]. The modeling model was presented to calculate the thermal and hydrodynamic characteristics when using an insulation thickness of 0.12 m. The simulation results indicated that the temperature of the indoor air was \( 2.7^\circ C-4.9^\circ C \) for the shade room with the new roof. The influence of the velocity and temperature contours by using hot water tubes along with the greenhouse model by using commercial CFD package ANSYS-Flotran and using the RNG turbulence model was simulated by [10]. Three different situations are introduced: natural convective heating, artificial heating tubes, natural ventilation, and artificial heating tubes. The results showed that the air temperature for cases A, B and C increased by \( 2.2^\circ C, 6.7^\circ C \) and \( 3.5^\circ C \), respectively. Also, [11] focused on the problem of crop growth under extreme cold weather by proposed an active greenhouse heating system by analyzing the heat transfer based on thermal equilibrium theory which solved by finite element method (FEM) software under the conditions of the effective operation range was defined with soil temperature more than \( 15^\circ C \) at 20 cm underground and the opening
temperature of heating system should be no less than 28 °C. The results showed that an increase of air inlet temperature by 2 °C could extend the axial effective operating range by 2.4 m–2.8 m. ANSYS-FLUENT software used by [12] to analyze the heat transfer of greenhouse under-floor heating by studying several parameters that influence on temperature distribution such as pipe spacing, pipe diameter, supplied water temperature, laying depth and water flow rate. The results showed that the parameters of pipe spacing, water supply temperature, and pipe diameter have a uniformity impact on the room and ground temperature. Three models of greenhouses that unheated and equipped with canopy rows was studied by [13]. Their results showed that the temperature of the ambient air in the vertical wall greenhouse was homogenous and warmer. However, [14] presented a comprehensive review of the modeling of mass and heat transfer in order to control the climate for the greenhouse by using artificial intelligent systems. They also examined the effect of using some new technologies such as solar thermal collectors (T), photovoltaic modules (PV), hybrid collectors (PV/T) and phase change material (PCM) techniques. Their results indicated that the energy-saving up to 70 % when using the hybrid collectors (PV/T) technique. In addition, [15] provided mathematical modeling for mass and heat transfer during the air ventilation in poultry houses with air ventilation systems that used the moisture pads or injectors. Their system is different from the existing ones by using special construction heat exchangers with using a cooling medium in heat exchangers with special construction is the water from the underground wells. The ANSYS-Fluent software is used for receiving numerical simulation velocity, temperature and pressure fields.

As mention above, several previous studies neglected the radiation heat transfer of the thermal system of the greenhouse under certain conditions although it is considered very important. Therefore, the objective of this numerical study is in order to highlight and consider the influence of the thermal radiation in a mono-chapel greenhouse with a shape ratio of A = 1.5. Also, the research problem is summarized to study the effect of using a modified model of greenhouses, which includes the presence of opening ventilation in one of the walls and the presence of air outlet in the opposite wall at an appropriate height on the distribution of temperature and air velocity inside the greenhouse. The main aim of this study is to investigate the effect of using different solid blocks inside the cavity on the heat transfer inside the greenhouse.

2. Mathematical Procedure

The greenhouse simple model is presented in Figure 1. The incompressible airflow is proposed as laminar, permanent and two-dimensional. Also, the approximation of Boussinesq is used in order to simplify the mathematical analyses. The dry air is considered as the fluid circulating in the greenhouse cavity model and the dry air physical properties expect its density at the average temperature $T_o$, are assumed to be constant. The Radiation surfaces are assumed to be gray and diffuse in emission/reflection.

![Figure 1. Physical domain of the greenhouse cavity studied.](image-url)
The fluid properties are assumed constant except for the density variation that is treated according to Boussinesq approximation. The present flow is considered steady, laminar, incompressible and two-dimensional [7]. The viscous incompressible flow and the temperature distribution inside the cavity are described by the Navier–Stokes and the energy equations, respectively [8]:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$  \hspace{1cm} (1)

x- component of momentum equation:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right]$$  \hspace{1cm} (2)

y- component of momentum equation:

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left[ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right] + g \beta (T - T_e)$$  \hspace{1cm} (3)

The energy equation:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right]$$  \hspace{1cm} (4)

The variables of non-dimensional are defined as:

$$X = \frac{x}{L}, \; Y = \frac{y}{L}, \; U = \frac{u}{u_i}, \; V = \frac{v}{u_i}, \; P = \frac{p}{\rho u_i^2}, \; \theta = \frac{T - T_i}{T_e - T_i}, \; \theta = \frac{T_e - T_i}{T_e - T_i}$$

And the dimensionless parameters of Re, Ri, Pr and K are defined as [18]:

$$Re = \frac{u_E}{v}, \; Ri = \frac{g \beta (T_e - T_i) E}{u_i^2}, \; Pr = \frac{v}{\alpha}$$

Using dimensionless parameters variables defined above, the non-dimensional forms of the governing equations of the present problem. These simplifying assumptions allow us to write the dimensionless governing equations as follow:

Continuity equation [16]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$  \hspace{1cm} (5)

Momentum equation [16]:
\[ U \frac{\partial u}{\partial x} + V \frac{\partial u}{\partial y} = - \frac{\partial p}{\partial x} + Pr \Delta^2 U \]  \hspace{1cm} (6)

\[ U \frac{\partial v}{\partial x} + V \frac{\partial v}{\partial y} = - \frac{\partial p}{\partial y} + Pr \Delta^2 V + Ra Pr \theta \]  \hspace{1cm} (7)

Energy equation [16]:

\[ U \frac{\partial \theta}{\partial x} + V \frac{\partial \theta}{\partial y} = \alpha \Delta^2 \theta \]  \hspace{1cm} (8)

Boundary Conditions:

\[ X = 0 \text{ at } 0 \leq Y \leq 0.75, \quad U = V = 0, \quad \frac{\partial \theta}{\partial x} - Nr \theta_r = 0 \]

\[ 0 \leq X \leq 1 \text{ at } Y = 0.25X + 0.75, \quad U = V = 0, \quad \theta = -0.5 \]

\[ 1 \leq X \leq 2 \text{ at } Y = -0.25X + 1.25, \quad U = V = 0, \quad \theta = -0.5 \]

\[ X = 2 \text{ at } 0 \leq Y \leq 0.75, \quad U = V = 0, \quad \frac{\partial \theta}{\partial x} - Nr \theta_r = 0 \]

\[ 0 \leq X \leq 1 - \frac{H}{2} \text{ at } Y = 0, \quad U = V = 0, \quad \frac{\partial \theta}{\partial x} - Nr \theta_r = 0 \]

The above systems of the fluid flow and heat transfer governing equations systems have been discretized by a method of finite volumes method with a centered discretization scheme for the transport terms. The coupling pressure-velocity was ensured by the SIMPLER algorithm [11] and the resulting systems were solved by the method of conjugated gradients. A mesh study was carried out and we concluded that the optimal mesh size allows to have a better compromise (precision/calculation time) is (120×80). To resolve the above systems of the governing equations, the radiation surfaces of the solid walls of the cavity and the block have been analyzed into a number N of radiation surfaces. N is equal to the total number of interfaces between solid and fluid control volumes. Thus, the dimensional density \( \theta_{r,i} \) of radiation flux lost is given by the surface Si that given by [14]:

\[ \theta_{r,i} = R_i = \sum_{j=1}^{N} R_j F_{i-j} \]  \hspace{1cm} (9)

And the dimensional radioactivity is given by solving the following equation [14]:

\[ \sum_{j=1}^{N} (\delta_{ij} - (1 - \epsilon_i F_{i-j}) R_j = \epsilon_i \theta^4 \]  \hspace{1cm} (10)

Where \( F_{i,j} \) is the form factor between the surfaces \( \delta_i \) and \( \delta_j \). \( F_{i,j} \) is determined using an approximation by boundary elements, performing integration by Monte Carlo methods and using the algorithm that deals with the shadow effect [12]. Finally, the average Nusselt number along the block is defined by [15]:

\[ Nu = 2 + \int_0^H \left[ \frac{\partial \theta}{\partial x} \right]_{(X=1-H/2,Y)} + Nr \theta_r (X = 1 - H/2, Y) \] \[ dY + \int_{1-H/2}^{1+H/2} \left[ - \frac{\partial \theta}{\partial y} \right]_{(X=1-H/2,Y)} \] \[ + Nr \theta_r (X, Y = H) \] \[ dH \]  \hspace{1cm} (11)

Grid Generation and Numerical Solution

The heat transfer studied parameters in heated greenhouse cavity for various Rayleigh number along bottom wall was determine in this study, by using the finite-volume grids it was generated along whole geometrical domain. The Auto CAD and Gambit 2.3.16 software used to simplify the construction of each of this geometry and mesh files. Also, the tetrahedral mesh was employed in order to model the air space by 2017421 nodes or (120×80) in the x, y and z directions. A section of the mesh of cavity was presented
in (Figure 2). The two-dimensional mesh of the computational domain was exported to the ANSYS FLUENT 18.0 program. In this program to couple the inlet and outlet pressure boundary conditions the SIMPLE algorithm was employed. The model is terminated when the mass, momentum, and energy for each simulation evaluated over the course, residuals drop below $10^{-7}$. Also, the pressure and momentum calculations were altered the under-relaxation factors at 0.70 and 0.30 respectively to improve the convergence rate of the models, but the density and energy were left at the default values. Moreover, in these numerical simulations, the convergence criterion for temperature, pressure, and velocity is [19]:

$$\text{Error} = \frac{\sum_{k=1}^{n} \sum_{j=1}^{m} \sum_{i=1}^{p} |r_{i,j,k}^{n+1} - r_{i,j,k}^{n}|}{\sum_{k=1}^{n} \sum_{j=1}^{m} \sum_{i=1}^{p} |r_{i,j,k}^{n+1}|} \leq 10^{-7} \quad (12)$$

3. Results and Discussion

Throughout the study, the greenhouse model is taken with $A = 1.5$ and $H = 0.2$. The main objective of this study is to calculate the influence of thermal radiation on the fluid flow and thermal characteristics in a greenhouse cavity. Thus, the isotherms and streamlines currents are presented corresponding to the case of natural convection for the pure case ($ε = 0$) and for the coupled case of natural convection with thermal radiation of ($ε = 1$) as showed in Figure 3. In all cases, the airflow circulation is presented by two cells of recirculation symmetrically located in the vertical region of the greenhouse cavity. This structure of the hot air plum is explained by the fact of the cold air that heats up near the solid block rises towards the top roof of the greenhouse. So, the symmetrical region of the greenhouse structure cavity of the roof and the middle zone of the block are responsible for the lines of the current. It is found that the air circulation increases with increasing the number of Rayleigh and under the influence of the thermal radiation. Regarding isotherms, the effect of radiation thermal is remarkable just near the adiabatic walls. This is due to the fact that the air is considered perfectly transparent vis-à-vis the radiation exchanges, and therefore only the surface companies participate in radiation exchanges. Indeed, in pure natural convection, the isotherms are perpendicular to the adiabatic walls, whereas they are inclined combined because of radiation fluxes. The results indicate that the increase in the Rayleigh number promotes heat transfer in the vicinity of the solid block. Indeed, the greater the Rayleigh number is great plus the speed of the fluid accelerates and allows the extraction of a larger amount of heat. As a result, the isotherms are denser near the solid block when the $Ra$ is increased. Therefore, for large Rayleigh numbers, the temperatures are almost constant in the majority of the interior volume, with the exception of areas close to the solid block and the roof. Also, the effect of using the various height of the solid block inside the greenhouse model on the velocity streamlines and temperatures contours are presented in Figures 4 and 5. The results showed that when increased the block height the air symmetrically recirculation zone becomes more and more
biggest and very spread in the core of the greenhouse cavity. The average Nusselt number is used for thermal characterization from the block towards the rest of the cavity is shown in Figure 6. It is found that Nu increases rapidly with the Rayleigh number, because of natural convection effects and radiation thermal that become more significant at large values of Ra. The number of local Nusselt is plotted in Figure 7 at the level of the hot wall has a maximum in the heart of the greenhouse because, at this place, we are in the presence of a very intense temperature gradient translated by heat exchange between the cold jet and the hot wall. This heat exchange stabilizes along the hot wall because the temperature gradient remains substantially constant all along the hot surface. Finally, Figure 8 represents the evolution of the average Nusselt number as a function of the Grashoff number Gr for a fixed Reynolds number value. This curve shows that the heat transfer increases as the Richardson number increases.

![Figure 3: Isotherms and lines of currents for case of natural convection and thermal radiation coupled.](image-url)

| (a) | (b) |
| --- | --- |
| (c) Ra = 10^5 | (d) Ra = 10^6 |

Figure 3: Isotherms and lines of currents for case of natural convection and thermal radiation coupled.
Figure 4: Temperatures and streamlines contours for case of natural convection and thermal radiation coupled for without air flow inlet.
Figure 5: Temperatures and streamlines contours for case of natural convection and thermal radiation coupled for with air flow inlet.
Figure 6: Effect of thermal radiation on average Nusselt number.

Figure 7: Variation of local Nusselt Number along the hot wall with the Rayleigh number.
4. Conclusion

In this study, we have studied numerically the effect of radiation on thermal performance and fluid flow characteristics in a shape report of greenhouse cavity with $A = 1.2$ aspect ratio. The greenhouse cavity temperatures are increased by a central solid heated block, hot and isothermal, placed in the middle of the greenhouse floor. It is concluded that the thermal radiation affects the structure of isotherms at the neighborhood of the walls. It also increases the number of middle Nusselt to the walls of the heating element. However, the influence of thermal radiation is all the more important when the Rayleigh number is high. The numerical study of mixed convection in greenhouse horticulture, we have predicted the behavior of the flow structure between a multicellular structure dominated by natural convection in a closed system with a varying Richardson number, and a structure multicellular dominated by forced convection when the Reynolds number fixed and Richardson's number vary. We have been able to highlight the existence of an influence on convection when it increases the number of Richardson with a fixed Reynolds number $Re = 100$ practically high. The amount of heat discharged through the bottom hot wall increases as a function of Reynolds and Richardson numbers to a power law.

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