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Numerical Analysis of Airflow and Temperature Distribution in a Naturally Ventilated Greenhouse

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*Abstract***—*****An analysis of the climate in a four-span tunnel type greenhouse equipped with insect proof screens and crop inside is numerically examined. The current study includes the effect of various wind speed and temperatures with natural ventilation and by considering convective mode of heat transfer on the specific greenhouse design. The results are represented in both 2D and 3D for the air flow and temperature distributions for various external wind speed and temperatures. The complete modeling and mesh generation is created using Gambit and analysed using ANSYS Fluent code. The current study is likely to be useful to improve greenhouse structures and the horticulturists to gain more knowledge and for better understanding the greenhouse climate and its control over the period of time.***

***Keywords*— Greenhouse, Climate, Temperature, Ventilation, CFD**

I. Introduction

The crop production under protected environment is increasing steadily. The design and ventilation system performance are the most important factors responsible for climatic control and yield quality of protected cultivation. The exchange of air between inside and outside in order to dissipate excess heat, maintains humidity and increase the exchange of carbon dioxide and oxygen is influenced by the ventilation of greenhouse. Ventilation provides cooling and removes humidity based on inside conditions during summer whereas it removes excess humidity during winter. The ventilation may be natural or forced. The pressure differences caused by the wind effect or temperature effect or both are responsible for natural ventilation. Forced ventilation is caused by the use of fans. The natural ventilation type is most widely used as it consumes less energy, requires less equipment maintenance and is much cheaper than other systems for controlling greenhouse climate. The airflow patterns oversee the temperature, humidity as convective heat and mass transfers dictate the exchange process in ventilated structure [1]. Hence there is a need to understand these air flow patterns in order to control climate inside greenhouses and to improve naturally ventilated greenhouse designs. The utilization of Computational Fluid Dynamics (CFD) to analyse the greenhouse climate distribution is growing with the advent of better computers. Some studies are carried out employing either two dimensional (2D) or three dimensional (3D) CFD models taking into account influence of insect screen, wind direction [2], wind speed, direction, and vent opening size [3] effects on the climate inside the greenhouses. However the results achieved could not be generalized [4] due to different designs and conditions. The CFD has also been employed to redesign the shape of the greenhouse roof [5] in order to reduce the overall temperature level to help increasing natural flow rate for improving the crop productivity. The present study utilizes both 2D and 3D CFD models to analyse the airflow and temperature distributions inside a particular greenhouse design consisting of two spans by considering different external velocities of air at the inlet, temperatures and two types of insect-proof screens, utilizing ANSYS FLUENT software package. The mesh is generated using GAMBIT v.2.3.1 module and the problem is solved using FLUENT v.6.3.26 module which is based on finite volume method.

II. MATHEMATICAL FORMULATION

A. Physical Model and the Coordinate System

A Cartesian coordinate system is opted to describe the geometry. The origin is placed at the middle of the greenhouse floor with the positive direction along the x-axis, the negative direction away from the x-axis and the positive direction of the y-axis is considered vertically upwards. I and J are the unit vectors along x- and y directions .The z-direction comes into picture only when 3D model is considered, with the positive direction towards the front and the negative direction towards the rear axially as shown in Fig. 2. In Fig. 1, LMNOWVUTSRPL represents the outside environment of the greenhouse (extended computational domain), PQRSTUVWX represents the inside environment of the greenhouse (computational domain). The air flow inlet on the left side LM of the domain is of height H1+ H2 and the outlet is also of the same height on the right side NO. The height of the ridge is H1+ H2+H3 and that of the eaves PR and XV is HH2. RQ and VW are the side ventilators of the greenhouse with opening height H2 and the side walls PQ, XW are of height H1. The soil outside the greenhouse is given by LP, XO with total width W1 + W2 and the inside soil represented by PX is of width W2. The width and height of the crop is W2 + W3 and H1. The overall width and height of the whole domain in 2D are W and H respectively. In 3D, the total axial length of the total domain is L. Therefore volume of the total domain in 3D is W*H*L.

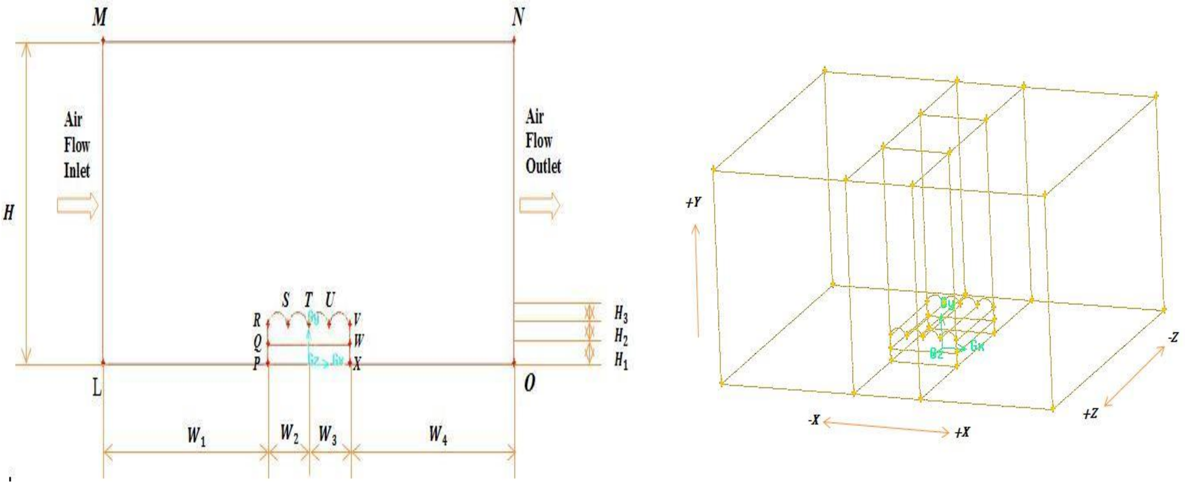

Fig. 1 The Physical Model and Coordinate System in 2D (a) and 3D(b)

B. *Governing Equations*

The partial differential equations expressing the conservation of mass, momentum, energy, turbulence kinetic energy and turbulence kinetic energy dissipation rate represent the governing equation for the present problem.

Continuity equation

$$\vec{\nabla}.\vec{u} = 0 \qquad (1)$$

Momentum equation

$$(\vec{u}.\vec{\nabla}) = -\frac{1}{\rho}\vec{\nabla}p + [(\gamma+\gamma_t)(\overrightarrow{\nabla^2}.\vec{u})]) - \beta(T-T_r)\vec{g}.\frac{\vec{u}}{|\vec{u}|} - \frac{1}{\rho}[\frac{\mu}{\alpha}\vec{u} + \frac{C_2}{2}\rho\vec{u}.\vec{u}] \qquad (2)$$

The forth term in the RHS is included only in the regions of the crop and insect screens which are considered as porous media.

Energy equation

$$E(\vec{\nabla}.\vec{u}) = -\frac{P}{\rho_f}[\vec{\nabla}.\vec{u}] + \frac{1}{\rho_f}\vec{\nabla}[keff(\vec{\nabla}.T)] \qquad (3)$$

The complete set of equations of the K-ε is found in [6] and their commonly used sets of parameters are C^{μ}=0.09, $C2^{\varepsilon}$=1.92, $\sigma_k = 1, \sigma_\varepsilon = 1.3$ [7]

C. *Boundary Conditions*

The starting conditions for the iterative solutions are quiescent state and a uniform temperature throughout the domain. The fluid enters at the inlet LM with a known velocity and exits at the outlet NO as a fully developed flow. A no slip and no permeability hydrodynamic conditions is prescribed at the top and bottom surfaces LO and MN of the total domain. The fluid enters the domain at the specific temperature and is assumed to leave at the outlet with no temperature gradient. The temperature of the soil inside and outside the greenhouse PX, LP and XO are constant and the side walls PQ and XW have zero heat flux. A pressure gradient is specified along screens RQ and VW.

III. NUMERICAL FORMULATION

A. *Solution Procedure*

The present problem is solved using ANSYS FLUENT software package. The mesh is generated using GAMBIT v.2.3.16 module which is imported into FLUENT v.6.3.26 module and the results are obtained by global iterative process with the choice of implicit steady state equations and pressure based solver. The Semi Implicit Method for Pressure Linked Equations (SIMPLE) algorithm is applied for pressure-velocity coupling. The Boussinesq model is activated to account for the effects of buoyancy force due to air density differences on the greenhouse ventilation. The high air flow rates and heat transfer interactions in the flow field cause turbulent motion of air [8]. Hence a standard K-ε model assuming isotropic turbulence in the core with standard wall functions near the walls is adopted. The porous medium approach is utilized to consider the effects of insect-proof screens [9] and the input values for screen are found in [10]. The crop is simulated as porous obstacles with inertial and viscous resistance [11]. A second order upwind discretization scheme is used for momentum, turbulence equations to obtain better accuracy. For pressure PRESTO discretization scheme is chosen since it yields good results in the presence of the porous medium and the Power law is used for energy equations to obtain favourable convergence. Tables 1,2,3 shows the basic components, greenhouse dimensions and boundary values used in simulations.

TABLE I: THE BASIC COMPONENTS OF CFD MODEL

Model	Setting
Solver	2D, 3D Implicit formulation Absolute velocity formulation Steady state analysis
Energy	Activated
Viscous	Standard K- model Standard wall function

TABLE II: GREENHOUSE DIMENSIONS

Parameters	Dimensions (m)
Greenhouse Length (L_2)	15
Greenhouse width (W_2)	11
Ridge height ($H_1 + H_2 + H_3$)	3
Eaves height ($H_1 + H_2$)	4
Vent opening (H_1)	1.5
Crop height (H_2)	1.5

TABLE III: BOUNDARY VALUES USED IN SIMULATIONS

Parameters	Input values
Wind direction	Perpendicular to screen
Inlet Velocity	3m/s 4m/s 5m/s
Outside Air temperature	298K 300K
Outside Soil temperature	303K
Inside Soil temperature	308K
Roof film temperature	318K
Turbulence intensity	2%
Turbulence scale	0.04
Inertial Resistance	1.534(1/m)
Viscous Resistance	27380(1/m2)

B. Grid Sensitivity

Grid independency tests are carried out for both 2D and 3D models. For 2D model tests are carried out considering convective heat transfer mode for five meshes containing quadrilateral cells numbering 34416, 26385, 22290, 17468 and 15243 where as for 3D model meshes containing hexahedron cells numbering 931401, 793242, 655083, 598368 and 526752 are employed. Since there is no appreciable change in results the mesh of 26385 quadrilateral elements and 655083 hexahedron elements are opted for 2D and 3D computations respectively.

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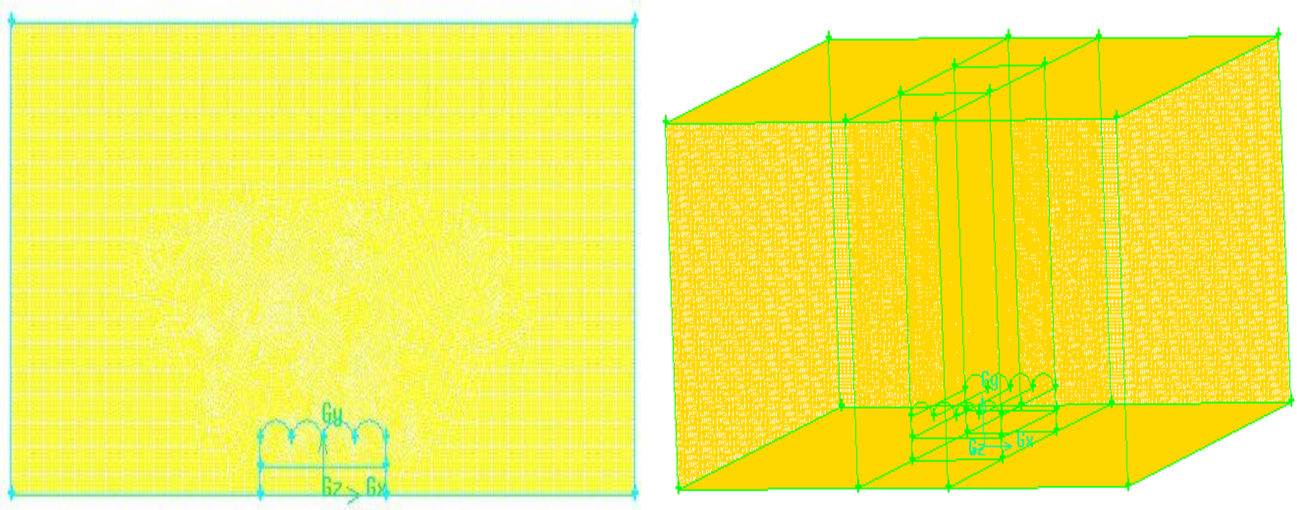

(a) **(b)**

Fig. 2 Typical 2D model (a) Mesh with 22290 cells and 3D model (b) mesh with 655083 cells

IV. RESULTS AND DISCUSSIONS

A. Flow Field

The air velocity inside the greenhouse has maximum values near the openings and it can also be seen that the air speed in the crop canopy region is much lesser. Considering the canopy region, from 2D analysis and 3D analysis, the average air velocity inside the canopy is lower which depends on the parametric inlet velocity range chosen in the greenhouse equipped with different insect proof screens. The average velocity values obtained from 2D and 3D analysis in the crop region are tabulated in Tables 4 and 5, respectively.

It is also evident that the difference in the average air velocity is marginally less when the external air temperature is varied. By considering the space between the crop canopy and roof, from 2D analysis and 3D analysis, the average air speed varies depending on the parametric inlet velocity range and with different screens. These results are tabulated in Tables 6 and 7. Tables 6 and 7 show the average velocity values in the space between top of the canopy and the greenhouse roof obtained from 2D and 3D analysis respectively. Here too the 3D velocities are relatively smaller compared to the 2D results. The difference in velocities between the canopy and the upper regions is caused due to the flow deceleration. Hence the presence of plants plays a serious role in the greenhouse climate.

TABLE IV: AVERAGE VELOCITY VALUES INSIDE THE CANOPY FROM 2D ANALYSIS

Velocity at the inlet uin in m/s	Average velocity (uavg) in m/s with Econet fl screen		Average velocity (uavg) in m/s with Econet sf screen	
	Tin = 299 K	Tin = 296 K	Tin = 300 K	Tin = 298 K
5	0.6722	0.6702	0.6728	0.6796
4	0.5386	0.5313	0.5378	0.5334
3	0.4053	0.4032	0.3448	0.3448

TABLE V: AVERAGE VELOCITY VALUES INSIDE THE CANOPY FROM 3D ANALYSIS

Velocity at the inlet uin in m/s	Average velocity (uavg) in m/s with Econet fl screen		Average velocity (uavg) in m/s with Econet sf screen	
	Tin=299 K	Tin=296 K	Tin=299 K	Tin=296 K
5	0.6303	0.6351	0.6395	0.6396
4	0.4915	0.4936	0.4929	0.4974
3	0.3696	0.3603	0.3119	0.3123

TABLE VI: AVERAGE VELOCITY VALUES BETWEEN TOP OF CROP CANOPY AND THE GREENHOUSE ROOF FROM 2D ANALYSIS

Velocity at the inlet uin in m/s	Average velocity (uavg) in m/s with Econet fl screen		Average velocity (uavg) in m/s with Econet sf screen	
	Tin=299 K	Tin=296 K	Tin=299 K	Tin=296 K
5	0.9610	0.9653	0.9218	0.9291
4	0.7680	0.7590	0.7261	0.7195
3	0.5746	0.5749	0.5399	0.5401

TABLE VII: AVERAGE VELOCITY VALUES BETWEEN TOP OF CROP CANOPY AND THE GREENHOUSE ROOF FROM 3D ANALYSIS

Velocity at the inlet uin in m/s	Average velocity (uavg) in m/s with Econet fl screen		Average velocity (uavg) in m/s with anti Econet sf screen	
	Tin=299 K	Tin=296 K	Tin=299 K	Tin=296 K
5	0.7604	0.7685	0.7909	0.7979
4	0.6096	0.6105	0.6110	0.6147
3	0.4568	0.4601	0.4589	0.4607

B. Temperature Distribution

The average temperature values found from the analysis inside the crop canopy and in the space between the top of the canopy and the roof are shown in tables. Tables 8 and 9 show the average temperature values obtained from 2D analysis whereas tables 10 and 11 from 3D analysis.

From 2D analysis, the average temperature inside the canopy is higher and the increase in temperature when compared to the inlet temperature is 2.53 K and 2.35 K, 2.76 K and 2.83 K whereas from 3D analysis the increase in temperature is 2.62 K and 2.42 K, 2.85 K and 3.97 K depending on inlet velocity range and inlet temperature range equipped with Econet fl and Econet sf insect proof screen, respectively. Results are tabulated in table 8 and 9.

By considering the space between the crop canopy and roof, from 2D analysis, the increase in temperature when compared to the inlet temperature is 2.83 K and 3 K, 3.33 K and 3.66 K whereas from 3D analysis the increase in temperature is 2.01 K and 3.15 K, 3.76 K and 3.89 K depending on inlet velocity range and inlet temperature range equipped with Econet fl and Econet sf insect proof screen, respectively. Results are tabulated in table 10 and 11.

The temperature inside the canopy as well as in the space between the top of the canopy and the roof is found to increase slightly in a greenhouse equipped with Econet sf screen on comparing with Econet fl insect proof screen. This present analysis gives agreement that the Econet sf screen is less permeable than the Econet fl screen. The values obtained from 3D analysis is somewhat higher than 2D analysis because the front and rear domain in 3D model offer resistance on the fluid viscosity causing decrease in the air velocity which finally leads to rise in temperature.

TABLE VIII: MEAN TEMPERATURE VALUES INSIDE THE CANOPY FROM 2D ANALYSIS

Velocity at the inlet(m/s)	Mean temperature values with Econet fl screen in K		Mean temperature values with Econet sf screen in K	
	Tin=299 K	Tin=296 K	Tin=299 K	Tin=296 K
5	301.09	297.89	301	298.83
4	301.26	298.24	301.66	299
3	301.53	298.35	301.76	299.83

TABLE XI: MEAN TEMPERATURE VALUES BETWEEN TOP OF CROP CANOPY AND THE GREENHOUSE ROOF FROM 2D ANALYSIS

Velocity at the inlet (m/s)	Mean temperature values with Econet fl screen in K		Mean temperature values with Econet sf screen in K	
	Tin=299 K	Tin=296 K	Tin=299 K	Tin=296 K
5	301	298	301.833	299.33
4	301.66	298.66	302	299.5
3	301.83	299	302.333	299.666

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TABLE X: MEAN TEMPERATURE VALUES INSIDE THE CANOPY FROM 3D ANALYSIS

Velocity at the inlet uin(m/s)	Mean temperature values with Econet fl screen in K		Mean temperature values with Econet sf screen in K	
	Tin=299 K	Tin=296 K	Tin=299 K	Tin=296 K
5	301.21	297.96	301.09	298.97
4	301.37	298.36	301.75	299.11
3	302.12	298.42	301.85	299.97

TABLE XI: MEAN TEMPERATURE VALUES BETWEEN TOP OF CROP CANOPY AND THE GREENHOUSE ROOF FROM 3D ANALYSIS

Velocity at the inlet uin(m/s)	Mean temperature values with Econet fl screen in K		Mean temperature values with Econet sf screen in K	
	Tin=299 K	Tin=296 K	Tin=299 K	Tin=296 K
5	301.14	298.13	301.94	299.54
4	301.17	298.83	302.09	299.63
3	301.91	299.15	302.76	299.89

C. Ventilation Rate

The air flow rate is obtained using the relation Vr= ∫ Udy and ventilation rate is expressed as air renewals per hour given by N= (Vr*3600)/volume of greenhouse. The ventilation rate is found to increase with the external wind speed and the values are summarized in Table 12, 13 and Table 14, 15 for 2D and 3D respectively.

TABLE XII: EFFECT OF THE INLET VELOCITY ON AIR FLOW RATE AND AIR RENEWALS EQUIPPED WITH ECONET FL AND ECONET SF SCREEN AND EXTERNAL TEMPERATURE 299 K FROM 2D ANALYSIS

Inlet velocity (m/s)	Econet fl insect proof screen		Econet sf insect proof screen	
	Air flow rate (m3/s)	Air renewals (h-1)	Air flow rate (m3/s)	Air renewals (h-1)
5	1.7812	156.36	0.8913	78.24
4	1.3901	122.02	0.6696	58.78
3	0.9998	87.766	0.4630	40.64

TABLE XIII: EFFECT OF THE INLET VELOCITY ON AIR FLOW RATE AND AIR RENEWALS EQUIPPED WITH ECONET FL AND ECONET SF SCREEN AND EXTERNAL TEMPERATURE 296 K FROM 2D ANALYSIS

Inlet velocity (m/s)	Econet fl insect proof screen		Econet sf insect proof screen	
	Air flow rate (m3/s)	Air renewals (h-1)	Air flow rate (m3/s)	Air renewals (h-1)
5	1.7813	156.37	0.8914	78.25
4	1.3902	122.03	0.6697	58.79
3	0.9999	87.770	0.4631	40.65

TABLE XIV: EFFECT OF THE INLET VELOCITY ON AIR FLOW RATE AND AIR RENEWALS EQUIPPED WITH ECONET FL AND ECONET SF SCREEN AND EXTERNAL TEMPERATURE 299 K FROM 3D ANALYSIS

Inlet velocity (m/s)	Econet fl insect proof screen		Econet sf insect proof screen	
	Air flow rate (m3/s)	Air renewals (h-1)	Air flow rate (m3/s)	Air renewals (h-1)
5	27.11	159.65	14.59	85.956
4	21.18	124.72	11.08	64.820
3	15.26	89.90	7.49	44.144

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TABLE XV: EFFECT OF THE INLET VELOCITY ON AIR FLOW RATE AND AIR RENEWALS EQUIPPED WITH ECONET FL AND ECONET SF SCREEN AND EXTERNAL TEMPERATURE 296 K FROM 3D ANALYSIS

Inlet velocity (m/s)	Econet fl insect proof screen		Econet sf insect proof screen	
	Air flow rate (m3/s)	Air renewals (h-1)	Air flow rate (m3/s)	Air renewals (h-1)
5	27.19	160.12	14.71	86.62
4	21.30	125.43	11.10	65.36
3	15.45	90.980	7.651	45.09

V. CONCLUSION

India possesses about 11% of the world's arable land but has to feed 18% of the world's population. Though India has achieved self-sufficiency in food grains but the productivity of Indian farms is below that of developed nations and the main reason is because of minimal use of advanced technology. One such technology is greenhouse technology. Hence a detailed analysis is required.

In this regard, CFD application to the greenhouses was considered for the study. The influence of wind speed with two different external inlet temperature on the ventilation performance and the inside climate in a naturally ventilated four span tunnel type greenhouse utilizing both 2D and 3D CFD model were studied. The airflow field and temperature distributions generated by the wind perpendicular to the greenhouse side openings equipped with two different types of insect proof screens was also studied. The following conclusions were drawn after the detailed study.

- The results from both 2D and 3D analysis showed that the wind entered the greenhouse only through windward side vent opening.
- No presence of buoyancy effect was seen on the ventilation performance for the inlet velocity range chosen.
- The air renewals per hour were found to decrease with the decrease in inlet velocity for a definite external temperature of air.
- It was observed that when the external temperature was reduced from 299 K to 296 K for a specific external wind speed the increase in the ventilation rate was found to be marginal.
- The air speed played an important role on the inside greenhouse temperature pattern for a specific external air temperature.
- The air speed inside the crop canopy was found to be much lower than the external wind speed.
- The air renewals per hour obtained from 2D and 3D analyses in a greenhouse equipped with Econet fl insect proof screen was found to be higher than the Econet sf insect proof screen.

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