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Estimation of Ventilation Rate in Naturally Ventilated Greenhouse with Continuous Roof Vent

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Abstract In this paper, hourly variation of ventilation rate was determined using energy balance model (EBM) and physical mechanism approach (PMA). Energy balance model uses incoming, outgoing and stored radiation within the greenhouse for estimation of ventilation rates. Physical mechanism approach uses two main driving forces of natural ventilation such as stack effect and wind effect for the estimation of ventilation rates. The temperature and relative humidity inside and outside the greenhouse were recorded using a handheld device. Simultaneously hourly outside temperature, relative humidity, wind speed, solar radiation were recorded from the automatic weather station located nearby greenhouse. From the recorded meteorological data and using these (EBM and PMA) models, the ventilation rates were determined. The ventilation rate estimated from energy balance model varied between 0.02 m^3s^{-1} and 0.67 m^3s^{-1}. The ventilation rates estimated from physical mechanism approach showed a cyclic trend i.e. the ventilation rates were minimum during 8 am, 10 am and 6 pm and maximum during 12 pm, 2 pm and 4 pm, A regression analysis was done between estimated ventilation rate and recorded parameters like inside temperature, solar radiation and wind speed. The ventilation rate estimated by EBM showed poor correlation with the inside temperature (R^2 = 0.33), solar radiation (R^2 = 0.34) and wind speed (R^2 = 0.32). The ventilation rate estimated by PMA had good correlation with wind speed (R^2= 0.99) but poor correlation with inside temperature (R^2 = 0.57) and solar radiation (R^2=0.64). A regression model is proposed to estimate the ventilation rate based on the measured wind speed.

Keywords Ventilation rate, Energy balance model, Physical mechanism approach, Greenhouse, Roof vent.

Introduction

The rate exchange of air between interior and exterior of greenhouse is known as ventilation rate. It plays an important role in determining the environmental conditions within the greenhouses. Ventilation provides three major functions: Temperature control, moisture control and elimination of other indoor pollutants. A lot of research work has been carried out on greenhouse technology for the last few decades in estimating and maintaining the ventilation rates within the greenhouse. Ventilation rates can be predicted

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using an energy balance model for the greenhouse. Fernandez and Bailey (1992) showed good agreement between the values predicted by energy balance model and measured values for larger ventilator openings, but at low ventilation rates the agreement was poor. Boulard and Draoui (1995) presented the measurements of air exchange rate carried out in a full-scale greenhouse using three different methods; namely decay rate method using N_2O as tracer gas, the constant rate tracer gas technique using CO_2 as tracer gas and the green house water vapor balance method based on the measurement of crop transpiration, inside and outside air humidity.

Boulard and Baille (1995) tested and calibrated various types of models for determining the ventilation rates in greenhouses which include two driving forces namely wind and buoyancy forces. Considering the wind and buoyancy effects, a simple formula for determining the ventilation rates were derived. Boulard et al. (1996) presented the physical mechanisms involved in natural ventilation of a greenhouse equipped with continuous lateral windows and used air exchange rate measurements, using tracer gas or heat and water balance techniques; direct determination of the air and heat flows through an opening, using an eddy correlation system, comprising a sonic anemometer and a fine wire thermocouple; measurements of mean and turbulent pressure differences at ground level between inside and outside. The methods employed, allow the prediction of greenhouse air exchange rates as well as the characterization of stack and wind effects. Zhang et al. (1997) adopted an one dimensional numerical model to predict the microclimate inside an unheated commercial greenhouse during a continuous period of 51 days.

Boulard et al. (1998) explained about the measurement of mean and fluctuating pressures to deduce the airflow pattern induced at the vent opening using a simple model based upon Bernoulli's equation. Those results are compared with directly measured airflows and results of tracer gas measurements.

Tanny et al. (2006) focused on airflow, turbulence, ventilation rate, evapotranspiration and energy balance in a large commercial flat-roof banana screenhouse in northern Israel. Teitel et al. (2008) carried out experiments in a naturally ventilated mono-span greenhouse with continuous screened side vents to determine the ventilation rate, temperature, humidity and air velocity distributions and the energy partitioning of the incoming radiation. Results indicated that the ventilation rate increases linearly with wind speed.

Molina-Aiz et al. (2012) described the efficiency of two different discretization methods which is used as computational fluid dynamics (CFD) solvers for the simulation of natural ventilation in greenhouses. Ghany (2011) estimated the ventilation rates of greenhouses by considering the spatial variation of transmitance in greenhouses, expressing the overall heat transfer coefficient of greenhouse cover as function of inside and outside conditions of greenhouses and considering the heat capacities of the greenhouse components and the soil heat flux. Reyes-Rosas et al. (2017) semi-empirical dynamic model of energy balance was developed to predict temperatures (air, plants, greenhouse cover and soil) in a naturally ventilated greenhouse with polypropylene mulch covering the soil in a Mediterranean climate. The model was validated using experimental data of 5 non-successive periods of 5 days throughout the crop season in the province of Almeria (Spain).

This paper adopts energy balance model and physical mechanism approach to estimate the ventilation rates for a greenhouse located in a semi-arid region. A regression analysis is done between estimated ventilation rate and meteorological parameters. From that, a regression equation is proposed to determine the ventilation rate directly from the wind speed for this semi-arid region.

Materials and Methods

Two models used in this paper are explained below.

Energy balance model

Ventilation rates can be predicted using an energy balance model (Fernandez and Bailey 1992) of the greenhouse. When no heating is used, the energy removed by the processes of leakage (E_L) and ventilation (E_V) is equal to the solar energy collected in the greenhouse (E_S) minus the thermal losses through the cover (E_C) minus the stored energy (E_{ST}). The leakage rate is air exchange with closed ventilators and ventilation rate is air exchange with open ventilators. The energy balance equation is as follow as :

$$E_L + E_V = E_S - E_C - E_{ST} \quad (1)$$

The energy lost by leakage and ventilation has two components, one component is due to sensible heat and the other component is due to latent heat. Therefore,

$$E_L + E_V = E_{SEN} + E_{LAT} \quad (2)$$

The sensible (E_{SEN}) and latent (E_{LAT}) heat fluxes are given by :

$$E_{SEN} = \frac{\phi_v}{A_g} \rho C_p (\theta_i - \theta_o) \text{ (W m}^{-2}\text{)} \quad (3)$$

$$E_{LAT} = \frac{\phi_v}{A_g} \rho L (w_i - w_o) \text{ (W m}^{-2}\text{)} \quad (4)$$

Where ρ is the density of the air (kg m^{-3}), C_p is the specific heat of the air (J kg^{-1} K^{-1}), L is the latent heat of vaporization of water (J kg^{-1}), θ is temperature of the inside and outside air (K), w is absolute humidity of inside and outside air (kg kg^{-1}),φ_v is the ventilation rate (m^3 s^{-1}) and Ag is the ground area (m^2). The different components of energy balance are shown in Fig 1.

The solar energy collected in the greenhouse depends on the coefficient of absorption of solar radiation (*a*)

$$E_s = \alpha I_0 = I_i - I_r \text{ (W m}^{-2}\text{)} \quad (5)$$

Where I_i is the internal solar radiation and I_r is solar radiation reflected from the crop. The thermal losses through unit area of the cover is given by the following equation.

$$E_{CL} = U \frac{A_c}{A_g} (\theta_i - \theta_o) \text{ (W m}^{-2}\text{)} \quad (6)$$

Where A_{CL} is the cladding materials area (area

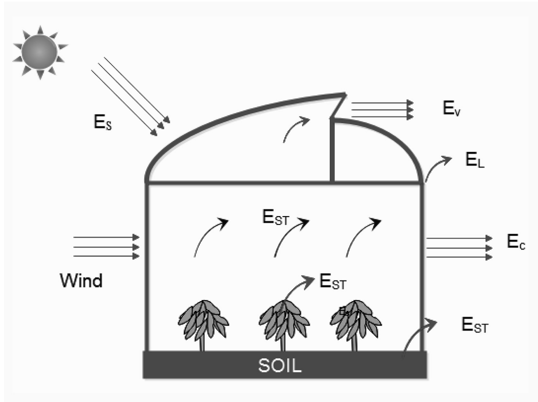

Fig. 1. Energy balance model in greenhouse.

of greenhouse cover) (m^2). The thermal transmittance of the cladding (U factor) was calculated using the following equations developed by Jolliet et al. (1991).

$$U = K_o + K_s + K_s q_s \text{ (W m}^{-2}\text{ K}^{-1}\text{)} \quad (7)$$

This equation considers separately thermal exchange with the sky (K_s) amd the outside air (K_o).

$$K_o = \frac{1}{A_g} \left(\frac{G_{CL}\text{-}in * G_{CL}\text{ - }out}{G_{CL}\text{ - }in + G_{CL}\text{- }out + G_{CL}\text{ - }sky} \right) \text{ (W m}^{-2}\text{ K}^{-1}\text{)} \quad (8)$$

$$K_s = \frac{1}{A_g} \left(\frac{\text{GCL - in *GCL - sky}}{\text{GCL - in + GCL - out + GCL - sky}} \right) \text{ (W m}^{-2}\text{ K}^{-1}\text{)} \quad (9)$$

$$q_s = \frac{\theta_o - \theta_s}{\theta_i - \theta_o} \quad (10)$$

Where the G factors are the thermal coupling coefficients between inside air, outside air, sky and the outside surface of the cladding (W K^{-1}). These coefficients were calculated by using the equations given by Jolliet et al. (1991). The sky temperature (θ_s) was calculated from the atmospheric long wave radiation assuming unit emissivity. The long wave radiation flux was obtained as the difference between total radiation flux measured by a pyradiometer and solar radiation measured by a pyranometer. The influence of the sky temperature is characterized by the ratio q_s.

The transfer of stored energy inside the greenhouse involves cover, inside air, crop and soil.

$$E_{ST} = E_{ST}^{cover} + E_{ST}^{air} + E_{ST}^{crop} + E_{ST}^{soil} \qquad (11)$$

In each case, the transfer of stored energy is given by the following equation :

$$E_{ST} = \frac{MC_p (\theta_B - \theta_E)}{t_E - t_B} \quad (W\ m^{-2} K^{-1}) \qquad (12)$$

Where M is mass per unit greenhouse area (kg m^{-2}), θ_B and θ_E are the temperatures (K) of the component at the beginning and at the end of the experiment, respectively and t_B and t_E are the start and end time of the experiment, respectively.

Physical mechanism approach

Airflow through an opening is caused by pressure difference. Bernoulli's equation is generally used to describe the relationship between the pressure drop and the air velocity through an opening.

Assuming that the airflow is incompressible, the vertical pressure profile is given by,

$$\Delta P(y) = \frac{1}{2} \rho \zeta v^2 (y) \qquad (13)$$

Where ΔP(y) and v (y) are respectively the vertical profiles of the pressure drop and air speed through the opening, ρ is the air density and ζ is the pressure drop coefficient.

The discharge coefficient (A_t) of the opening is given by,

$$A_t = \frac{1}{\zeta^{0.5}} \qquad (14)$$

The distribution of air speed v(y) through the opening can be deduced from (13) and (14), Knowing ΔP.

$$v(y) = \frac{|\Delta P(y)|}{\Delta P(y)} A_t \left(\frac{2}{\rho} |\Delta P(y)| \right)^{0.5} \qquad (15)$$

Where the sign of the ratio $\frac{|\Delta P(y)|}{\Delta P(y)}$ gives the direction of the airflow v (y) through the opening. The airflow rate G (m^3/s) can be defined by integrating the equation (15) over the vertical height of the opening, H. If L is the length of the opening of the surface S (S = LH), then we get.

$$G = L \int_0^H v(y) * dy \qquad (16)$$

If we consider a single opening, the total surface will be split into an inward surface S/2 and an outward surface (S/2) disposed as for buoyancy forces in the lower and upper part of the opening is given by,

$$G = L \int_0^{H/2} v(y) * dy \qquad (17)$$

Equation (15) and (17) allow the air exchange rate to be determined from the pressure distribution between inside and outside and the discharge coefficient.

Thermal buoyancy and wind forces

Pressure difference are induced by two main forces (1) buoyancy forces (often called as chimney or stack effect) and (2) the wind forces (wind effect) (Figs. 2 and 3).

The buoyancy effect

If the pressure difference at ground level, ΔP0 and the vertical distribution of air temperature are known,

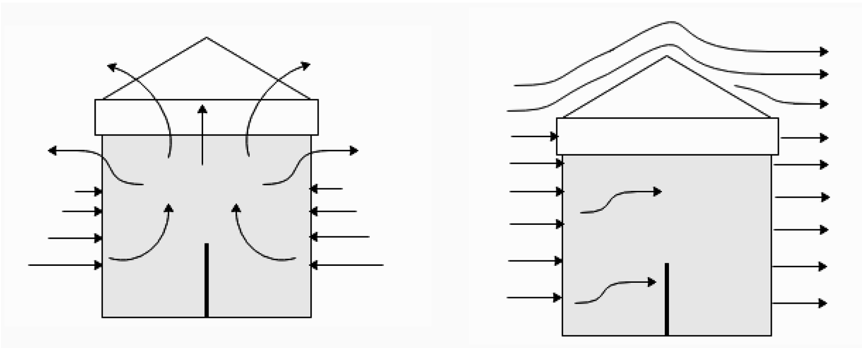

Fig. 2: Stack or Buoyancy Effect **Fig. 3: Wind Effect**

Fig. 2. Stack or buoyancy effect. **Fig. 3**. Wind effect.

we can deduce, using the Boussinesq approximation, the vertical distribution of the pressure difference. If we assume, in order to simplify the problem, that the temperature field is homogeneous inside and outside then.

$$\Delta P(y) = \Delta P_0 - \rho g \left(\frac{\Delta T}{T}\right) y \qquad (18)$$

Where T (K) is the outside air temperature and ΔT (K) is the temperature difference between inside and outside. The equation (3) becomes.

$$v(y) = \left(\frac{|\Delta P|}{\Delta P}\right) At \left[\frac{2}{\rho}\left(\Delta P_0 - \rho g\left(\frac{\Delta T}{T}\right) y\right)\right]^{0.5} \qquad (19)$$

Integration of equation (25) with v(y) given by equation (27) gives G, the airflow.

$$G = \frac{LA_t}{3\left(\frac{\Delta T}{T}\right) g}\left[\left(2g\frac{\Delta T}{T}\right)\left(\frac{H}{2}\right)^{3/2}\right] \qquad (20)$$

Where L is the length of the ventilator and H is the vertical height of the opening.

The wind effect

The wind action on the structures such as building or greenhouses results in a pressure distribution around these obstacles. Wind effects are usually split into two components. The first of them is a mean or steady effect induced by a mean pressure distribution, related to the mean wind speed V, by a non-dimensional pressure coefficient, $\bar{C}$.

$$\Delta P = \frac{1}{2}\rho \bar{C} V^2 \qquad (21)$$

A greenhouse equipped with both upwind and downwind vents will be crossed by a mean flow of air going from the openings situated in area with a positive $\bar{C}$ to the area of the negative $\bar{C}$. The second component is a turbulent wind effect induced by the fluctuating pressure distribution, described by the fluctuating pressure coefficient $\bar{C}$. Consider the large multi-span greenhouse, equipped with roof openings only, all open in the same direction. The pressure coefficient $\bar{C}$ is same for each opening so the air exchange cannot be induced by the differences of $\bar{C}$ and air exchange is induced by the wind fluctuation creating the pressure fluctuation that depend on the turbulent characteristics of the wind in interaction with the greenhouse itself or immediate surroundings.

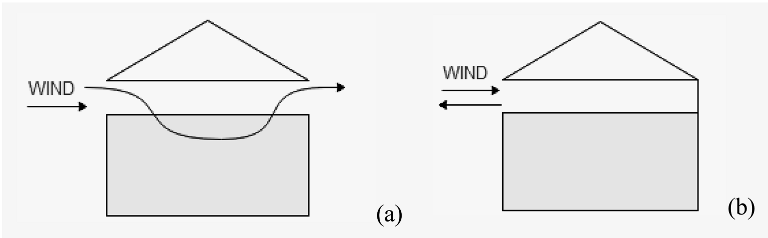

Fig. 4. Steady and turbulent wind effects.

In this case, air exchange is caused through the vents are driven by two mechanisms: (i) the pressure variations caused by a change of internal pressure due to the air compressibility (ii) a turbulent diffusion, in large opening generated by the spatial fluctuations of pressure causing the air to be exchanged between the inside and outside.

The Fig. 4a represents the direction of the current of air generated by a pressure difference between a windward and leeward opening and Fig. 4b represents currents of air genearated by fluctuation of wind speed within a single opening.

In spite of the complexity of this turbulent phenomenon, we will consider that a single parameter $\bar{C}$ is able to describe the effect of fluctuating wind pressure.

$$\Delta \bar{P} = \frac{1}{2} \rho \bar{C} V^2 \quad (22)$$

Few values of $\bar{C}$ is available in literature. As our measurements are global measurements, C_w is used instead of $\bar{C}$ and is used to represent both steady and turbulent effects, which is as follow as :

$$\Delta P_w = \frac{1}{2} \rho CwV^2 \quad (23)$$

Equations describing the system

Combining the wind and stack effects, we get

$$G = \frac{LA_t}{3\left(\frac{\Delta T}{T}\right)g}\left[\left(2g\frac{\Delta T}{T}\right)\left(\frac{H}{2}\right) + C_w V^2\right]_{3/2} - \left[C_w V^2\right]_{3/2} \quad (24)$$

Thus the ventilation rate G is obtained using the combined wind and stack effects.

Data collection

The climatic parameters were recorded inside the greenhouse (Fig. 5) located at central farm of Agricultural Engineering College and Research Institute, Kumulur, Trichy, Tamil Nadu. The specification of the greenhouse in which the study is conducted is given Table 1. The temperature and relative humidity inside and outside greenhouse was recorded using the handheld recorder for a period of seven days (07-12-2017 to 13-12-2017) at the centroid of the greenhouse. From morning 8 am to evening 6 pm, at an interval of 2 h, the data were recorded. Simultaneously the radiation data recorded by the automatic weather station located nearby were collected from the www.tawn.com website, which provides data in hourly basis.

Table 1. Specification of the greenhouse.

Sl. No.	Specification	Particulars
1	Type of greenhouse	Saw-tooth type
2	Orientation	East-west
3	Span	Single span
4	Length of the greenhouse	12 m
5	Width of the greenhouse	4 m
6	Volume of greenhouse	290 m^3
7	Height of vent	0.75 m
8	Length of vent	12 m
9	Crop grown	Marigold
10	Stage of crop	Flowering

Table 2. Assumptions and model calculation of energy balance method.

Parameters	Values	Units/Equation
Dimension L	12.0	m
Dimension W	4.0	m
Physical volume V	290.0	m^3
Ventilators L_0	12.0	m
Ventilators H_0	0.75	m
Time	9.0	am
Inside temperature	31.1	^0C
Outside temperature	27.9	^0C
Inside RH	88.0	%
Outside RH	87.5	%
Wind speed	4.5	kmph
Solar radiation	38.0	cal/cm^2
Inside temp	304.1	K
Outside temp	300.9	K
Inside AH	0.025	kg/kg
Outside AH	0.021	kg/kg
Del T	3.2	
Del AH	0.00457	
$E_{SEN} * \varphi_v$	81.667	$E_{SEN} = \frac{\phi_v}{A_g} \rho C_p (\theta_i - \theta_0)$
$E_{LAT} * \varphi_v$	268.132	$E_{LAT} = \frac{\phi_v}{A_g} \rho L (w_i - w_o)$
Crop absorptance	0.61	Assumption for Marigold crop
Soil absorptance	0.30	Assumption for soil
Cover absorptance	0.02	Assumption for covering material
Cover transmittance	0.62	assumption for covering material
Crop reflectivity	0.22	Assumption for Marigold crop
Cover area Ac	176	m^2
U factor	0.68	
E_{CL}	7.979	$E_{CL} = U \frac{A_c}{A_g} (\theta_i - \theta_0)$
	(W/m^2)	
Incoming solar radiation	18.414	(W/m^2)
Transmitted radiation	11.417	(W/m^2)
Reflected radiation by crop	2.512	(W/m^2)
E_S	8.905	(W/m^2) $Es = \alpha I_0 = I_i - I_r$
Absorbed radiation by crop	6.964	(W/m^2)
Absorbed radiation by soil	3.425	(W/m^2)
Absorbed radiation by cover	0.228	(W/m^2)
E_{ST}	10.617	(W/m^2) $E_{ST} = \frac{MC_p (\theta_B - \theta_E)}{t_E - t_B}$
$E_S = E_L + E_Y + E_C + E_{ST}$		
RHS	27.501	
LHS	349.799	
Energy balance ϕ_v	0.079	m^3S^{-1}

Table 3. Assumptions and model calculation of physical mechanism method.

Parameters	Value	Unit/Equation
Dimension L	12.0	m
Dimension W	4.0	m
Physical volume V	290.0	m^3
Length of vent L_0	12.0	m
Height of vent H_0	0.75	m
Time	9.0	am
Inside temperature	31.1	^0C
Outside temperature	27.9	^0C
Del T	3.2	^0C
g	9.8	$m\ S^{-2}$
H	1.0	m
C_w	0.09	
A_t	0.644	
$\phi_V = \frac{LA_t}{3\left(\frac{\Delta T}{T}\right)g}\left[\left[\left(2g\frac{\Delta T}{T}\right)\left(\frac{H}{2}\right) + C_w V^2\right]^{3/2} - \left[C_w V^2\right]^{3/2}\right]$		
Physical mechanism ϕ_V	0.40	$m^3\ S^{-1}$

Using energy balance model and physical mechanism approach, the ventilation rates of greenhouse was determined. The assumption and model calculation of energy balance method and physical mechanism method is shown in the Table 2 and 3.

Results and Discussion

The temperature and relative humidity inside and outside greenbouse recorded during the period of seven days (07-12-2017 to 13-12-2017) is shown in the Fig. 6 and 7. Tietel and Tanny (1999) also conducted ventilation experiments over a period of five days for natural ventilation greenhouses. The relative humidity was maximum during morning time and evening time. It reaches the lowest value around 39% during 2 pm. During the period of seven days, no irrigation was given to the crop. Hence the relative humidity inside greenhouse is little higher than outside greenhouse. The temperature within the greenhouse is relatively higher than the outside temperature. Using the energy balance model and physical mechanism approach, ventilation retes of greenhouse were determined and the variation of ventilation rates is

Fig. 5. Saw-tooth type greenhouse at AEC&RI, Kumulur.

shown in Fig. 8. The ventilation rate estimated from energy balance model reaches a maximum value of 0.67 m^3s^{-1} during 4 pm and minimum value of 0.02 m^3s^{-1} during 6 pm. The ventilation rates estimated from physical mechanism approach showed a cyclic trend i.e. the ventilation rates are minimum during 8 am, 10 am and 6 pm and during the afternoon time 12 pm, 2 pm and 4 pm it reaches maximum values. Most of the times, the ventilation rate estimated by energy balance model is lesser compared to physical

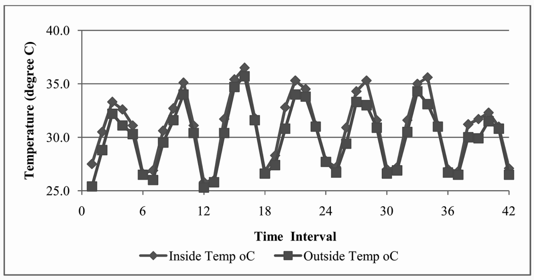

Fig. 6. Variation of temperature inside and outside greenhouse.

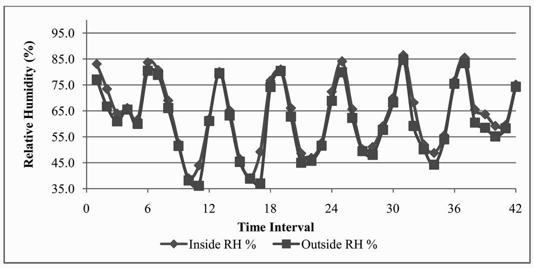

Fig. 7. Variation of relative humidity inside and outside greenhouse.

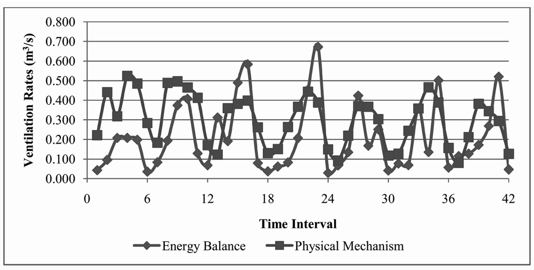

Fig. 8. Variation of ventilation rates calculated using the two approaches.

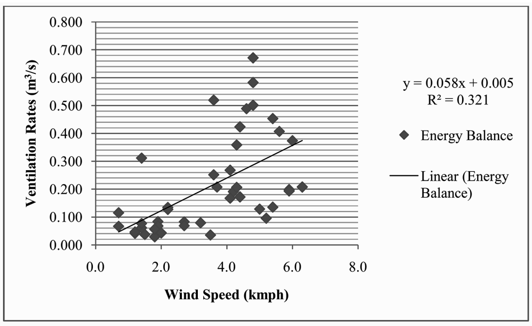

Fig. 9. Wind speed vs Ventilation rate from EBM.

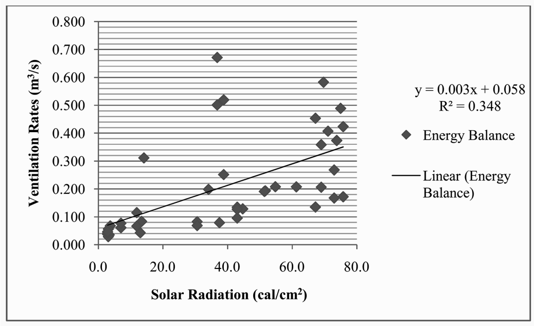

Fig. 10. Solar radiation vs Ventilation rate from EBM.

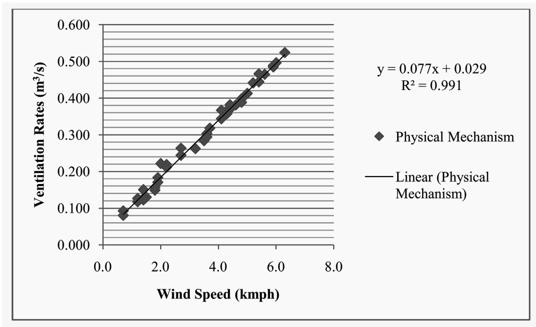

Fig. 12. Wind speed vs Ventilation rate from PMA.

mechanism approach.

The regression analysis between ventilation rate estimated from EBM and the parameters like wind speed, solar radiation and inside temperature is shown in the Figs. 9 to 11 and the regression analysis between ventilation rate estimated from PMA and the para meterslike wind speed, solar radiation and inside temperature is shown in the Figs 12 to 14 respectively. The ventilation rate estimated by EBM showed poor correlation with the inside temperature (R^2 = 0.33), solar radiation (R^2 = 0.34) and wind speed (R^2 = 0.32). The ventilation rate estimated by PMA had good correlation with wind speed (R^2 = 0.99) but poor correlation with inside temperature (R^2 = 0.57) and solar radiation (R^2 = 0.64). Similarly, Tietel and Tanny (1999) showed that effect of ventilation increase with increase in wind speed and decrease in solar radiation. Teitel et al. (2008) also gave similar results indicated that the ventilation rate increases linearly with wind speed in which the experiments were carried out in a naturally ventilated mono-span greenhouse with continuous screened side vents. A regression model is proposed to estimate the ventilation rate based on the measured wind speed which is as follow as :

$$y = 0.077x + 0.029 \tag{13}$$

Where y is ventilation rate in m^3s^{-1} and × is wind speed in kmph. By knowing the wind speed from weather station, ventilation rate for similar greenhouse located in semi-arid region having natural vent can be estimated.

Conclusion

Natural ventilation is probably the most important low cost method of climate control in the greenhouses. To optimize the design and operation of natural

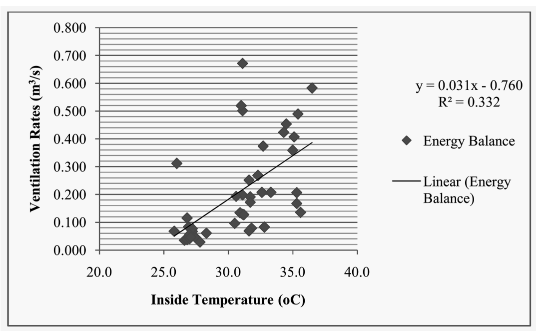

Fig. 11. Inside temperature vs Ventilation rate from EBM.

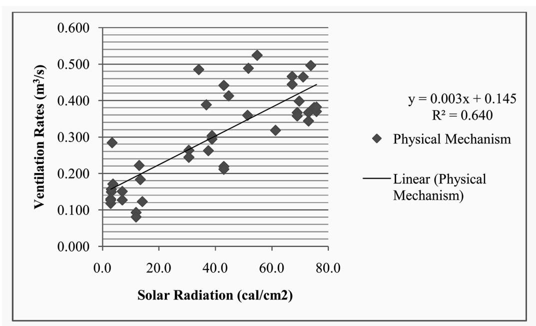

Fig. 13. Solar radiation vs Ventilation rate from PMA.

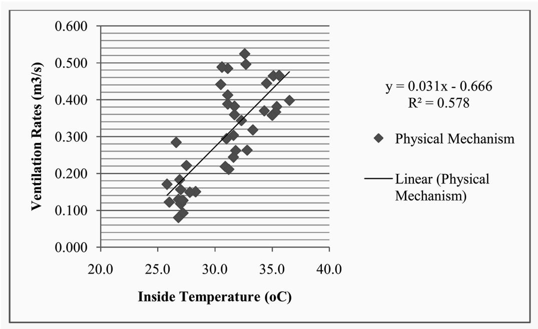

Fig. 14. Inside temperature vs Ventilation rate from PMA.

ventilation systems, it is mandatory to understand the natural ventilation mechanism quantitatively. In view of this, two simple models i.e. energy balance model and physical mechanism approach, were used to determine the ventilation rates on hourly basis for a greenhouse located in semi-arid region. The estimated ventilation rates were compared with parameters like inside temperature, solar radiation using regression analysis. The results showed that the ventilation rate varied linearly with the wind speed. Finally, a simple regression model is proposed to estimate the ventilation rate based on the measured wind speed directly.

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