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Research Paper :

Thermal modeling and its experimental validation in predicting and controlling environmental parameters inside a greenhouse

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ABSTRACT

The present work was carried out to study the thermal behaviour of greenhouse by developing a suitable analytical model by which inside environmental conditions can be predicted corresponding to the outside atmospheric situation. Based on the predicted inside conditions, heating and cooling requirements for a particular crop can be decided to maintain suitable environment for the crop. The various controlling parameters *i.e.*, solar radiation, ambient air temperature, transmittance of greenhouse cover, ventilation, relative humidity etc. have been taken into consideration for studying the thermal behaviour of the naturally ventilated greenhouse. For quantitative analysis of the model developed, numerical calculations have been made to predict the effects of the above controlling parameters on the thermal behaviour of the greenhouse. The model developed has been validated for typical days in the months of September 2009 to February 2010 to know its accuracy and found to be in fair agreement between experimental and theoretical values. Various controlling parameters can accordingly be adjusted suitable for the better growth of a plant inside the greenhouse after studying the thermal bahaviour of greenhouse through the model developed.

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Key words : Greenhouse, Solar energy, Thermal modeling, Shade net

The control of various environmental parameters like solar radiation, air temperature, transmittance of greenhouse cover, ventilation, relative humidity inside the greenhouse, suitable for favourable growth of plant can be studied mathematically by developing a suitable thermal model, which is required to optimize those parameters involved in either heating or cooling of greenhouse. The modeling can also be used to optimize greenhouse air temperature (one of the important constituents of the environment inside the greenhouse) for higher yield of a plant inside greenhouse for a given climatic condition (Singh and Tiwari, 2000). The objective of designing a greenhouse is to maximize yield from a plant by providing suitable environmental conditions. Thermal modeling requires basic energy balance equations for different components of greenhouse system for a given climatic (solar radiation, ambient air temperature, relative humidity, wind velocity etc.) and design (volume, shape, height, orientation, latitude etc.) parameters. Basic knowledge of heat and mass transfer is also of great importance in deriving energy balance equation for heating and cooling operations of a greenhouse under given climatic conditions (Nelson, 1985). The transfer of heat energy occurs as a result of driving force called temperature difference and mass transfer takes place in the form of evaporative heat transfer.

To facilitate the modeling procedure, a greenhouse is considered to be composed of a number of separate but interactive components (Sharma, 1998). These are greenhouse cover, the floor, the growing medium, enclosed air and the plant. The crop productivity depends on the proper environment and more specifically on the thermal performance of the system. The thermal performance of a greenhouse can be studied with the help of a mathematical model with suitable assumptions. Energy balance equations are derived to formulate the model, which permits the prediction of environmental conditions in a greenhouse from outside atmospheric conditions (Das, 2010).

In this study, an attempt has been made to develop a mathematical model based on energy balance equations for each component of the greenhouse. The mathematical model so developed would be validated by the recorded experimental findings for its applicability in enhancing production and productivity of a crop in a given climatic condition with the following objectives to develop a thermal model for predicting environmental parameters like temperature, humidity and light intensity in a greenhouse and to validate the model so developed for knowing its accuracy.

METHODOLOGY

Experimental site:

A semi circular shaped greenhouse (Fig.1) covering the floor space of 4 m x 12 m (48 sq m) oriented in East-West direction was used for study. The greenhouse was covered with ultra violet (UV) low density polyethylene (LDPE) film of 200 micron thickness. The greenhouse was covered with a netlon make shade net of 50 per cent as a shading device as and when required.

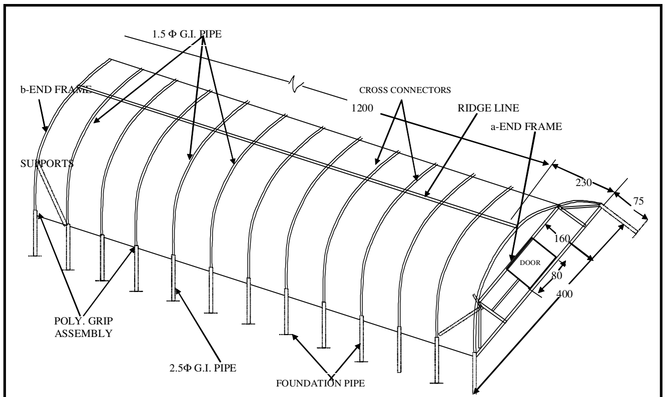

Fig. 1 : Semi cylindrical greenhouse (all dimensions in cm)

The experimental greenhouse is located in the nursery site of the Department of Horticulture, Orissa University of Agriculture and Technology, Bhubaneswar and experimental observations were taken during the year 2009-10. The place is situated at $20^0$15'N latitude and $85^0$52'E longitude with an elevation of 25.9 m above the mean sea level and nearly 64 km west of the Bay of Bengal and coming under the warm and humid climatic condition. The mean air temperature varies from 25 to 37.17^{0}C in summer, 24.53 to 32.72^{0}C in rainy and 14.88 to 28.33^{0}C in winter seasons. The photograph of experimental greenhouse is shown in Fig. 2.

Energy balance equation for a greenhouse:

The energy balance equations for various components of greenhouse with energy flow processes (Fig. 3) can be written on the basis of following assumptions:

– Analysis is based on quasi-steady state condition
– Storage capacity of greenhouse cover materials is neglected

Fig. 2 : Photograph of experimental greenhouse

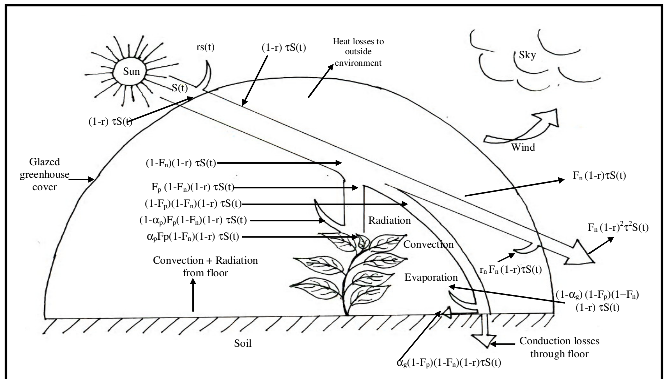

Fig. 3 : Cross sectional view of a greenhouse with energy flow at different components

– Absorptivity and heat capacity of air is neglected
– Heat flow in the ground is one dimensional
– Thermal properties of plants in the greenhouse are nearly same as those of water
– There is no radiative heat exchange between the walls and roofs of greenhouse due to negligible temperature differences

The energy balances for various components like plant mass, floor and air of greenhouse can be written as follows:

Greenhouse plant mass

[Rate of thermal energy absorbed by plant mass in the greenhouse] = [Rate of thermal energy stored in the plant mass] + [Rate of thermal energy transferred from plants to greenhouse air]

Greenhouse floor

[Rate of thermal energy absorbed by the greenhouse floor] = [Rate of thermal energy transferred from ground surface to greenhouse air] + [Rate of thermal energy conducted into the greenhouse floor]

Rate of thermal energy conducted into the ground is equal to the rate of overall heat transfer from floor to the higher depth of ground.

Greenhouse enclosed air

[Rate of thermal energy retained in greenhouse air after absorption by plant mass] + [Rate of thermal energy retained in greenhouse air after absorption in floor] + [Rate of thermal energy retained in greenhouse air after reflected from glazed north wall]

+ [Rate of thermal energy transferred from plants to greenhouse air] + [Rate of thermal energy transferred from floor to greenhouse air] = [Rate of overall heat loss between greenhouse air and ambient air] + [Rate of thermal energy lost due to ventilation]

The above energy balances can be solved mathematically for determining the temperature of greenhouse air and plants (Das, 2010).

Computational procedure and input parameters:

The mathematical model has been solved with the help of the computer programme. Numerical calculations were made corresponding to the hourly variations of solar radiation and ambient air temperature for typical winter days (clear sunny days (Sept. 2nd 2009), (Dec. 12nd 2009), (Jan. 15th 2010) and (Feb. 5th, 2010) of Bhubaneswar. Solar radiation falling on different walls and roofs of the greenhouse was calculated with the help of Liu and Jordan formula by using the beam and diffuse components of solar radiation incident on the horizontal surface. The input parameters and design parameters has been used for experimental validation. Hourly variations of air and plant temperatures for greenhouse enclosure both during day time and night time were recorded during experimentation. While studying the effects of parameters like infiltration/ ventilation, relative humidity, heat capacity of plants, transmissivity of greenhouse cover, absorptivity of plant, plant area on the temperatures of air and plants inside the greenhouse, the single parameter was changed and others were kept constant. For analysis of thermal environment of greenhouse, quasi-steady state method was used. In order to verify the accuracy of the model developed, the predicted values of temperatures of air and plants inside greenhouse were validated against the experimental results for typical sunny days. The closeness of predicted and experimental values has been presented with coefficient of correlation (r) and root mean square of per cent deviation (e).

RESULTS AND DISCUSSION

The experimental validation of the model developed was carried out for typical days during November, 2009-February, 2010. The experimental and the predicted values of plant and air temperatures (T_p and T_r) of greenhouse along with ambient air temperature (T_a) for typical days during 08.11.2009, 17.12.2009, 12.01.2010 and 06.02.2010 have been shown in Fig. 4 to Fig. 7. It can be observed from the figures that the predicted values of plant and greenhouse air temperatures were fairly close to their experimental values. Thus, there was a fair agreement between the experimental and predicted values. The model, therefore, developed can be used for prediction of temperatures inside the greenhouse both in heating and cooling mode of operation.

The statistical analysis of the experimental and the theoretical values of the plant and the enclosed greenhouse air temperatures was carried out by linear regression method to determine the correlation ship between the two. From the value indicated in the figures, it is seen that the coefficient of correlation (r) and root mean square per cent deviation (e) for the experimental and predicted values of plant (r_p and e_p) and enclosed greenhouse air temperatures (r_r and e_r) vary from 0.92 - 0.96 and 5.89 - 8.84 per cent, respectively which were within the permissible range for the accuracy in analysis.

The greenhouse when covered with shade net, the enclosed greenhouse air temperature (T_r) and plant temperature (T_p) attained the highest value at around 1-2 pm, which was also not good for the crops. At this stage the sides of the greenhouse were kept opened for natural ventilation and also there was an appreciable reduction in the plant temperature (T_p) during these peak sunny hours due to shade effect, which reduced the entry of incoming solar radiation. During peak sunny hours the greenhouse air temperature inside the shade net was 2 to 3 ^{0}C higher than the ambient air temperature and in the night hours, the inside temperature was 3 to 5^{0}C higher than the ambient air temperature which is more congenial for plant growth in the typical coastal winter days. The observed plant temperature inside shade net during peak sunny hours was 1 to 2^{0}C lower than ambient temperature and during night hours also it is observed that, the plant temperature was 2 to 4^{0}C more than the ambient temperature. During the night hours the greenhouse air as well as plant temperatures remained with a higher value due to the blanket effect of the shade net which was fairly good for the plants during peak winter days.

Greenhouse with shade net increased greenhouse air temperature up to 3 ^{0}C than the ambient air temperature during peak sunny hours in winter days which was more suitable for plant growth than greenhouse without shade which increased temperature up to 7^{0}C. Also during night hours in winter days shade net increased greenhouse air temperature up to 5^{0}C, but greenhouse without shade net the temperature increased only up to 2^{0}C.

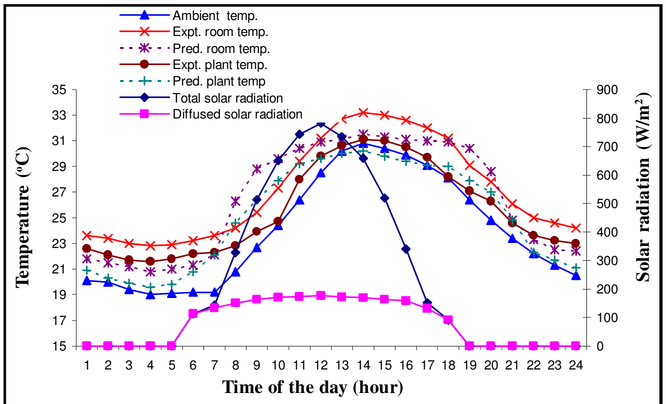

Fig. 4 : Hourly variation of plant and greenhouse air temperatures (experimental and predicted, ambient air temperature and solar intensity of greenhouse covered with shade net on 8.11.09)

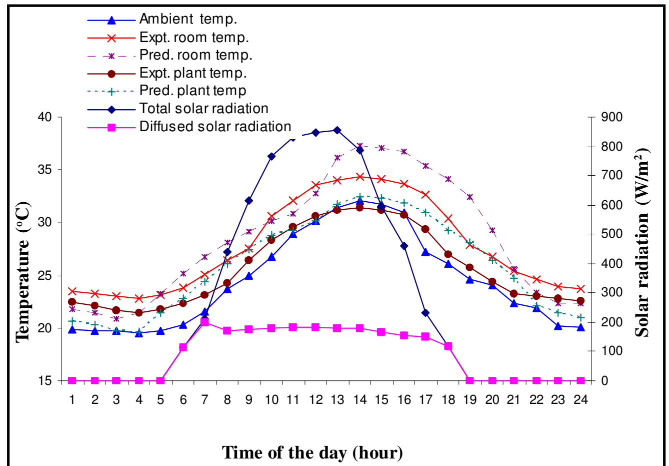

Fig. 7 : Hourly variation of plant and greenhouse air temperatures (experimental and predicted, ambient air temperature and solar intensity of greenhouse covered with shade net on 06.02.10)

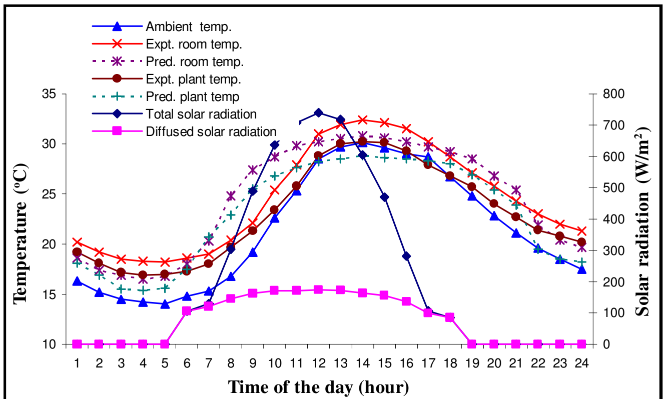

Fig. 5 : Hourly variation of plant and greenhouse air temperatures (experimental and predicted, ambient air temperature and solar intensity of greenhouse covered with shade net on 17.12.09)

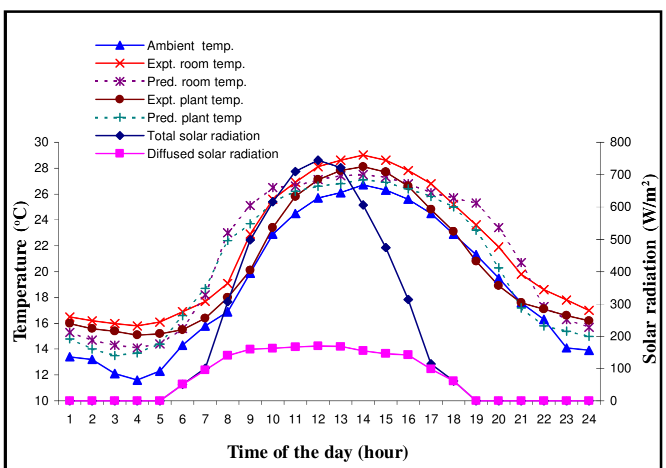

Fig. 6 : Hourly variation of plant and greenhouse air temperatures (experimental and predicted, ambient air temperature and solar intensity of greenhouse covered with shade net on 12.01.10)

Taking into account the peak sunny hours and mid night, the variation of temperature was less in case of greenhouse with shade net than without shade net due to the partial elimination of incoming radiation during sunny hours and prevention of the radiative heat losses to the cold night sky for maintaining better heat distribution inside the greenhouse during night hours due to shade. Also adequate ventilation through the side of the greenhouse helps in decreasing the temperature of air inside the greenhouse to the desired level.

Conclusion:

On the basis of the above study, the following conclusions are drawn.

– During peak sunny hours, the greenhouse air temperature inside the shade net was 2 to 3^{0}C higher than the ambient air temperature and in the night hours, the inside air temperature was 3 to 5^{0}C higher than the ambient air temperature.

– The observed plant temperature inside the greenhouse with shade net during peak sunny hours was 1 to 2^{0}C lower than ambient air temperature and during night hours it is observed that, the plant temperature was 2 to 4^{0}C more than the ambient air temperature.

– Natural ventilation was done (10 am to 4 pm) to keep the greenhouse air temperature within 3 to 4 ^{0}C lower than the ambient air temperature to make it suitable for the growth of the crops inside the greenhouse.

– The predicted air and plant temperature inside greenhouse with shade net by the model developed are in good agreement with experimental values which has been confirmed by statistical analysis.

– Based on predicted temperature, crop to be grown inside the greenhouse can be decided. Also based on the predicted temperature, heating or cooling requirements for maintaining required temperature conditions for a particular crop inside the greenhouse can be evaluated for better plant growth and higher yield.

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