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Heliogreenhouse Air Temperature Forecasting Technology Research

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Abstract: Based on the comparison and observations of the internal and external meteorological conditions of the heliogreenhouse, BP neural network, stepwise regression and energy balance principle were used, respectively, to construct the greenhouse air temperature prediction model. The results showed that although the BP neural network-based prediction model had a high forecasting accuracy, due to the comparatively different growth characteristics of cultivated crops, there was a lack of wide adaptability of services; the mechanism of the prediction model constructed by the energy balance principle was strong, but it was difficult to obtain the relevant parameters and had a poor prediction accuracy and a short effective service period; the greenhouse temperature prediction model constructed by the stepwise regression had a comparative advantage over the previous two models and the forecasting effectiveness can be for the next 1-7 days.

Keywords: Air temperature, forecast, heliogreenhouse, model

INTRODUCTION

The heliogreenhouse created by the Chinese farmers and transformed by the scientists is one of the cultivation structures of the major facilities with typical Chinese characteristics. It mainly made the efficient production of the horticultural crops and anti-season cultivation as industrial orientation. The output value per unit area is generally up to 7 to 10 times of field grown or even higher. Since the 1980s, in northern China, the heliogreenhouse has developed rapidly and become the local rural economic pillar industries in autumn, winter and spring (He and Ma, 2007; Yang, 2010; Li *et al*., 2008). Because of the relatively simple structure of its facilities and the poor ability to resist natural disasters and adversity, its production has a great dependence on external weather conditions. For this reason, the reasonable regulation of the greenhouse climate according to the external weather conditions is critical to production, while based on the external meteorological factors of the greenhouse and the forecast information, it is particularly important to carry out the prediction of the greenhouse microclimate factors. At present, the professional heliogreenhouse microclimate forecasting is still at its initial stage.

Relatively large number of domestic and foreign scholars aimed at the research of greenhouse microclimate simulation (Xin *et al*., 2006). Based on previous studies, Kindelan (1980) fully considered the thermal properties of the greenhouse soil and the characteristics of vertical distribution and the dynamic model of the greenhouse thermal environment was established. Avissar (1982) conducted a validation study to numerical climate models based on the greenhouse physical and biological processes. Kurpaska and Slipek (1996) carried out test observations of variation characteristics of temperature in different depths of soil under heating conditions of hot air and established a corresponding greenhouse thermal environmental model (Kurpaska and Slipek, 1996). Wang Shaojin applied the Brooklyn greenhouse dynamic model used by large glass greenhouses to plastic greenhouses and the greenhouse microclimate of different climatic conditions was stimulated (Wang and Deltou, 1995; Wang and Zhu, 1997). Li *et al*. (1994) made use of the basic theories of thermodynamics, heat transfer and architectural lighting to simulate and analyse the effects of the dynamic process and distribution patterns of the environmental parameters in the heliogreenhouse as well as solar radiation, greenhouse structures and covering materials on the environmental parameters. Chen and Wang (1996) used the theories of heat transfer and bioenvironmental engineering and established the dynamic mathematical model of the heliogreenhouse thermal environment. The quantitative interpretation of the variation of the heliogreenhouse thermal environment was obtained by solving the model and they proved that the model can be used to simulate the variation patterns of heliogreenhouse indoor air temperature and humidity as well as the greenhouse walls and the soil heat transfer. Xin *et al*. (2006) used the heat balance principle and established the heliogreenhouse environment prediction model, which has the ability to predict the temperature and humidity in the greenhouse. On the basis of algorithm optimized artificial neural network prediction method, He and Ma (2008) established a neural network model for forecasting the air humidity of solar

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greenhouses during winter in North China. Although domestic and foreign scholars had conducted extensive research on the greenhouse climate models, the foreign researches mainly concentrated on the glass or large multi-span modern greenhouses (Teitel *et al*., 2009; Teitel and Tanny, 1999; Bournet *et al*., 2007) and the related models lacked adaptability compared with the heliogreenhouse with typical Chinese characteristics. However, because of more parameters and input variables (Dai *et al*., 2006) involved, the domestic research could not be applied to conventional business services.

In this study, based on the comparison and observations of the internal and external meteorological conditions of the heliogreenhouse, the stepwise regression, BP neural network and the energy balance principle were used, respectively, to construct the greenhouse air temperature prediction model for dynamic forecasting. The advantages of prediction accuracy and effective period were compared, in order to provide the technical support for heliogreenhouse microclimate forecasting service.

EXPERIMENTAL DESIGN AND RESEARCH METHODS

Experimental design: The experiment was conducted from December 2007 to May 2010 in Shouguang, Shandong Province. In this experiment, the energy-saving heliogreenhouse was used, with single-sided slope as the structure type, facing south, east-west direction, with a span of 10 m and length within 70 m. There were steel integration semi-arch trusses in the front of the slope and rear of the slope. The wall height of the rear slope was 4 m; the ridge height was 1.5 m. The three walls facing east, north and west are solid walls with thickness of 1 m. The greenhouse covering films used were polythene anti-fogging films with the light transmission coefficient of 75%. The greenhouse films were covered with straw mats and the basic management method was to daily expose the straw mats after 08:00 and cover with the straw mats at 16:00. Usually when the greenhouse indoor temperature reached 29°C, the natural ventilation was carried out. In winter, the width of the ventilation opening was 5 cm and the ventilation time was 1 h. In spring and autumn, the vent width was 20 cm and the ventilation time was 2 h. The ZQZ-A automatic weather station was used as the apparatus for the observation of meteorological factors inside the greenhouse. The factors observed were indoor air temperature, humidity, radiation and ground temperature (0, 5, 10, 20, 40 cm) and data was collected once per hour. The external meteorological data of the greenhouse originated from the Shouguang automatic weather station. The crop planted inside the greenhouse was sweet pepper (*Capsicum frutescens* L. grossum Bailey) and the cropping pattern was ridge culture; planting density was 4 plants per/m^2; the field management was carried out under the requirements of high-yield cultivation. The leaf area index was measured every 20 days; the observational instrument was the United States LI3000C Desktop Leaf Area Meter.

Research methods and principles: Modelling based on BP neural network. BP (Back Propagation) network is a multilayer feed forward network trained by the error back propagation algorithm and able to learn and store large amounts of input-output model mapping relations and does not require the mathematical equations describing the mapping relations to be revealed beforehand. The construction of the model constituted of both the forward propagation and error back propagation processes and its learning rule was to use the steepest descent method, undergoing back propagation to adjust the network weights and thresholds so that the sum of error squares of the network was smallest. The model topological structure included the input layer, hide layer and output layer.

Modelling based on stepwise regression method. The floor and the walls of the greenhouse are all heat storage systems in the heliogreen house. During the day, the solar radiation is absorbed and heat is stored; at night, heat dissipates to the surroundings in the form of the long-wave radiation; the external weather conditions certainly have lagged effects on the greenhouse microclimate. For this reason, during the construction of the prediction model, the previous meteorological factors were all used as dependent variables for screening of the influencing factors. In this study, the greenhouse indoor temperature, relative humidity, surface temperature, 5 cm, 10 cm, 20 cm, 40 cm ground temperature average value, maximum value and minimum value as well as the greenhouse outdoor temperature, relative humidity, wind speed, sunshine hours, average daily total cloud amount were mainly considered and the five or six main influencing factors were selected by the stepwise regression method to construct forecasting models. In addition, the solar elevation angle was considered as the driving factor.

Modelling based on the energy balance method. The internal air of the greenhouse would be considered as a whole, assuming that the air mixed evenly. The heating and cooling of the air was mainly decided by the exchange of sensible heat and latent heat in the greenhouse system, which includes the solar radiation, the greenhouse internal and external heat exchange caused by natural ventilation, the sensible heat exchange between air and crops, the sensible heat exchange between the air and the soil surface within the greenhouse, crop transpiration, soil surface evaporation, roof condensation (Fig. 1). The energy consumption of crop respiration and photosynthesis is negligible; the greenhouse energy balance model equation is as follows:

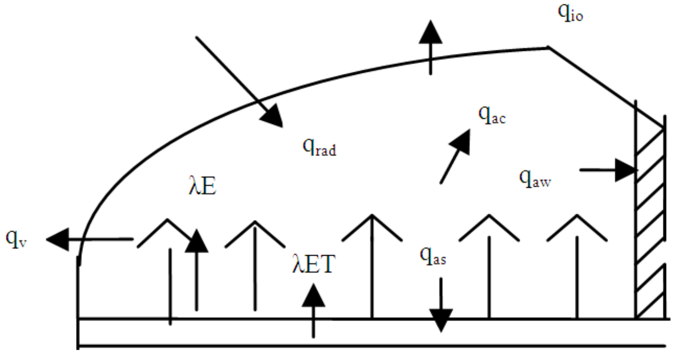

Fig. 1: Heliogreenhouse energy budget diagram

$q_a = q_{rad}-q_v-q_{i,o}-q_{a,s}-q_{a,c}-q_{a,w}-\lambda E-\lambda ET$

where,

- q_a = The greenhouse energy change caused by the temperature rise and fall
- q_{rad} = The incident solar radiation in the greenhouse
- q_v = The sensible heat exchange capacity caused by the outdoor air ventilation
- $q_{i,o}$ = The heat exchange capacity between the internal air and the external air through the greenhouse covering materials
- $q_{a,s}$ = The sensible heat exchange capacity between the greenhouse air and the soil surface
- $q_{a,c}$ = The sensible heat exchange capacity between the air and the crops in the greenhouse
- $q_{a,w}$ = The sensible heat exchange capacity between the greenhouse indoor air and the rear wall
- λE = The latent heat consumption by crop transpiration
- λET = The consumption of latent heat of vaporization by the greenhouse soil surface
- W/m^2 = The dimension of all of the above
- m^2 = To unit surface area

In this experiment, due to the greenhouse surface being covered with plastic film, the above energy balance equation does not consider the soil surface evaporation and the sensible heat exchange capacity between the air and the soil surface.

TEST METHOD FOR FORECASTING MODEL

The model verification was carried out by the internationally used Root-Mean-Square-Error (RMSE) to analyze the conformity between the measured value and the predicted value; the smaller the RMSE value, the higher the prediction accuracy of the model. RMSE values are calculated as follows:

where,

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - S_i)^2}{N}}$$

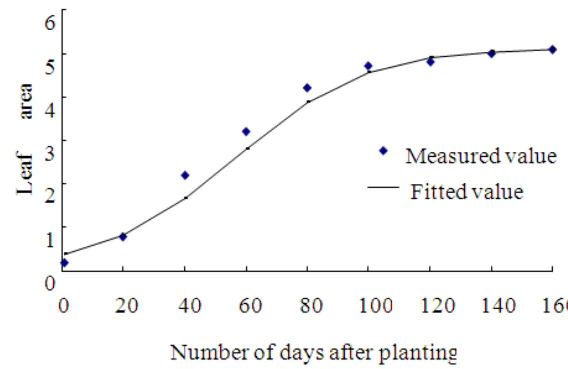

Fig. 2: The relationship of sweet pepper leaf area index with time after planting

where, O_i, S_i, N indicate the actual value, predicted value and the sample size, respectively.

CONSTRUCTION AND ANALYSIS OF THE GREENHOUSE AIR TEMPERATURE PREDICTION MODEL

The greenhouse air temperature prediction model based on bp neural network:

Vegetable leaf area index simulation: The heliogreenhouse microclimate conditions subjected to not only the influence of external weather, but also the morphology of the crops planted inside, while the crop morphological factor showed up as the dynamic change along with the growth and development of the crops (Fig. 2). For this reason, according to the observation data of leaf area index obtained in this experiment, the dynamic changes over time on the leaf area index were simulated and the simulation model of the leaf area index that used day as time-step was obtained:

$LAI = 5.1408/[1+12.98\exp(-0.0458t)]$ $R^2 = 0.9785$.

where,

- LAI = The leaf area inde
- t = The planting time (days)

Table 1: Model training input data and simulation data

Item	Training input data	Number of samples	Simulation data	Number of samples
Spring	1 -10 March 2008	240	11-17 March 2008	168
Autumn	1-10 October 2008	240	11-17 October 2008	168
Winter	24 December 2008-2 January 2009	240	3-9 January 2009	168

After planting the sweet pepper in the greenhouse, the leaf area index for an arbitrary day could be obtained by the abovementioned formula.

Construction and analysis of the BP neural network-based model. From the statistical analysis of the correlation between the greenhouse internal temperature and greenhouse external meteorological factors as well as leaf area index, it was found that there exists a good correlation between the factors including the greenhouse external air temperature, relative humidity, radiation as well as leaf area index and the greenhouse internal air temperature. Taking the aforementioned factors as input and by means of the BP neural network, the greenhouse indoor air temperature prediction models were constructed for spring, autumn and winter. Due to the large difference in the order of magnitude between various factors, normalization processing was applied to each factor of a sample respectively, which enabled the data after normalizing the factors to fall into the interval [0, 1] and eliminated the impact of the various dimensions.

In the construction process of the model, through continuous adjustment, the parameter values associated with the final selection were: initial learning rate η = 0.1, maximum number of iterations = 1000 times, the target error = 0.001. The training input data and the simulation data of the model are shown in Table 1.

The constructed model was used to carry out forecast prediction for the greenhouse indoor temperature in January-February 2010. From the comparison chart of the forecast value and the actual value (Fig. 3), it can be seen that the variation trend of the greenhouse indoor air temperature predicted values and the measured values was basically the same; the RMSE value between both was 1.9°C.

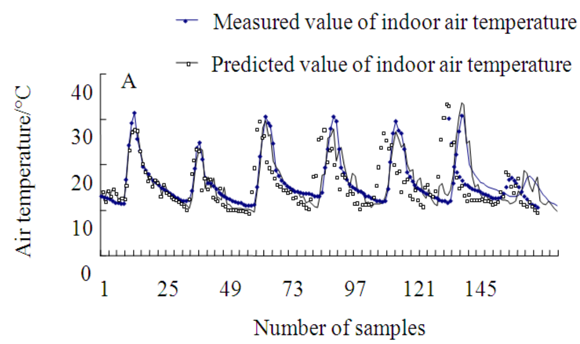

Fig. 3: Comparison of predicted and measured values of indoor air temperature in winter

GREENHOUSE AIR TEMPERATURE PREDICTION MODEL BASED ON THE STEP REGRESSION MODEL

For the characteristics of heliogreenhouse in Shandong province, according to different seasons of the month (December to February, March, April, May), weather types (sunny, overcast sky, cloudy), three periods within one day (0:00-7:00, 8:00-17:00, 18:00-23:00), the classification criteria of which type of weather is: sunny, 0≤cloud amount≤2; cloudy days, 2≤cloud amount≤8; overcast sky, 8≤cloud amount≤10 and using the greenhouse indoor microclimate automatic observation stations as well as the forecast values for external maximum and minimum temperature and other meteorological factors, respectively, the greenhouse indoor air temperature prediction model was constructed.

Figure 4 to 6 is a 1:1 comparison chart of the predicted values and the measured values of greenhouse indoor temperatures in different weather types during January-February 2010 using prediction model. The results showed that the three hour period (0:00-7:00, 8:00-17:00, 18:00-23:00) average forecast error in sunny conditions was 0.44°C, 3.10°C and 0.67°C, respectively; the three hour period average forecast error for cloudy days was 0.40°C, 3.59°C and 0.93°C; the average error for overcast days was 0.28°C, 1.77°C and 0.19°C. The predicted values and measured values of the overcast days were more consistent than those of sunny or cloudy days, mainly because the greenhouse was ventilated for a short time or was poorly ventilated during overcast days, the change of the greenhouse indoor temperature was affected largely by the meteorological factors of outside and inside the greenhouse. At the same time, the meteorological factors of the previous one or two days by the greenhouse soil, walls and other thermal mass indirectly had a greater impact on the greenhouse temperature. The comprehensive analysis of all the predicted and measured values under the three types of weather conditions, the stepwise regression method was used to construct the prediction model with the average RMSE value of 2.53.

GREENHOUSE MICROCLIMATE PREDICTION MODEL BASED ON ENERGY BALANCE

Based on the energy balance principle and using the observational data of greenhouse microclimate

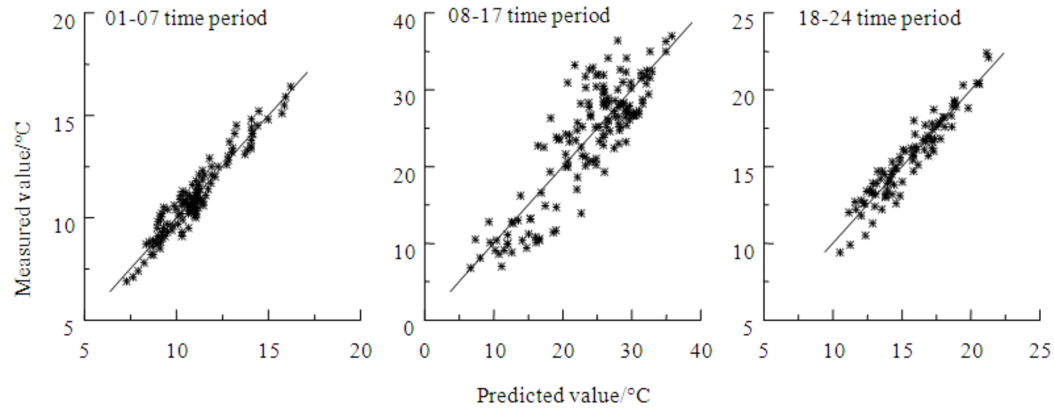

Fig. 4: Comparison of the predicted and measured values of the heliogreenhouse indoor temperature in sunny days

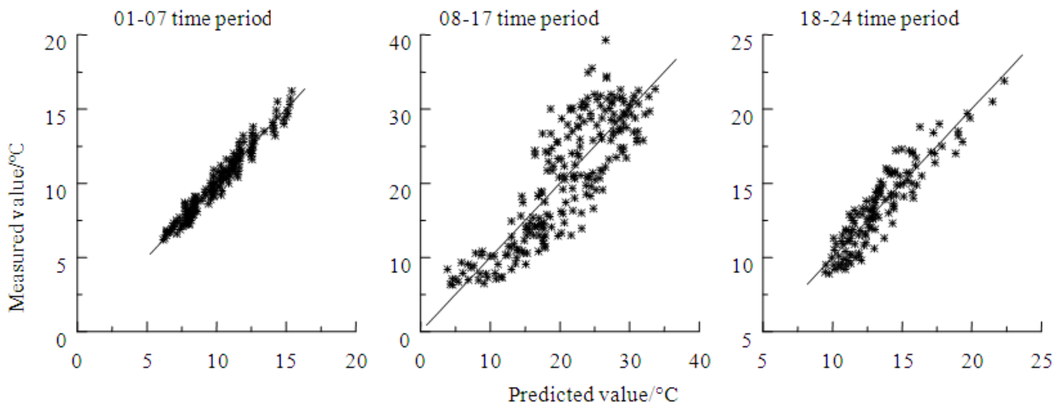

Fig. 5: Comparison of the simulated and measured values of the heliogreenhouse indoor temperature in cloudy days

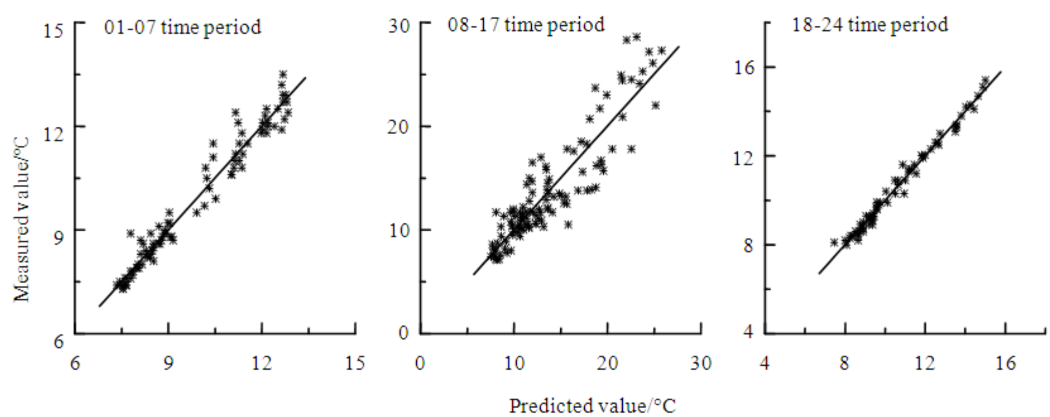

Fig. 6: Comparison of the simulated and measure values of the heliogreenhouse indoor temperature in overcast days

factors, the greenhouse temperatures for 2-27 February 2010 were simulated and forecasted, in which the sweet pepper leaf area index was 3.5 and the prediction time step was 1 h. Figure 7 shows a comparison of the predicted and measured values. From Fig. 7, it could be seen that after 1 h, the predicted and measured values of greenhouse indoor temperature had an RMSE value of 3.42 predicted by using the model.

CONCLUSION AND DISCUSSION

In this study, based on the internal and external meteorological data of the heliogreenhouse and using the three kinds of methods including BP neural network, stepwise regression and energy balance, the greenhouse hourly temperature prediction model was constructed and the basic information needed for

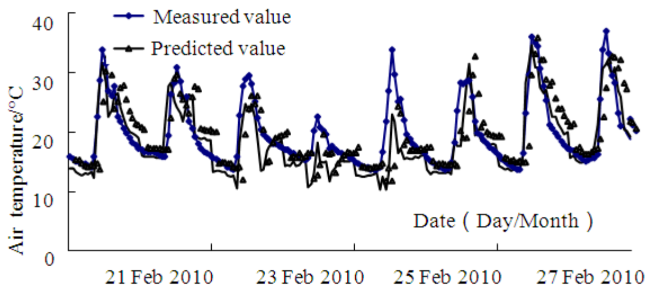

Fig. 7: Comparison of predicted and measured values of indoor temperatures (2011)

business application of the three kinds of methods was pointed out, which provided technical support for the meteorological department to carry out heliogreenhouse meteorological services; however, the abovementioned three kinds of methods had advantages and disadvantages.

Due to the interactions between the crops in the greenhouse and the microclimate, the authors used the BP neural network to construct the model and not only considered the external meteorological influencing factors but at the same time, the dynamic changes of the vegetable leaf were used as an input factor and compared to the prediction model constructed by He and Ma (2008), this model had a certain degree of universality because of its ability to better reflect the nonlinear characteristics between the dependent and independent variables more fully. Since the changes in the greenhouse external environmental conditions were classified as open and non-reproducible, the model was based on existing observational data; the sample data used to train the model was limited and did not reflect all hidden information, which implied that its prediction accuracy had certain constraints.

The stepwise regression method better reflected the relationship between the internal and external meteorological elements of the greenhouse under normal conditions. This study gave full consideration to the impact of the greenhouse variation characteristics and the daily production management and according to applied to different weather types and different time periods, the prediction model was established respectively, which reflected the characteristics of the greenhouse temperature more realistically with higher forecast accuracy. However, there was a need to construct more models, heavy workload, in addition, under the extreme weather conditions; its prediction accuracy was affected.

For the model constructed based on energy balance, all kinds of physical processes in the greenhouse were fully considered including latent heat consumed by crop transpiration, long-wave radiation of walls and floors as well as convection heat exchange of indoor air with the walls and the soil covering layer. The mechanism of this model was the strongest. Since for the model, in this study, there were no considerations the heat transfer of the gable walls of the east and west side and the back-roof, latent heat loss of condensation of the covering layer, the open shed ventilation time as well as the exposing or covering of the straw mats time and other factors, so the prediction time and accuracy were subject to constraints.

From the comprehensive analysis of the basic principles and the prediction results of the above-mentioned three kinds of methods, it is concluded that even though the BP neural network model has the highest accuracy, the further testing and refinement is still needed when it is applied to other crops because the growth characteristics and leaf area index of different crops vary over time. The energy balance method has a good mechanism and can provide technical support for the structural design and planting regionalization of the greenhouse. In the actual business service, the relevant parameters are not readily available, resulting in limited prediction time and accuracy as well as poor universality. The stepwise regression method is based on the preliminary actual observed data outside the greenhouse and future weather forecast as the driving factors and the weather types and the period of time have been considered, having higher prediction accuracy and universality. The prediction time is the next 1-7 days and this model is more suitable for carrying out facilities for agriculture meteorological services at present in the meteorological department.

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