STUDY ON THE CHANGE RATE OF THE INDOOR TEMPERATURE OF A SUNKEN SOLAR GREENHOUSE
/
下沉式日光温室温度变化机制的研究

Weiwei CHENG, Zhonghua LIU* [1]
Shanxi Agricultural University, College of Urban and Rural Construction, Taigu/China
Tel: +86-0354-6287420; E-mail: chengweiwei280@126.com
Corresponding author: Zhonghua LIU
DOI: https://doi.org/10.35633/inmateh-68-12

Keywords: *sunken solar greenhouse, thermal environment, change rate, wire sensor*

ABSTRACT
A sunken solar greenhouse has a good heat preservation environment. The influence of the general indoor temperature on the temperature of the roots was evaluated. A wireless sensor and U disk recorder were used to determine the indoor temperatures of a single section and multiple sections in a sunken solar greenhouse. The results showed that the temperature change rate was the greatest along the vertical direction of the greenhouse and less along the longitudinal direction of the greenhouse at the moment of opening in the morning and at the moment of strong light at noon. The temperatures in the single cross-section and multiple cross-sections were approximately equal during winter from 00:00 to 8:00 in the morning. These values can be used for calculating theoretically the heat loss in a greenhouse.

摘要
下沉式日光温室温室保温效果较好，室内温度会影响植物根区温度，利用无线传感器和 U 盘记录仪测定室内单截面和多截面的温度值，结果表明:在开启时刻和强光时刻，室内三维方向的温度变化速率由大到小依次为竖向、水平和纵向；冬季 00:00 ~ 8:00，单截面温度值与多截面温度值近似相等，可作为理论公式中计算温室热损失的依据。

INTRODUCTION
The temperature in a solar greenhouse has an obvious diurnal variation pattern and the indoor temperature of a greenhouse can increase by 0.25–3.9°C compared with the open-field temperature *(Wei et al., 2010; Tu et al., 2011)*. *Zhang, (2015),* studied the effects of indoor temperatures and humidity on the growth and fruiting of strawberry and soil-borne diseases in a greenhouse. The results showed that within the range of day at 20–28 °C, night at 5–12 °C and relative humidity of 40%–80%, the combination of temperature and humidity was more beneficial to the growth of strawberry and reduced the occurrence of soil-borne diseases than the individual same temperature and humidity. *Xu, (2018),* conducted an experimental study on the variation of indoor temperature and light in a solar greenhouse in the desert during winter. The results showed that the indoor temperature value fluctuated greatly, and the difference in the indoor temperature between day and night was substantial. The solar greenhouse in the desert could better convert solar energy into heat energy, and the indoor relative humidity was low. Regardless of the weather conditions outdoors, temperature varies in a greenhouse *(Guo and Zhao, 2009)*. In addition, the temperature changes in the vertical direction are more drastic, whilst the changes in temperature distribution in the horizontal direction are more moderate *(Yang XG et al., 2005)*. Considering the internal temperature in the different directions of sunlight in a greenhouse, *Hu et al., (2014),* used a thermometer and wall temperature of a thermistor to measure the sunlight greenhouse and temperature in the east–west central portion of three sections of the greenhouse during the over-wintering stage in the Lishi District. The results showed that the greenhouse temperatures along the vertical, horizontal and longitudinal directions showed regular changes during the day and night. The length of sunshine affected the distribution of the indoor air temperature.

Liu et al., (2013) conducted an experimental study on the characteristics of changes in the indoor air temperature and ground temperature with time and space in a solar greenhouse. The results indicated that indoor air temperature was not evenly distributed in space. *Zhang et al., (2009),* used CFD software to simulate the indoor temperature field of a sunken solar greenhouse during winter.

[1] *Weiwei Cheng, As Lec. Ph.D. Eng.; Zhonghua Liu*, Asoc.Prof.Ph.D. Eng,*

The results showed that the average temperature in the eastern part of the indoor area was lower than those in the western and central parts, and the air temperatures near the indoor wall and ground were higher. *Sun et al., (2020),* also used CFD to study the changes in the internal temperature of a solar greenhouse in different environments. The results demonstrated that ventilation time should be paid attention to in the internal ventilation and dehumidification of a greenhouse during winter to prevent frostbite of crops. *Albright et al., (2001),* proposed a classical model of the indoor temperature and relative humidity in a greenhouse. *Jang et al. (2011),* found that the relationship between crops and the environment in a greenhouse is strong and interactive. *Taki et al., (2016)* found that a high temperature in a greenhouse has a strong impact on crop photosynthesis. This condition affected the crop photosynthetic rate, transpiration rate, intercellular CO_2 concentration and greenhouse output, resulting in economic losses. *Khoshnevisan et al., (2014),* showed that both high and low temperatures inside the greenhouse would affect the quality and quantity of crops planted in the greenhouse. *Cheng et al., (2021),* evaluated the changes in temperature in a sunken solar greenhouse through a single cross-section. In the absence of protective measures, indoor plants would also suffer damage or disease during extreme external temperatures. *Md Shamim Ahamed et al.*, (2020) modelled heating demands in a Chinese-style solar greenhouse using the transient building energy simulation model TRNSYS. *Stefano Morelli et al., (2022)* optimized the temperature field in a greenhouse in order to make it suitable for basil cultivation.

A sunken solar greenhouse is the preferred greenhouse for three-dimensional planting. Previous studies have demonstrated the uneven distribution of indoor temperature in a solar greenhouse. Amongst the various indicators for measuring plant growth, the plant body temperature is the most sensitive factor for the healthy growth of plants, whilst amongst the numerous environmental factors, air temperature is the most synergistic with plant body temperature *(Yu M.H. et al., 2015)*. These two factors have the same trend *(Yu et al., 2015)*. In addition, the matrix temperature of three-dimensional substrate cultivation is also closely related to air temperature *(Shi et al., 2016)*. However, studies have mainly focused on the variation rules of the internal temperature, wall temperature and indoor soil temperature of greenhouses. A qualitative study on the indoor temperature along the horizontal, vertical and longitudinal temperature distribution rate is lacking. However, greenhouses heating is essential to provide favourable climatic conditions for growing plants under cold periods (*Bazgaou A. et al., 2021*). The study of the rate of temperature change in different directions inside the greenhouse can determine the relationship between the rate of change in the three-dimensional direction, thus determining the direction of temperature control, as well as the low and high temperatures, thus providing experimental data support for greenhouse regulation.

MATERIALS AND METHODS

Experimental greenhouse

The experimental greenhouse was a sunken three-dimensional planting solar greenhouse, as shown in Figure 1. The greenhouse faced south with a length of 108 m and a span of 12 m. The sinking depth of the south wall of the greenhouse was 1.2 m, and the width of the south corridor was 1.1 m. The width of the north corridor was 1.2 m. The external height of the back wall of the greenhouse was 4.3 m, and the ridge was 5 m high. The width of the north wall was 6 m at the bottom and 2 m at the top. The main load-bearing skeleton was made of an elliptical steel tube. The frame spacing was 1 m, and the covering material was made of plastic film.

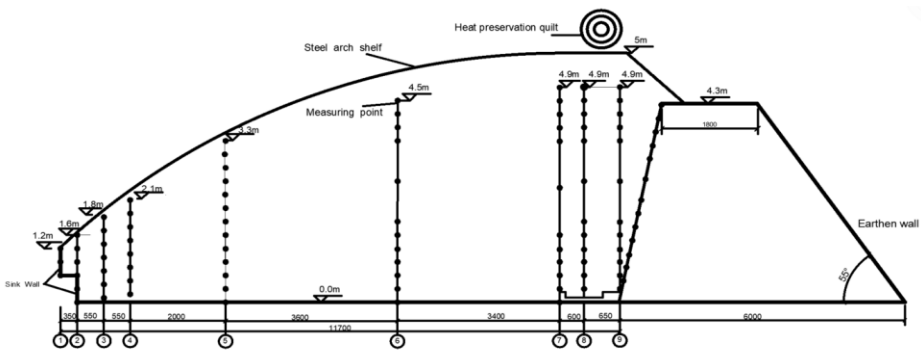

Fig. 1 - Layout of the measuring line and measuring points in the greenhouse

Testing instruments

The indoor temperature and humidity collection instrument in solar greenhouse was the HT59-Li-A1 wireless temperature and humidity collector developed by Shenyang Winen Technology Co., LTD., calibrated by Liaoning Provincial Institute of Metrology Science and coordinated with WG59 gateway and U-disk temperature collection instrument.

The collected temperature and humidity data were transmitted by the wireless temperature and humidity collector to the WG59 gateway through GPRS. The WG59 gateway collected the private network data to the cloud server through the Internet and obtained the data information through mobile phones or computers. Temperature measurement range of the wireless temperature and humidity collection instrument was 40– 85 °C, with an accuracy of ±0.2 °C in the 0–65 °C and ±1 °C in the other temperature range. The transmission period between the wireless temperature and humidity collector and the gateway was 6 min. The data were measured and transmitted continuously for 24 h a day.

The PRECISION Chuang RC-5 temperature recorder and USB automatic data temperature and humidity recorder were adopted. The instrument had a built-in wide temperature CR2032 battery. The recording interval was set to 6 min. The recorder could continuously record for 3 months. The built-in battery was regularly replaced to ensure the continuous operation of the temperature recorder. The temperature range of the recorder was from −30 °C to 70 °C, with accuracy of ±0.5 °C in the temperature range from −20 °C to 20 °C and 1 °C in the other ranges. The USB disk recorder had a built-in NTC thermistor and could store 32000 sets of data.

Test method for single cross-section temperature and humidity in the sunken solar greenhouse

The variation in the indoor air temperature in the horizontal and vertical directions of the greenhouse was substantial, and the rate of indoor temperature in the vertical direction was smaller. When the vertical and horizontal distance changed at the same time, the difference in the temperature in the vertical direction of the indoor temperature was more than 2 times that in the horizontal direction. Therefore, an experimental study on the vertical and horizontal variations of the indoor temperature in the sunken solar greenhouse was firstly carried out; that is, the single cross-section temperature and humidity test. In the test, sensors with smaller spacing were arranged along the vertical and horizontal directions, and the vertical spacing of the measuring points was mostly 300 mm. A total of 96 sensors were arranged. The experiment period was from March 8, 2019 to June 8, 2019 and from August 31, 2019 to December 23, 2019. The temperature and humidity inside the tested greenhouse were tested using the HT59-LI-A1 wireless temperature and humidity tester, and the data were collected at an interval of 6 min.

The cross-section at 30 m from the west wall was selected as the cross-section to be measured, and the coordinate system was established using this cross-section. The intersection point between the indoor ground and the extension line of the sinking wall was 0, and the vertical upward direction was the positive z-axis. The intersection line between the indoor ground and the cross-section was north and was the positive y-axis. The established coordinate system is shown in Figure 1, which illustrates the position of the measuring line. Table 1 provides the heights of the measuring points.

Table 1

Height values of the measured lines and points on the indoor floor (m)

		Line number									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
y-coordinate		0	0.4	0.9	1.5	3.5	7	10.5	11	11.7	WALL
Height of measuring point (m)	1	1.2	1.6	1.8	2.1	3.3	4.5	4.9	4.9	4.9	4.3
	2	0.9	1.3	1.5	1.8	3	4.2	4.6	4.6	4.6	4
	3	0.6	1	1.2	1.5	2.7	3.9	4.3	4.3	4.3	3.7
	4		0.7	0.9	1.2	2.4	3.6	4	4	4	3.4
	5		0.4	0.6	0.9	2.1	2.7	3.7	3.7	3.7	3.1
	6		0	0.3	0.6	1.8	1.8	2.7	2.7	2.7	2.5
	7			0	0.3	1.5	1.5	1.5	1.7	1.7	1.9
	8				0.1	1.2	1.2	1.2	1.4	1.4	1.6

Table 1
(continuation)

	Line number									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
9					0.9	0.9	0.9	1.1	1.1	1.3
10					0.6	0.6	0.6	0.8	0.8	1.0
11					0.3	0.3	0.3	0.5	0.5	0.7
12					0	0	0	0.3	0.2	0.4

Test for the indoor multi-cross-section temperature in the sunken solar greenhouse

Based on the test results, a number of cross-sectional temperature tests were carried out for indoor temperature, with vertical spacing mainly increased to 600 mm. Six positions were selected horizontally and 7 auxiliary sections were selected along the longitudinal direction to explore the variations along the longitudinal, transverse and vertical indoor temperatures.

The experiment lasted from December 26, 2019 to June 2, 2020. The temperature in the sunken solar greenhouse was measured by a wireless temperature sensor and USB disk temperature recorder. In the cross-sections, the intersection point between the indoor ground and the sinking wall was 0, the y-axis was horizontally oriented to the north, and the z-axis was vertically upward on survey line 1. The vertical direction of the sinking greenhouse was the positive direction of the x-axis along the east direction. Figure 2 and Tables 2 and 3 show the position of the indoor cross-sections and the layout of measuring points on the measuring lines at each cross-section. A U-disk type temperature recorder was installed at 1.5 m outdoor height without shelter to record the outdoor temperature.

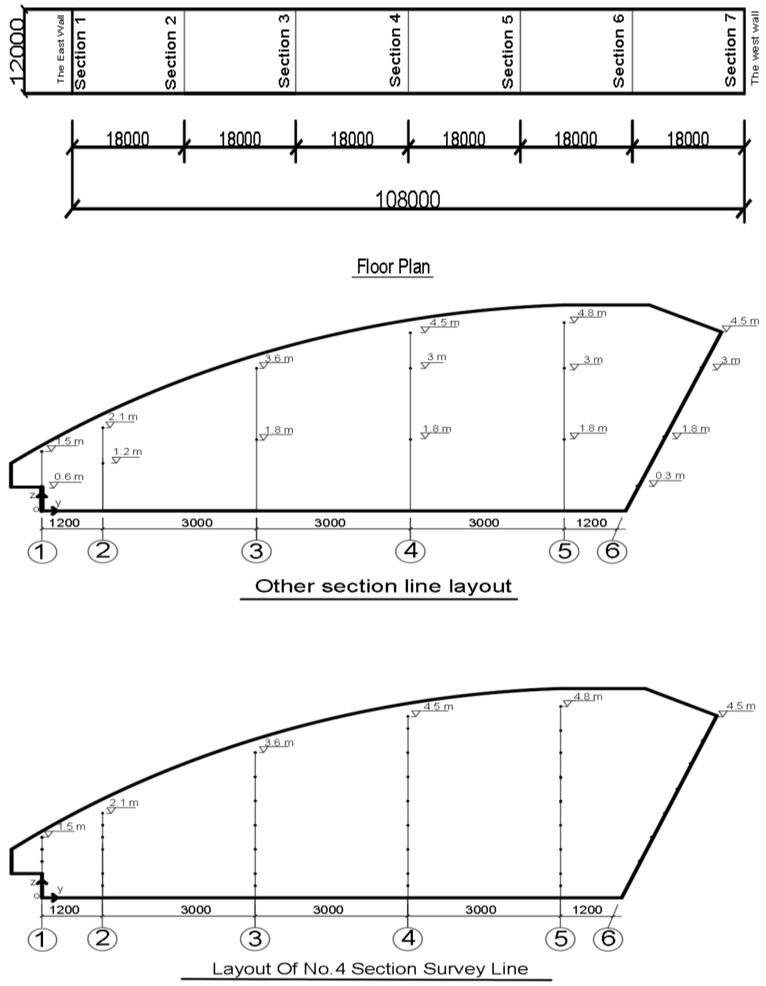

Fig. 2 - Layout of the cross-sectional survey lines and points

Table 2

Layout of the other cross-section survey lines and points (m)

		Line number					
		1	**2**	**3**	**4**	**5**	**6**
y coordinate		0	1.2	4.2	7.2	10.2	墙体
Height of measuring point (m)	1	1.5	2.1	3.6	4.5	4.8	4.5
	2	0.6	1.2	1.8	3	3	3
	3	0	0	0	1.8	1.8	1.8
	4	-	-	-	0	0	0.3

Table 3

Layout of no. 4 cross-section survey line and point (m)

Code number		**Line number**					
		1	**2**	**3**	**4**	**5**	**6**
y coordinate		0	1.2	4.2	7.2	10.2	墙体
Height of measuring point (m)	1	1.5	2.1	3.6	4.5	4.8	4.5
	2	1.2	1.8	3.3	4.2	4.5	3.9
	3	0.9	1.5	3	3.9	4.2	3.3
	4	0.6	1.2	2.4	3.6	3.6	2.7
	5	0.3	0.6	1.8	3	3	2.1
	6	0	0.3	1.2	2.4	2.4	1.5
	7	-	0	0.6	1.8	1.8	0.9
	8	-	-	0.3	1.2	1.2	0.3
	9	-	-	0	0.6	0.6	-
	10	-	-	-	0.3	0.3	-
	11	-	-	-	0	0	-

RESULTS

Distribution of the lowest temperature in a single cross-section during winter

During winter, the earlier the strawberries ripen, the higher the price. Thus, studying the minimum indoor temperature during the flowering and budding period of strawberry in winter is very important to make the harvest early and the strawberry less vulnerable to freezing damage. The lowest outdoor temperature (−12.9°C) was recorded during November–December 2019.

The weather on November 25, 2019 was as follows: clear all day; southwest force, 1–2; sunrise, 7:20; and sunset, 17:13. The shed was opened at 8:28. Given the low room temperature, the quilt was raised to 1/3 span of the greenhouse. All quilts were removed at 9:58, and the upper air outlet was opened for ventilation at 10:15.

The maximum difference in the temperatures at the measuring points on the same measuring line at the same time was 2.9 °C. These points were measuring points 1 and 12 on the measuring line 6. The vertical height difference was 4.5 m, and the change rate of temperature in the vertical direction was 0.64 °C/m. The maximum difference in temperature between the measuring lines at the same time and at the same height was 3.1 °C, and the horizontal distance was 11.7 m. The change rate in the temperature along the horizontal direction was 0.26 °C/m, and the maximum change rate of the temperature in the vertical direction was 11.9 times that in the horizontal direction. Therefore, the temperature distribution in the vertical direction was more uneven than that in the horizontal direction.

During the period from 00:00 to 8:00, the outdoor temperature dropped by 5.4 °C, and the indoor temperature dropped by approximately the same range at each measuring point, with a difference of less than 0.4 °C. The drop in the indoor temperature at each measuring point was 2.4 °C±0.3 °C. Covering using an insulation cotton showed good insulation of the sinking greenhouse. The air temperature in the different areas of the sunken solar greenhouse decreased at the same rate with time at night.

Lowest temperature distribution at the longitudinal multi-section in winter

January 14, 2020 was the coldest day during the winter of 2020, and the lowest outdoor temperature was −19.8 °C. The lowest indoor temperature was recorded at 8:00, and the highest indoor point temperature was determined at 11:48.

The lowest temperature of 86% of the indoor measuring points was lower than 5 °C, which was unfavourable to the growth and development of strawberry. The minimum indoor air temperature of the sunken solar greenhouse varied in the horizontal, vertical and longitudinal directions. This result was consistent with the studies of Sun et al. (2019) and Zhang et al. (2019), but these groups did not study the variation rate of indoor night low temperature in three-dimensional coordinates and the length of the low temperature region.

The maximum difference in temperature was 4.8 °C (the longitudinal horizontal spacing was 90 m) in the measuring points equal to the horizontal distance y from the sinking wall and equal to the height z of the indoor ground, namely, the measuring points at the same height on the same longitudinal section. The change rate of the lowest indoor temperature at night along the longitudinal maximum temperature difference was 0.053 °C/m. For the measuring points with the same cross-section and height, the maximum difference in temperatures of the measuring points was 2.8 °C (horizontal spacing was 7.2 m), and the change rate in the maximum difference in temperature along the transverse direction was 0.38 °C /m. In the same section and measuring line, the maximum difference in the temperatures of the measuring point was 4.2 °C (the vertical distance was 3.6 m) on the measuring line 3 of section 7. The change rate of the lowest indoor temperature at night along the maximum vertical temperature difference was 1.17 °C/m. Thus, the distribution of the indoor temperature along the vertical height had larger inhomogeneity than that along the longitudinal distribution. In addition, the change rate of the maximum temperature along the height direction in the greenhouse was 13 times that along the longitudinal direction and 3 times that along the horizontal direction. Therefore, studying the variations in the indoor temperature distribution in vertical direction of a sunken solar greenhouse is of great significance.

The temperature drop at each section and each measuring point from 00:00 to 8:00 on January 14, 2020 were calculated. The results showed that points 1, 2, 3, 4, 5, 6 and 7 in the corresponding cross-section dropped by 2.7 °C ± 0.4 °C, 2.7 °C ±0.4 °C, 2.6 °C ± 0.4 °C, 2.5 °C ±0.2 °C, 2.6 °C ±0.3 °C, 2.6 °C ± 0.4 °C and 2.8 °C ±0.3 °C. The differences in the temperature drops at the measuring points on each section were less ≤ 0.8 °C, and the temperature drop of the outdoor measuring points was 5.5 °C in this period. The temperature drops of the measuring point were approximately equal in this period.

Distribution law of maximum temperature in a single cross-section during winter

At 11:48, the outdoor temperature was 9.2 °C. At 11:48, the lowest temperature of the measuring points in the single cross-section was 15.6 °C (2–6 measuring points), and the highest temperature was 34.9 °C (10–6 measuring points). The temperature difference between the two measuring points was 19.3 °C.

The maximum temperature difference of the different measuring points on the same measuring line at the same time was 13.7 °C, and the vertical height difference was 4.5 m. At this time, the vertical variation of the indoor temperature was 3.04 °C/m. The maximum temperature difference of measuring points at different horizontal distances at the same time and height was 14.7 °C and the horizontal distance was 11.7 m. At this point, the indoor temperature changed at 1.25 °C/m in the horizontal direction. The maximum change rate of indoor temperature in the vertical direction was 2.4 times that in the horizontal direction. The temperature distribution in the vertical direction was more uneven than that in the horizontal direction.

Distribution law of maximum temperature at the longitudinal multi-section measuring points in winter

The temperature at 11:48 was the maximum value of 85% of the measurement points, and the maximum temperature of each measurement point occurred between 11:42 and 11:54.

At the same height and horizontal distance, the maximum difference in temperature between the measuring points was 13.2 °C (the horizontal distance between the two sections was 36 m). At this point, the change rate in the maximum difference in the indoor temperatures along the longitudinal direction was 0.37 °C/m. The maximum difference in temperature was 5 °C for the measuring points at the same section and at the same height at different horizontal positions (transverse horizontal distance was 7.2 m). The change rate of the maximum difference in temperatures along the transverse direction was 0.69 °C/m. At the same section and horizontal distance, the maximum difference in temperature of measuring points at different water heights was 14.9 °C (the vertical distance between two measuring points was 3 m). At this point, the indoor temperature changed by 4.97 °C/m along the vertical direction. The change rate of the maximum difference in the indoor temperature along the vertical height was 13.4 times that along the vertical direction and 7.2 times that along the transverse direction.

The change rates of the maximum and minimum temperatures in the greenhouse along the vertical direction were greater than those along the horizontal direction. The change rates of the maximum and minimum indoor temperature along the horizontal direction was greater than that along the vertical direction. Therefore, evaluating the law in the vertical change of the indoor temperature in a sunken solar greenhouse is very important.

CONCLUSIONS

In this paper, the law of the change in indoor temperature and humidity of a sunken solar greenhouse was analysed. The following conclusions were drawn:

(1) From 00:00 to 8:00 in winter, the difference in the temperature drops of the measuring points in the single cross-section was less than 0.4 °C, whilst this difference in the multi-cross section was less than 0.8 °C. The temperature drops of the measuring points were approximately equal at night. These values could be used as the basis for calculating the heat loss in a greenhouse.

(2) Temperature differences were found in the indoor temperatures along the vertical, horizontal and longitudinal directions of the sunken solar greenhouse. The change rate in the indoor temperature in vertical direction was greater than those in the horizontal and longitudinal directions.

ACKNOWLEDGEMENT

The authors appreciate the assistance of Professor Wang Shuangxi and Associate Professor Liu Zhonghua. During the doctoral study, the professors have revised and provided guidance in the experimental scheme many times. They have also reviewed and corrected the manuscript. Their figures and teachings are evident in this work. The authors were in the office at night for the revision and guidance of the experimental scheme. The professors were always available in the campus to revise and make suggestions for the paper. They provided valuable guidance at the greenhouse test site. The authors are deeply grateful for the assistance of the two professors.

REFERENCES

[1] Albright L.D., Gates R.S., Arvanities K.G. et al (2001). Environmental Control for Plants on Earth and In Space. *IEEE Control System Magazine*. 21(5): 28-47.

[2] Bazgaou A., H. Fatnassi, R. Bouharroud et al (2021). Effect of active solar heating system on microclimate, development, yield and fruit quality in greenhouse tomato production, Renew. *Energy* 165: 237–250.

[3] Cheng W.W., He J.L., Liu Z.H. (2021). Evaluating how the temperature changes in a sunken solar greenhouse. *Engenharia Agrícola*. (3):279-285.

[4] Guo H.G., Zhao H. (2009). Effect of sunny and cloudy days on temperature of solar greenhouse with different structure（晴阴天对不同结构日光温室温度影响）. *Journal of Anhui Agricultural Sciences*. 37(28): 13964-13966, 13973.

[5] Hu J.J., Fan GS, Gao Y.J. (2014). Experimental study on air temperature variation characteristics of solar greenhouse during overwintering period (越冬期日光温室空气温度变化特性的试验研究). *Journal of Taiyuan University of Technology*. 45(4): 490-495.

[6] Jang Y., Goto E., Ishigami Y., Mun B. et al (2011). Effects of Light Intensity and Relative Humidity on Photosynthesis Growth and Graft-take of Grafted Cucumber Seedlings during Healing and Acclimatization. *Hortic. Environ.Biotechnol*. 52(4): 331–338.

[7] Khoshnevisan B., Rafiee S., Mousazadeh H. (2014). Application of Multi-layer Adaptive Neuro-fuzzy Inference System for Estimation of Greenhouse Strawberry Yield. *Measurement*. 47 (1): 903–910.

[8] Liu S.M., Xue Q.Y., Li C. (2013). Temporal and spatial variation of air temperature and ground temperature in sunken solar greenhouse (下沉式日光温室气温和土温时空变化特征研究). *Tianjin Agricultural Sciences*. 19(5): 53-57.

[9] Liu S., Zhang L.H., Zhang F. (2009). Research progress on the influence mechanism of heat and humidity environment in solar greenhouse (日光温室热湿环境影响机理研究进展). *Journal of Shandong Jianzhu University*. 24(6): 587-593.

[10] Md Shamim Ahamed, Huiqing Guo, Karen Tanino (2020). Modelling heating demands in a Chinese-style solar greenhouse using the transient building energy simulation model TRNSYS. Journal of Building Engineering 29 : 101114

[11] Shi Y.L., Wang X.F., Wei M. et al (2016) Temperature variation and heat storage and release characteristics of soil wall in solar greenhouse (日光温室土墙体温度变化及蓄热放热特点). *Transactions of the CSAE.* 32(22):214-221.

[12] Stefano Morelli, Filippo Cossio, Danilo Monarca et al (2022). Parametric sweep simulation for greenhouse temperature field optimization: An Italian case study. Energy Reports 8:881–895

[13] Sun S.P., Dong C.Y., Li Z.F. et al (2020). Study on internal temperature change of solar greenhouse under different ambient temperature based on CFD (基于 CFD 的不同环境温度下日光温室内部温度变化研究). *Tianjin agricultural sciences*. 26(10): 43-47.

[14] Taki M., Ajabshirchi Y., Ranjbar S.F. et al. (2016). Heat Transfer and MLP Neural Network Models to Predict Inside Environment Variables and Energy Lost in a Semi-solar Greenhouse. *Energy Build*. 110: 314–329.

[15] Tu M.Y., Jiang G.L., Du J.C., et al (2011). Effects of temperature and humidity inside and outside greenhouse on growth and development of spring shoot and fruit of loquat japonica（温室内外温湿度对枇杷春梢和果实生长发育的影响）. *Southwest China journal of agricultural sciences*. 24(6): 2336-2341.

[16] Wei R.J., Wang C.Y., Fan Z.L (2010). Winter microclimate characteristics and its relationship with macroclimate in solar greenhouse in Shijiazhuang area（石家庄地区日光温室冬季小气候特征及其与大气候的关系）. *Chinese journal of meteorology*, 36(1): 97-103.

[17] Xu H.J., Li Y.R., Cui Y.M., et al (2018). Environmental Testing and analysis of solar greenhouse in hinterland of Xinjiang Hotan Desert (新疆和田沙漠腹地日光温室环境测试与分析). *Transactions of the Chinese Society of Agricultural Engineering*. 34 (suppl.): 60-65.

[18] Xu H.J., Cao Y.F., Li Y.R. et al (2019). Construction and application of solar radiation model in solar greenhouse (日光温室太阳辐射模型构建及应用). *Transactions of the Chinese society of agricultural engineering*. 35(7): 160-169.

[19] Yang X.G., Zhao B.C., Qi Z.G. (2005). Observation and analysis of temperature gradient in solar greenhouse (日光型温室内温度梯度变化的观察与分析). *Journal of Hebei normal university (natural science edition)*. 29(1): 79-84.

[20] Yu M.H., Gao G.L., Ding G.D. et al (2015) Review of plant body temperature research (植物体温研究综述). *Chinese journal of ecology*. 34(12): 3533-3541.

[21] Zhang J.J. (2015). Effects of greenhouse temperature and humidity conditions on growth and fruity and soil-borne diseases of strawberry（温室温湿条件对草莓生长结实及土传病害的影响. *Journal of Northwest S&F university (natural science edition),* 43 (5): 143-148.

[22] Zhang C.K., Wei M., Liu F.S. et al (2019). Unsteady thermal conductivity of soil at night in a downward-digging solar greenhouse (下挖式日光温室夜间土壤非稳态导热过程). *Journal of China Agricultural University.* 24 (1): 108-118.