9. Research on the temperature environment of solar greenhouse

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The energy conserving solar greenhouse which designates the single slope greenhouse with thermal insulation curtain and produces vegetables in winter, late autumn and early spring has become the main protected cultivating measure and the typical Chinese greenhouse in Middle and North China since 1980s'. The total area was as high as 25,000 hectares by the year 1992 and is still increasing. However, its structure forms are much different from each other and their thermal characteristics are also much different and not satisfactory and need further improvement. In the present paper, a program for the simulation of the indoor temperature of the greenhouse based on the unsteady heat transfer theory is developed and the geometrical factors and the structure of the envelop are optimized, an underground heat conserving and exchanging system was experimented and its effect on vegetable growing was also experimented. The research will contribute to the improvement of the structure and the temperature environment of the solar greenhouse and the reduction of capital cost.

9.1. The temperature simulation and structural optimization of the solar greenhouse

9.1.1 Introduction

As the most efficient energy conserving greenhouse, the single slope solar greenhouse which always orients south or south by east or west within 15 degrees and has a transmissive south roof has become the typical Chinese greenhouse and gained its popularity in Middle and North China since 1980s'. By making full use of the solar energy and preserving heat closely with a thermal insulation curtain, it can keep the indoor temperature of 25-30 ° C higher than the ambient temperature and can produce vegetables in winter with no or little supplementary energy. Due to its low capital cost, 4,000-15,000 Chinese Yuan income per 0.0667 hectares in one year, the wide choice of structural materials, and very low consumption of coal which is the main energy for greenhouse in China, it has achieved high economical benefit and has no or little pollution to the environment.

The Chinese solar greenhouse originated in 1930s' in the south area of Liaoning Province a and was extended and experimented in 1950s' with the glass covered south roof, but owing to the high capital cost, the area was very limited. With the production of the plastic film, the tunnel greenhouse was largely adopted during 1960s' to 1970s' and it can prolong vegetable producing period by 30-60 days. So it has not been paid much attention to again and was intensively extended until the shortage of coal happened in the early 1980s' and the requirement for fresh vegetables greatly increased in winter, early spring and late fall. Compared with the early solar greenhouse, the improved solar greenhouse, mostly covered with PE or PVC film has high solar energy gain and preserving ability. In the area with a north latitude equal or less than 40 degrees, it can produce foliage vegetables and some fruit vegetables such as cucumber and tomato in winter time without supplementary heating. In the area with north latitude of 40-42 degrees, it can produce foliage vegetables such as celery, Chinese chives and rape etc. Without extra heating it can produce fruit vegetables in winter time by heating temporarily in severe climate; and in the higher north latitude areas from 41-45 degrees, the coal consumption can be greatly reduced. The production is also satisfactory in most soar greenhouses which are well operated. By producing cucumber in winter time in the greenhouse shown in Fig.9.1.1 in Wafangdian City, Liaoning Province, the production got to 16350kg per 0.0667 hectare (245300 kg per a hectare) by the aid of covering ground with plastic film and grafting technology. The yield of celery is more than 105000kg per hectare during one growing period (usually 3-4 months).

Tab.9.1.1 The construction of the four typical solar greenhouses

Type	**North roof**	**North wall**
1 Anshan	0.02m wood board	0.12m clay brick
	0.05m rice straw cushions	0.12m dry pearlite
	0.20m rice straw	0.24m clay brick
2 Haiceng	0.12m maize stalk	1.0m dry clay
	0c 06m dry clay	
	0.80m rice straw	
3 Xinmin		0.37m clay brick**
		0.80m leaves
		0.37m clay brick
4 Wafangdian	0.06m reinforced concrete	0.50m stone
	0.20m dry maize straw	0.80m clay
	0.10m dray clay plastic film	

** The construction of north wall is too thick and unreasonable because the farmers do not know the construction principle

For the time being, there are mainly four typical structure forms of the solar greenhouse in China shown in Tab.9.1.1 and Fig.9.1.1. It is apparent that there exist great differences among these solar greenhouses in span, height of north wall, ridge height and the proportion of the horizontal length of the south roof and the north roof. The constructions of the north wall and north roof are also much different. The construction materials vary from wood and bamboo structure with two or three column

As mentioned above, solar energy is primary or even the sole energy source of the solar greenhouse. The solar energy gain of a greenhouse which affects its temperature environment is dictated by its slope, shape and cross section form. The south roof shapes of various existing solar greenhouses are much different from each other and there is not enough theoretical or experimental bases for its selection. Thus, it is necessary that the relation between the slope, shape of the cross section of the south roof and its heat gain and loss be studied and make a rational evaluation to various south roof to lay a foundation for the determination of the south roof.

How to chose the geometrical factors, the constructions of the enclosing wall and roof of a solar greenhouse to obtain an optimum microclimate has always been a matter of concern. Previous studies have usually been limited to the influence of a certain enclosing part such as the north wall or the north roof or the slope of the south roof separately on the inside air temperature and the heat balance is based on the steady heat transfer theory. Some studies on the optimization of the solar greenhouse structure and the south roof shapes are based on the maximum energy gain of the direct solar radiance. Actually, the constant daily change in the inside temperature is caused not only by the dynamic factors such as solar radiance and ambient temperature, but also by the north wall, north roof and the ground due to their great thermal storage abilities; and the diffuse radiance makes a noticeable proportion in the total solar radiance, so it is imperfect to employ the direct radiance heat gain solely as a basis for the determination of the south roof shape. Hence it is difficult and unreasonable to set up a target function based on steady heat transfer theory considered together with the geometric features and thermal properties of the enclosing members to optimize the structure of a solar greenhouse. An advisable way to optimize the solar greenhouse structure is to establish a dynamic temperature model to simulate the temperature environment and further to get an optimized structure which will have an optimum temperature environment.

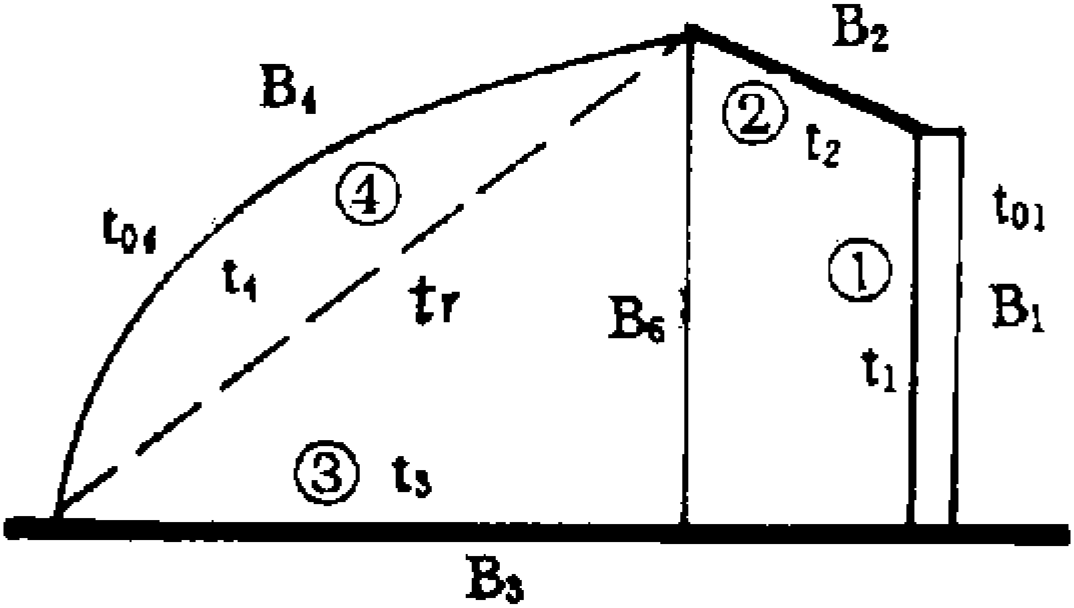
Fig. 9.1.1. Four typical structure forms of solar greenhouse piles to steel structures with one or no columns, and the thermal characteristics are different too. The greenhouse space is small and the roof structure materials are large and shade a considerable area of the south roof (the shading area is 10-15% except the columns), and it is not suitable for machine work and for the installing of the inner thermal blankets. Some researches on the structural improvement have carried out in recent years and achieved some results, but there still is not a thorough understanding of the structural forms and thermal properties of the solar greenhouse.

9.1.2 The Dynamic Simulation of the Temperature Environment Inside the Solar Greenhouse

A. The Simulation Object And The Hypothetical Conditions

Fig.9.1.2 shows the simulation object and the number of its various surfaces, lengths and temperature codes.

Fig. 9.1.2 The simulation object



To simplify the calculation, hypothetical conditions are given as follow:

- The solar heated south roof is covered with transparent materials including PVC film, PE film and other plastic films, or glass;

- One meter long part in the middle of the greenhouse is chosen as the simulation object and the influence of the two end walls on the object is neglected because the length of a solar greenhouse is generally much longer than its width;

- The lighted hours of the south roof is from the time of taking off the thermal curtain to the time of laying it on. The solar heat gain in the rest time is neglected. The time in the paper refers to Beijing time.

- Because of the differences and complications of the weather condition in various areas, a clear day in the calculation is assumed for the sake of general theoretical analysis in part 9.1.3 for optimization of the south roof, structural shape and the construction of north wall and north roof;

- The greenhouse orients south by east or west with 0-15 degrees.

B. The mathematical model of the solar energy gain by the south roof

Solar radiance $I_{t\Theta}$ on the south roof with a inclination Θ includes direct radiance $I_{B\Theta}$ and diffuse radiance $I_{d\Theta}$ which consists of sky radiance $I_{s\Theta}$ and ground reflective radiance $I_{r\Theta}$ i.e.

$$I_{t\Theta} = I_{b\Theta} + I_{d\Theta} + (I_{s\Theta} + I_{r\Theta}) \quad (1)$$

Direct radiance is expressed as:

$$I_{b\Theta} = I_0 P_m{}^m \cos i \quad (2)$$

where m is the atmospheric mass,

$h \geq 30°$, $m=1/\sin i$; $h<30$ •, $m= (1229-f-(614\sin h)\ 2)^{1/2}-612\sin h$.
i is incidant angle on the roof.

Sky radiance can be evaluated by the Berlage formula as follows:

$$I_{s\Theta} = \frac{1}{2} I_0 \sin h \frac{1-P_m{}^m}{1-1.4\ln P_m} \cos(\Theta/2)^2 \quad (3)$$

Based on the hypothesis that the ground is a perfect reflective surface, and its reflection is evenly distributed to a hemisphere, the ground radiance is

$$I_{r\Theta} = \beta_g (I_0 P_m{}^m \sin h + \frac{1}{2} I_0 \sin h \frac{1-P_m{}^m}{1-1.4\ln P_m})(1-\cos(\Theta/2^2)) \quad (4)$$

The total radiant energy gain through the south roof includes the energy transmitted into the greenhouse through the glazing and the energy conducted into the greenhouse by the glazing which absorbs part of the solar energy.

C. The Energy Balance Equations

The energy balance equations are based on the unsteady heat transfer calculating method Various temperature excitations are dispersed with an interval of one hour. Then, the energy balance equation of the north wall inside surface 1 and north roof inside surface 2 at moment is:

$$\sum_{K=1}^{N_s} Y_i(j) t_{oi}(n-j) - \sum_{j=0}^{N_s} Z_i(j) t_i(n-j) + \alpha_i^c [t_r(n) - t_i(n)] + \sum_{k=1}^{4} \alpha^r{}_{4,k} [t_k(n) - t_i(n)] + q_i(n) = 0 \quad (\text{k not equals i}) \quad (i=1,2) \quad (5)$$

The heat transfer through the ground surface 3 is calculated by the ground heat transfer coefficient and the outside temperature at one hour interval. Symbolically:

$$K_3 t_0(n) - \sum_{j=0}^{N_3} Z_3(j) t_3(n-j) + \alpha_3^c [t_r(n) - t_3(n)] + \sum_{k=1}^{4} \alpha^r_{3,4} [t_k(n) - t_i(n)] + q_{3r}(n) = 0 \quad \text{(k not equals 3)} \quad (6)$$

where K_3 is heat transfer coefficient of the ground, W/m² °C, when $B_3<8$m, $K_3= (0.96+ 0.23B_3) /B_3$.

Surface 4 is the inside surface of the south roof which is covered with plastic film or glass pane during daytime and is covered with paper blankets and straw curtain at night. The thermal capacities of the materials are ignored, and the energy balance equation based on steady state heat transfer theory is

$$\frac{K_4 \alpha_4}{\alpha_4 - K_4} [t_0(n) - t_4(n)] + \alpha_4^c [t_r(n) - t_i(n)] + \sum_{k=1}^{3} \alpha_{4,k} [t_k(n) - t_4(n)] + q_4(n) = 0 \quad (7)$$

where K_4 is the heat transfer coefficient of surface 4, W/m² °C, K4

includes the thermal resistances of a single layer of glazing and the air thermal resistances of the two opposite surfaces during daytime, adding the thermal resistance of the insulation materials at night. The heat transfer coefficient of the outside surface where convective heat transfers from the outside surface to the outside air is given by $a=7.2+ 3.8v$, W/m² °C., where v is the wind speed in m/S; a_4 is the heat transfer coefficient of the inside surface where convective heat transfer from the interior air to the inside surface, W/m^2 °C.

For the energy balance of inside air, the convective heat transfer from the inside air to each enclosing surface, the energy obtained from the sun, equipment and supplementary heating, ventilation, water evaporation and the latent and sensible heat of the air were all considered, i.e.

$$\sum_{k=1}^{4} B_k \alpha_k^c [t_k(n) - t_r(n) + L_a(n)(cp)_o [t_o(n) - t_r(n)]/3.6 + q_r(n) - q_w(n) = V(cp)_r [t_r(n) - t_r(n-1)]/3.6 \quad (8)$$

where $q_r(n)$ is the energy obtained from the sun, lighting, supplemental heat, equipment and so on, W; $L_a(n)$ is the air infiltration at moment, m³/hr.; $q_w(n)$ is the sensible heat loss of water evaporation, W; V is the volume of the simulating unit, m^3; $(cp)_o$, $(cp)_r$ are thermal capacity of the outside and inside air at moment respectively, KJ/m³. °C

$(cp)_o =352.2/T_o(n)$, $(cp)_r 352.2/T_r(n-1)$;

The following is the determination of some notations in Eqn. (5)-(8):

$\alpha^r_{i,k}$ is the coefficient of heat transfer by radiation between the inside surface i and k, W/m² °C,

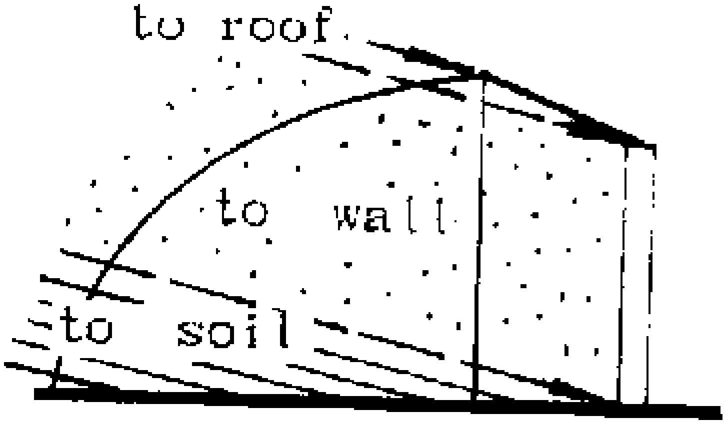
$\alpha^{r}{}_{i,k} \approx 4x10^{-8} C_b \in_{ik} \phi_{ik} [T_m (n)]^3$

where

C_b is Stephen-Bottzmann constant, 5.67W/m^2. °C^4;
$\in_{ik}$ is system blackness between surface i and k, and
ϕ_{ik} is view factor for radiation exchange from surface i to k;
T_m, (n) is the average temperature of surface i and k at moment, K.
T_m (n) is also an unknown value in the equation. Tm (n-1) is employed as T_m (n) to simplify the solution of the energy balance equation.
α_i^c is convective heat transfer coefficient of each surface, α_i^c =7.2 W/m2. °C

q_i^r is the solar energy gain by surface i at moment, W/m$^{2.}$
Based on the concerned formulae (1)-(4), the hourly solar energy gain on the simulating day is available. The energy gain by the surfaces includes direct radiation and diffuse radiation. The direct radiation distributes to the surfaces according to sun elevation, while the diffuse radiation is allocated to the surfaces with respect to the length of the surfaces (shown in Fig.9.1.3).

Fig. 9.1.3 The distribution of direct solar radiation



$t_{01,}$ t_{02} t_{03} are the sol-air temperature of outside surface 1, 2 and 4 respectively. The solar energy gain by the south roof is considered in the calculation of t_{04}, i.e.

$$t_{04} = \frac{\alpha_s I}{\alpha_0}$$

where
α is the absorbence of the transparent surface;
I is the solar radiance on the south roof, W/m^2;
α_0 is the coefficient of convective heat transfer through the south roof, W/m^2. °C;
t_0 is the outside temperature, °C.

The sol-air temperature t_{01} and t_{02} are approximately equal to the outside air temperature.

D. The solving of the energy balance equations

After being put in order, the equations could be described in term of matrix:

AT (n) =B (9)

where

T (n) = [t1(n),t(n),t3(n),T4(n),tr(n)^T

A is coefficient matrix,

$$A = \begin{matrix} -[\alpha_1+z_1(0) & \alpha^r_{1,2} & \alpha^r_{1,3} & \alpha^r_{1,4} & \alpha^c_1 \\ \alpha^r_{2,1} & -[\alpha_2+z_2(0) & \alpha^r_{2,3} & \alpha^r_{2,4} & \alpha^c_2 \\ \alpha^r_{3,1} & \alpha^r_{3,2} & -[\alpha_3+z_3(0) & \alpha^r_{3,4} & \alpha^c_3 \\ \alpha^r_{4,1} & \alpha^r_{4,2} & \alpha^r_{4,3} & -[\alpha_4+\dfrac{K_4\alpha_4}{\alpha_4-K_4}] & \alpha^c_4 \\ -B_1\alpha_1^c & -B_2\alpha_2^c & -B_3\alpha_3^c & -B_4\alpha_4^c & A_{55} \end{matrix}$$

In the coefficient matrix,

$$A_{55}=\sum_{I=1}^{4} B_i\alpha_{ic}+99.1B_1B_3[1/T_r(n-1)+N/T_o(n)]$$

where N is air changes per hour;

α_i is the total convective heat transfer coefficient of the inside surface,

$$\alpha=\alpha_i^4+\sum_{k=1}^{4}\alpha_{ik}^r \qquad \text{(k not equals I)} \quad (i=1,4)$$

Since the ground, north wall and north roof all possess high thermal capacity, the number of the thermal response factors is Ns=48. So the matrix of the constants is

$$B = \begin{matrix} -\sum_{j=0}^{47}{}_1(j)\,t_{01}(n-j)+\sum_{j=0}^{47}{}_1(j)\,t_1(n-j)-q_1^r(n) \\ -\sum_{j=0}^{47}{}_2(j)\,t_{02}(n-j)+\sum_{j=0}^{47}{}_2(j)\,t_2(n-j)-q_2^r(n) \\ -t_0(n)(0.96+0.23B_3)/B_3+\sum_{j=0}^{47}{}_3(J)\,t_3(n-j)-q_3^r(n) \\ -\dfrac{K_4\alpha_4}{\alpha_4-K_4}t_{04}(n)-q_4^r(n) \\ 99.1B_1B_3[\dfrac{t_r(n-1)}{T_r(n-1)}+\dfrac{t_0(n)}{T_0(n)}+q^r(n)-q_w(n) \end{matrix}$$

A computer program TEMP3. FOR was developed to simulate the inside air temperature and every surface temperature hour by hour. A program named RESP1.BAS copied from reference 4 was used to calculate the response factors of the north wall, north roof and the soil.

Given north latitude and east longitude of the site, the number of the day simulated in the year, the time of taking off the curtains and laying it on, the geometrical feature of the south roof, transmittance of the glazing material, the dimension of the cross section, the outside wind velocity, the emmitance of the surfaces, the thickness of the thermal curtain, thermal factors of the envelop and the outdoor temperatures, a simulation result of the temperatures of inside surfaces and air can be obtained.

E. The simulation of interior temperatures of solar greenhouses

To verify the program TEMP3.FOR, three typical solar greenhouses located in Shenyang city, Haiceng city and Anshan City were tested. Temperatures of outdoor, inside surfaces and indoor air hour by hour for three days were recorded. The tested greenhouses were built in different types with different materials (Fig.9.1.1 1-3). The practical values and the simulated results shown in Tab. 9.1.2 prove that program TEMP3. FOR can be used to simulate the thermal environment of solar greenhouse with a small deviation. The small deviation maybe caused by the following reason:

a. The response factors was calculated to No.48 which maybe small for heavy construction materials especially for Xinmin greenhouse. Xinmin greenhouse is not a common pattern for its north wall is too thick.

b. In the calculation of the view factors, the south roof was treated as a straight line that may cause a small error in radiation heat transfer coefficients. It is difficult to calculate the view factors of the concave south roof.

c. The theory used to calculate the solar radiation on the south roof may not be exactly suitable for the meteorological condition of simulated day.

d. The ground was considered of 1.0 m soil in the calculation of the response factors that may cause the day temperature of the soil to be higher than the tested value and the night temperature to be lower than the tested value because the thickness of the ground is infinite.

The program can be used to predict the performance of a solar greenhouse in different locations and also to compare the thermal factors of greenhouses built with different materials and different dimensions.

9.1.3 The optimization of the solar greenhouse

Because the factors that influence the interior thermal environment are very complicated and are changing momently, it is impossible for practical test to compare the thermal performance of the different types of solar greenhouses. Using a mathematical model TEMPS.FOR to simulate every type of greenhouse under different condition can provide a comparison of the influence of one factor under the condition that other factors are exactly the same without any accidental test error. In the following simulation, the outside air temperature is a nine-year average value of 21st 22nd and 23rd in January from 1980-1988 in Shenyang city. Generally the three days are considered as the coldest days in a year in this region. The north roof is constructed with 0.06m reinforced concrete, 0.12m dry pearlite, 0.025m cement mortar and water barrier surface of asphalt felt.

A. The selection of the shape of south roof

There are many papers published in China concerned with the selection of the south roof. But these papers only pay heed to the direct solar radiation or the total solar energy gain. Actually, a straight line glazing cover with a certain inclination can obtain the largest amount of net heat gain and the glazing cover with any other shapes can get total energy more than the straight one, but net energy gain is smaller than the

Tab.9.1.2 The tested results and simulated results of the three greenhouses (° C)

Types	**Haiceng type**				**Anshan type**				**Xinmin type**			
Time	**Soil sur. temp.**		**Air temp.**		**Soil sur. temp.**		**Air temp.**		**Soil sur. temp.**		**Air temp.**	
	Tested	**Simu.**	**Tested**	**Simu.**	**Tested**	**Simu.**	**Tested**	**Simu.**	**Tested**	**Simu.**	**Tested**	**Simu.**
8: 0									7.7	7.5	6.4	3.6
9:0	11.8	12.4	10.1	11.6	14.7	15.0	12.3	14.8	15.6	11.1	16.4	10.0
10: 0	16.0	17.3	19.8	18.9	20.4	21.9	20.0	22.3	21.7	17.4	23.6	18.4
11: 0	21.5	22.6	25.6	24.8	29.5	28.8	27.5	28.7	26.0	24.0	30.3	25.8
12: 0	25.5	26.7	28.1	28.4	34.8	34.0	34.7	33.6	30.8	29.4	32.0	29.6
13: 0	25.0	28.8	30.2	30.0	36.5	36.7	35.6	35.0	30.3	31.6	32.3	31.1
14:0	24.0	28.0	29.6	28.2	33.5	35.4	34.5	33.5	27.5	30.7	28.4	28.8
15:0	23.8	24.7	24.7	22.5	32.1	31.3	30.3	28.0	24.2	26.8	22.4	23.0
16: 0	19.5	19.9	17.6	14.0	24.3	25.9	23.7	20.2	18.5	21.7	15.0	16.0
17:0	18.5	18.2	16.4	17.1	20.8	23.4	20.6	22.2	16.8	19.6	16.0	18.5
18: 0	16.5	16.7	15.1	15.6	20.0	21.6	20.0	20.5	16.0	17.9	15.4	17.0
19: 0	15.8	15.5	13.9	14.4	19.1	20.8	18.5	18.8	15.8	16.6	14.5	15.6
20:0	15.0	14.5	12.7	13.4	18.2	18.8	17.0	17.5	15.0	15.5	13.4	14.4
21: 0	14.8	13.7	12.2	12.5	17.5	17.8	16.2	16.4	14.3	14.5	12.9	13.5
22: 0	14.5	12.9	11.6	11.7	16.8	16.8	15.4	15.6	13.7	13.7	12.4	12.6
23: 0	14.0	12.2	11.1	11.0	16.3	16.0	15.0	14.8	13.3	13.0	12.0	11.9

24: 0	13.5	11.5	10.6	10.3	15.9	15.3	14.4	14.1	12.9	12.3	11.6	11.2
1: 0	13.2	11.1	10.1	10.0	15.4	14.8	13.8	13.7	12.5	11.8	11.2	10.6
2: 0	12.9	10.6	9.8	9.5	14.9	14.3	13.3	13.2	12.1	11.3	10.8	10.1
3:0	12.6	10.2	9.6	9.1	14.5	13.8	12.7	12.7	12.0	10.8	10.2	9.6
4: 0	12.3	9.8	9.3	8.8	14.3	13.4	12.5	12.4	11.9	10.4	10.0	9.2
5: 0	12.0	9.5	9.0	8.4	14.0	13.0	12.2	12.0	11.8	9.9	9.4	8.7
6: 0	11.8	9.1	8.6	8.1	13.7	12.6	11.9	11.6	11.7	9.5	8.5	8.3
7: 0	11.5	8.8	8.2	7.7	13.5	12.2	11.6	11.2	11.3	9.2	7.8	8.1
8: 0	11.0	8.5	7.6	7.5	13.0	11.9	11.4	11.1				
Test date	Jan. 28th, 1994				Feb. 6th, 1992				Feb. 2nd, 1994			
Outdoor temp.	Max. -8.7 Min. -17.5				Max. -2.1 Min. -14.1				Max. 0.5 Min. -10.5			

Tab.9.1.3 Simulated temperatures of the solar greenhouses with different south roof (°C)

No. Of south roof	**Soil surface temp.**			**Air temperature**			**Outdoor air temp.**		
	Max.	**Min.**	**Ave.****	**Max.**	**Min.**	**Ave.****	**Max.**	**Min.**	**Ave.****
1	29.35	9.66	16.76	28.45	8.41	15.46	-15.2	-4.8	-11.34
2	28.76	9.40	16.43	28.69	8.11	15.17	-15.2	-4.8	-11.34
3	29.28	9.49	16.58	27.24	8.19	15.06	-15.2	-4.8	-11.34
4	29.13	9.42	16.49	26.91	8.11	14.90	-15.2	-4.8	-11.34
5	29.07	9.31	16.38	26.11	7.97	14.62	-15.2	-4.8	-11.34

** Average value of 24-hour temperatures straight one.

Furthermore, the solar energy transferring into the greenhouse is partly absorbed and stored by soil, north roof, north wall and plants and gradually released with respect to the interior temperatures. So it is necessary to use the temperature simulating program TEMP3.FOR to calculate the interior temperatures under the same condition except for the shape of the south roof and compare the thermal performances of these greenhouses. Fig.9.1.4 shows the shape and the number of south roof and the dimension of these greenhouses. Tab.9.1.3 shows the simulation results.

The conclusion drawn from Tab.9.1.3 is:

No.1 straight line roof has the best thermal performance. But it is not suitable for cultivation because of its low space;

No.3 roof has the second high soil temperature and the third high air temperature. It is high enough for plant growing and easily to be constructed with bamboo strips. It is the recommended roof for solar greenhouses:

No.5 roof has the lowest air temperature because its area is the largest one and has the largest heat loss; when the height of the roof and the width of horizontal projection of the roof arc determined, the longer the curve is, the lower the air temperature is.

B. The selection of the north wall construction

The construction of the north wall affect the interior temperatures and the capital cost. Tab.9.1.4 presents 6 kinds of north wall constructions and the simulation of the interior temperature values based on the condition that the greenhouses are located in Shenyang city, the south roof shape is a parabola numbered 3 and the dimension is shown in Fig.9.1.5 (2)

Fig. 9.1.4 The shape and the number of south roof

Tab.9.1.4 The thermal performance of the greenhouses with different north wall constructions (° C)

Wall number	Soil surface temp.			Air temperature			The construction of the north wall presented from inside to outside
	Max.	Min.	Ave.**	Max.	Min.	Ave.**	
1	29.28	9.49	16.58	27.24	8.19	15.06	0.24m clay brick; 0.12m pearlite; 0.12m clay brick
2	29.33	9.23	16.38	27.32	7.98	14.68	0.12m clay brick; 0.12m pearlite; 0.24m clay brick
3	28.91	8.65	15.89	26.48	7.17	13.97	0.24m clay brick; 0.80m clay
4	28.89	8.62	15.88	26.44	7.13	13.94	0.50m rock; 0.80m clay
5	28.89	8.61	15.87	26.45	7.11	13.93	1.00m clay
6	29.13	8.55	15.91	26.91	7.00	13.97	0.24m foamed concrete brick

** Average value of 24-hour temperatures

Tab.9.1.4 shows that No.1 and No.2 have the best thermal performance, but for No.2 the 0.12m clay brick is built in the inside of the wall which is not very stable to support the north roof. So No.1 wall construction is recommended. The other four constructions have a similar performance and all are built with local materials. They are cheaper and easily built.

C. The selection of greenhouse height

The height of the existing greenhouses varies from 2.2m to 3.2m in different regions. The problem of which one is better for plant cultivation and indoor thermal performance is puzzling the farmers. TEMP3.FOR is used to simulate the thermal reaction of three greenhouses with different height under the same meteorological condition. The south roof of these greenhouses are of parabola which is considered reasonable. The north walls are constructed as No.1 in Tab.9.1.4. The dimensions of the three greenhouses are described in Fig.9.1.5 and the simulation results is presented in Tab.9.1.5.

Fig. 9.1.5 The greenhouses with different height

Tab.9.1.5 Thermal performance of the greenhouses with different height (° C)

No. of ridge height	**Soil surface temp.**			**Air temperature**			**Ridge height**	**North wall height**
	Max.	**Min.**	**Ave.****	**Max.**	**Min.**	**Ave.****		
1	29.76	9.77	16.90	28.04	8.54	15.60	3.0 m	2.2 m
2	29.07	9.39	16.47	26.88	8.11	14.92	2.6 m	1.8 m
3	28.50	8.97	16.01	25.36	7.63	14.14	1.4 m	1.4 m

** Average value of 24-hour temperatures

According to the results in Tab.5, the higher the ridge is, the better the indoor temperature environment is. Actually, high ridge structure costs more than the lower one. So it is up to the temperature requirement of vegetables grown in winter.

D. The selection of horizontal length of the south roof

To make efficient use of the north roof and north wall which are constructed with durable materials and to get a more suitable thermal environment for plants, the length of south roof horizontal projection should be selected. Fig.9.1.6 shows three greenhouses with different south roof lengths. Tab.9.1.6 is the simulated results of these greenhouses. They are constructed with No.1 wall shown in Tab.9.1.4. and the south roofs are of parabola curves. The simulated result indicates that when the ridge height is determined, the shorter the south roof horizontal projection is, the better the indoor thermal performance is. It means that when the energy obtained by a vertical surface of a certain height is used to heat the a certain volume of space, the smaller the space is, the higher the inside temperature is.

Fig. 9.1.6 Greenhouses with different south roof length

Tab.9.1.6 Thermal performance of the greenhouses with different south roof horizontal projection (° C)

NO. of roof length	**Soil surface temp.**			**Air temperature**			**Ridge height**	**North wall height**
	Max.	**Min.**	**Ave.****	**Max.**	**Min.**	**Ave.****		

1	28.85	9.19	16.25	26.44	7.86	14.56	2.6m	1.8 m
2	29.07	9.39	16.47	26.88	8.11	14.92		
3	29.55	9.81	16.96	28.77	8.63	15.85		

** Average value of 24-hour temperatures

E. The selection of the ratio of horizontal projections of south roof and the north roof

When the ridge height is determined, the influence of the ratio of the horizontal projections of south roof and north roof should be analyzed. Given ridge height 2.6m and the different height of north wall shown in Fig.9.1.7, the simulated indoor temperatures are presented in Tab.9.1.7. The walls are built as No.1 in Tab.9.1.4. As shown in Tab.9.1.7, No.1 and No.2 have the highest soil and air temperature are recommended. But in the first two hours after taking off the thermal curtain, the temperatures are lower than that of the other two greenhouses that means the increase of energy gain by means of increasing the length of the south roof can not compensate the heat loss through the roof when the sun elevation is lower. This may be the drawback of No.1 and No.2 greenhouse.

9.1.4 Conclusion and discussion

The solar greenhouses presented in this paper are easily constructed with cheap materials. They can be cultivated in cold winter without or with little supplemental heat. Frequent maintenance such as laying on and taking off the thermal curtains is required that may not be convenient for the developed countries because of the high labor cost. But it may not be a problem for the developing countries when labor is very cheap.

In the simulation of greenhouse thermal performance, detail factors are considered and the program TEMP3.FOR can simulate the indoor temperatures with little deviation. It can be used as a tool to predict the indoor environment of a greenhouse.

Fig. 9.1.7 Greenhouses with different ratio of horizontal projections of south roof and north roof

Notation

B - the size of various parts of a solar greenhouse,
h - sun elevation, degree
I_0 - solar constant, W/m^2
j - the number of moniment, j=0, 47
K - heat transfer coefficient, W/m^2 °C
N_s - the number of thermal response factors
t_i - temperature of inside surface i, i=1, 4,°C
t_r - inside air temperature, °C
T - absolute temperature, K
Y - thermal transfer response factors of the inside surface, W/m^2 °C

Z - thermal absorbing response factors of the inside surface, W/m² °C
δ - sun declination, degree
Θ - inclination of a surface, degree
β_g - average reflectance of the ground surface

Tab.9.1.7 Thermal performance of greenhouses with differentiation of horizontal projections of south roof and north roof (°C)

No.	**No. 1**		**No. 2**		**No. 3**		**No. 4**	
time	**Temp.**		**Temp.**		**Temp.**		**Temp.**	
	Soil	**Air**	**Soil**	**Air**	**Soil**	**Air**	**Soil**	**Air**
9:0	12.53	7.29	12.85	8.79	12.74	9.52	12.88	10.26
10:0	17.38	14.56	17.56	15.82	17.47	15.70	17.35	15.64
11:0	23.00	21.13	22.98	21.80	22.71	20.48	22.19	19.97
12:0	27.44	24.98	27.29	25.52	26.59	24.21	26.09	23.16
13:0	29.25	26.29	29.07	26.88	28.52	25.53	27.75	24.84
14:0	28.23	24.58	28.17	25.62	27.54	25.51	27.13	24.87
15:0	24.62	19.68	24.71	21.02	24.40	21.59	24.03	21.95
16:0	20.21	13.89	20.41	14.94	20.32	15.65	20.17	16.31
17:0	18.89	18.28	19.01	18.46	18.89	18.50	18.69	18.35
18:0	17.16	17.39	17.80	17.37	17.69	17.38	17.49	17.19
19:0	16.74	16.26	16.74	16.20	16.65	16.23	16.46	16.06
20:0	15.86	15.33	15.84	15.23	15.76	15.28	15.57	15.12
21:0	15.06	14.43	15.01	14.31	14.95	14.37	14.77	14.22
22:0	14.34	13.64	14.27	13.50	14.22	13.56	14.04	13.42
23:0	13.67	12.92	13.59	12.75	13.54	12.82	13.37	12.68
24:0	13.05	12.21	12.94	12.03	12.91	12.10	12.74	11.96
1:0	12.62	11.70	12.50	11.51	12.46	11.58	12.29	11.43
2:0	12.15	11.17	12.01	10.97	11.99	11.03	11.82	10.89
3:0	11.68	10.63	11.53	10.43	11.51	10.49	11.34	10.36
4:0	11.22	10.12	11.07	9.91	11.05	9.98	10.88	9.85
5:0	10.78	9.61	10.62	9.41	10.60	9.49	10.44	9.36
6:0	10.34	9.13	10.18	8.93	10.17	9.01	10.01	8.89
7:0	9.93	8.66	9.77	8.48	9.75	8.56	9.60	8.45
8:0	9.55	8.30	9.39	8.11	9.38	8.18	9.22	8.07
Nor. roof	0.0m		1.2 m		2.0 m		3.0 m	
Sou. roof	6.5 m		5.3 m		4.5 m		3.5 m	

9.2. The underground heat exchange system of protected vegetable cultivation

9.2.1 Introduction

Vegetable production in protected cultivation has played an important role in vegetable supply of northern region cities, enrichment of farmers and the rising of people's living level. The area of plastic greenhouse has been increasing rapidly in recent years. However, in early spring and late autumn, the daytime temperature of non - heating greenhouse and plastic tunnel greenhouse can reach as high as 30°C or higher and ventilation is needed for cooling, but the nocturnal temperature can diminish below 0°C and the seedlings can be frozen. So planting time of seedlings was delayed to the end of March or the beginning of April and the autumn plant would be finished in early October. The cultivatable period of vegetables decreases by 1 - 2 months in a year. The solar energy utilizing efficiency is also decreased due to the ventilation during daytime high temperature period. To augment the year cultivatable period and solar energy utilizing efficiency, widely researches on underground heat exchange system (briefly named UHES) has been carried out in Japan and European countries. The surplus heat of solar energy during daytime is stored in underground soil and released at night to mitigate the descent of interior temperature. Researches have also been carried in China and many years experimental results have been put into practical cultivation. The experiments and researches carried out our group are introduced in this paper.

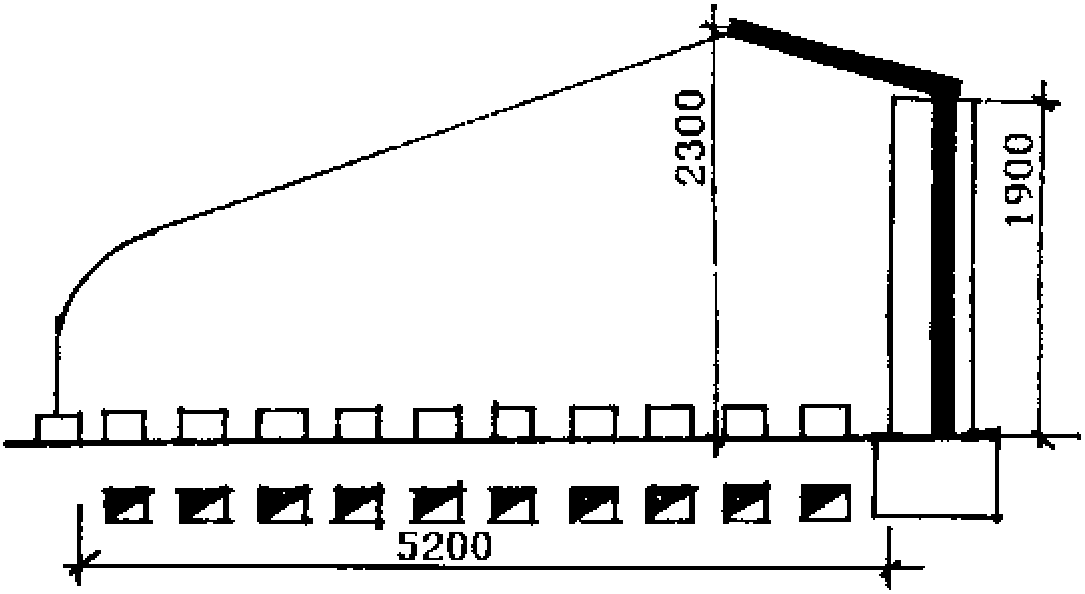
9.2.2 Experimental facilities and methods

A. Experimental facilities

Two 62.4 m^2 single slope solar greenhouses covered with PVC film were used for the experiment (Fig.9.2.1). the UHES was installed in one for test and the other for comparison. Fig.9.2.2 shows the layout of the UHES in the experimented greenhouse. Heat exchange ducts were laid from east to west. A lateral main duct was laid along the east wall with a distance of 0.3m. The main duct was covered with wood board tightly and a fan was installed in the middle of the duct on the board. The west ends of the ducts stand above the soil with vertical ducts. Heat is stored or released when air is drawn into the ducts. Three greenhouses with the same structure were built in the Energy Demonstrating Base of North Cold Region for extension (other similar greenhouses were also built in Liaoning province for extension). The UHES were installed in two of the three greenhouses with the area of 120m^2 respectively (24mx5m) and the other one with 60m^2 (5mx12m) was used for comparison. The north, east and west walls were built with 0.24m clay brick, 0.2m pearlite for insulation and 0.12m clay brick from the inside to the outside respectively; the north roofs were built with wood board and pearlite mortar.

Fig. 9.2.1 Layout of the solar greenhouse

Fig. 9.2.2 Cross section



The heat exchange ducts were built with clay brick instead of earthen ware pipes based on the experiment result that the heat storage and release effects of the two kinds of ducts are similar and the earthenware pipe costs two times higher than the clay brick duct. So it is easy for clay brick duct to be extended widely. The brick ducts have an area of $0.0168m^2(0.14mx0.12m)$ and were laid 0.45 - 0.6m deep in respect that they do not affect cultivating and are not influenced by daily temperature. In this experiment, it is laid 0.5m deep. The space between centre of the ducts is generally 0.5 - 0.6m to make sure that no overlap or margin of heat storage area exists. In this experiment, the ducts are spaced 0.5m. Ten ducts were laid in the greenhouse. The number of ducts is determined on the ratio of total inside surface area of the ducts Ap and the area of the greenhouse As ($\alpha = Ap/As$). According to the existing experimental results of Japan, it is about 0.38 - 3. Some specialists recommend $\alpha = 1$. The ducts were laid in one layer and $\alpha = 0.83$.

The lateral main duct was designed according to the depth and the number of the heat exchange ducts, the size of fan and the existing systems. The width is 0.5m, length 4.3m and depth 0.7m.

According to the along line resistance and local resistance of the system together with the market supply, low pressure axial - flow fan was chosen for air circulation. The performance parameters ares: power 370W, rotational speed 2800 r/min, flow rate 3280 m3/hr., and working pressure $<26mmH_2O$. The fan was automatically controlled by thermostat.

B. Experimental Method

In the west, east and middle of the two greenhouses, three groups of soil thermometers were arranged in the depth of 10, 15, 20, 25, 30cm to measure the soil temperature; thermometers for air inlet and outlets of ducts, auto - recording psychrometer for air humidity, and auto - recording thermometer for interior temperature were also arranged.

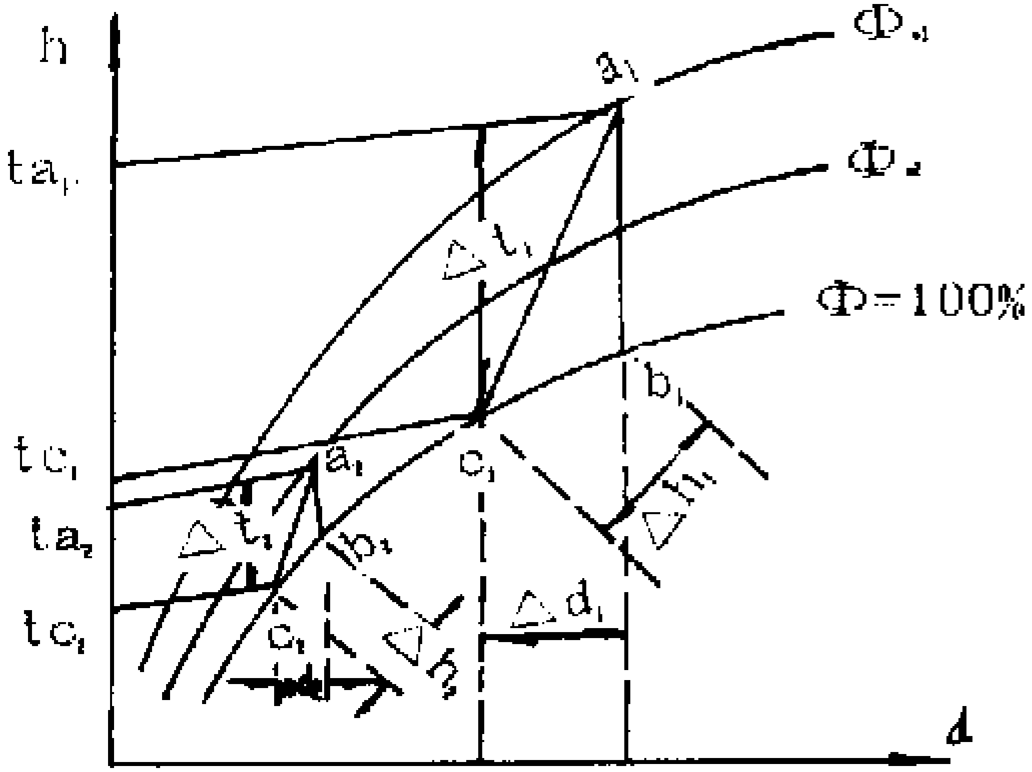
A group of thermometers were used for soil and air temperatures outside the green house. Radiometer was used for solar radiation (diffuse radiation direct radiation, reflecting radiation and total radiation). The two greenhouses were planted with same vegetables (tomato and sweet pepper) on the same day under the same manure and irrigation condition to compare the yield.

9.2.2 Performance and Effect of Heat Storage and Release of the UHES

A. Interior air circulation and heat storage and release performance

Forced by the fan, air circulates between the inside of the greenhouse and the underground ducts. When the inside temperature reaches a preset maximum value, generally 18 - 25 ° C, during daytime, the fan set to work drawing the inside air into the ducts. Sensible heat and latent heat are released while air temperature is descending and the moisture condensing while the heat was absorbed by the ducts and soil. This is called solar energy storage process. When interior temperature is lower than preset value, the fan stops automatically. In sunny day of early spring and late autumn, heat storage period can last 7 - 9 hours. When the interior temperature drops to the other preset minimum value, generally 8 - 15 ° C, during night time, the fan works again drawing the inside cold air into the ducts. The cold air absorbs the heat from the duct surface and the soil and its temperature increases and then releases energy to the greenhouse to retard the dropping of inside air temperature. This period is called heat release process. When the inside air: temperature is higher than this preset value, the fan stops again and the heat release process finishes. This period can last 9 - 12 hours. The heat storage and release process of the UHES can be qualitatively analyzed with enthalpy - moisture figure of inside air state change (h - d figure, Fig. 9.3). Line a1 - b1 - c1 - a1 presents heat storage process. Air flows from the inlet of duct (state a1) to the outlet (state c1) and its temperature drops by δ 5tl, which is usually 5 - 10 °C according to the test. 1kg air releases condensed water δ d1 while giving off sensible heat and latent heat δ h1 (KJ/kg.DA). This energy is absorbed by the duct and soil and their temperatures increases. Air flows from outlet to inlet via soil, walls, plants, etc (state c1 - a1) absorbing solar energy with temperature increasing and relative humidity dropping. This process is repeating continuously while the fan is working at daytime and heat is continuously stored in soil until the fan stops. Line c2 - a2 - b2 - c2 is soil energy release process when fan works at night. Air flows from inlet to outlet (c2 - a2) with temperature increasing by δ t2, generally 2 - 4 °C. 1kg air absorbs heat from ducts and soil by δ h2 and absorbs moisture by δ d2. Because of the rising of temperature, the relative humidity of air drops. The hot air from the ducts releases heat into the greenhouse (a2 - b2 - c2), which retards the decrease of inside air temperature. This process is repeating continuously while the fan is working and soil temperature is dropping by releasing energy.

Fig. 9.2.3 Progress of heat storage and relief



B. The effect of the heat storage and release and its influence on the thermal property of the greenhouse

Total energy in the process of heat storage and release is

$$Q=CV_f \delta h + Qe \quad (1)$$

where C is the air density (kg/m3); Vf is the actual air flow rate of the fan (m3/s); Qe is the heat given off by the fan while its working (KJ); and oh is the enthalpy difference of the inlet and outlet ducts of one kg dry air in the process of heat storage and release (KJ/Kg.DA). The enthalpy of the inlet and outlet can be represented as follows:

$$h=1.005t+ 0.001d (2501+ 1.859t) \quad (2)$$

where t is the air temperature of the inlet or outlet duct (°C); d is the moisture in the air of the inlet or outlet of one Kg dry air (g/Kg DA) and it can be calculated by the following equation:

$$d = 622\frac{\phi C_{sv}}{\beta - \phi C_{sv}} \quad (3)$$

where ϕ *is* the relative humidity of the air in the inlet or outlet duct; B is the local atmospheric pressure and can be measured by the air pressure gauge; C_{SV} is the saturated vapor pressure of the inlet or outlet under the air temperature and can be found in the water vapor table.

The relative parameters in the greenhouse on April 11th, 1987 were measured or calculated with the above equations, and the magnitudes of the heat storage or release at certain moment in the same day is shown in Table 9.2.1. The heat storage was 228027KJ from 8: 00 a.m. to 16: 00 p.m. which equals to the heat given off by the combustion of 7.78Kg standard coal.

Table 9.2.1 Air state parameters in the greenhouse and the heat storage and release of the UHES (April. 11th, 1987)

		t		**δ t**	**o**	**oo**	**working condition**	**δ h**	**Q**	**I**	**Q/I**
time	**t**	**ti**	**to**		**oi**	**00**				**(KJ/h)**	**(%)**
7	14	13	16.4	3.4	100	90	- *	5.02	9036		
8	15	14	9	5	95	100	+	7.12	12816	39085	32.70
10	22	21.2	15.8	5.4	90	100	+	8.37	15066	58120	25.92
12	26	25	18	7	82	100	+	16.75	30150	121317	24.85
14	30	28	19	9	68	100	+	18.84	33912	123516	27.45
16	28	26	19	7	75	100	+	17.59	30146	79189	38.06

* "-" indicates that ducts release heat to the greenhouse and "+" storage heat from the greenhouse.

a. The influence of the heat storage and release on soil temperature The ducts laid in the depth of 0.5 m gain heat from the air and conduct the heat to the soil around, thus heats the soil. The ten ducts in this experiment heat the soil of an area $62.4m^2$ and a depth 0.7m hypothetically. According to the theoretical deductions and the experiment results, the isothermal lines of soil around the ducts are a cluster of non - concentric circles and they are denser above the ducts than below the ducts; which indicates that the ducts transfer more heat to the above soil than the soil beneath. So it is reasonable to take 0.7m deep of soil as the analyzed depth. Hence, the average temperature increase of the ducts and the soil around caused by the heat storage or release can be expressed as follows:

$$\delta t = \frac{Q}{C_{sv} V_s C_{ps}} \quad (4)$$

C_{SV} and V_{SV} are the density of soil and duct, C_{ps} the specific heat under certain pressure. Based on the above statistics, the temperature increase of the soil and the ducts in 8 hours is 2.07 °C.

Because the temperature difference between the inlet and outlet at night is much less than that in the daytime, the heat release rate of the UHES at night is also much less than the heat storage rate in the daytime and it is not more than half of the average heat storage rate in daytime according to the statistics. Let the former parameter be half of the later and the heat release time be 12 hours at night, then the soil temperature decreases by 1.47 °C. Because the above soil temperature increase is more than the temperature decrease, the soil temperature will be increasing continuously in the working term of the UHES. This effect is indicated in the statistics shown in Table 9.2.2. As compared to the greenhouse without the UHES, the soil temperature is much more higher. By storing heat in daytime, the soil temperature in the depth of 30cm is relatively even, and it is 1.57-4.04 °C higher than the compared greenhouse and the difference becomes less with the ambient temperature increases. The minimum soil temperature happens at 8: 00 a.m. due to the heat release through the night and it is still 1.88-4.66 °C higher than the compared greenhouse.

Table 9.2.2. The comparison of the air and the soil temperatures in one plant growth phase in 1987

April.7th-15th				**April.16th-30th**				**May 1st-27th**			
0	**8:00**	**14:00**	**20:00**	**08:00**		**14:00**	**20:00**	**08:00**		**14:00**	**20:00**
ti	**ts**	**ti**	**ts**	**ti**	**ts**	**ti**	**ts**	**ti**	**ts**	**ti**	**ts**
Exp.14.61	16.69	28.78	21.32	12.80	15.87	26.68	26.06	17.05	17.81	26.26	21.40
Com.11.57	12.03	30.83	17.23	10.50	13.42	27.06	17.85	15.20	15.93	25.86	19.83
Amb.5.06	2.64	16.64	8.67	6..38	5.73	17.03	8.22	-	-	-	-
δ t1 3.04	4.66	-2.08	4.04	2.3	2.45	-0.43	2.21	1.85	1.88	0.4	1.57
δ 6t2 9.55	14.05	12.12	12.65	6.42	10.14	9.6	11.84	-	-	-	-

* Exp. is the experiment greenhouse, Com. is the compared greenhouse, and the Amb. is the ambient.
***δ** tl and **δ** t2 are the temperature difference of the experiment greenhouse with the compared greenhouse and the ambient respectively.

b. The influence of the heat storage or release on the interior temperature. It can be analyzed by the inside air energy balance equations. For the greenhouse without the UHES, it is

$$CVC_p \frac{d_N}{dT} = Q_{Ne} + Q_{Nm} + Q_{Ns} + Q_{Nv} - Q_{Nl} - Q_{Nd}$$

and for the greenhouse with the UHES, it is

$$CV\,C_p \frac{dt_y}{dT} = Q_{Yw} + Q_{Ym} + Q_{Ys} + Q_{Yv} + Q_{Ye} - Q_{Yl} - Q_{Yd} - Q_{Ye}$$

where dT is instant time, Qw is the heat transference between the inside air and the enclosing structure includes the two end walls, the north wall and the north and south roof; Qs is the heat transference between the inside air and the soil; Qp is the heat transference between the inside air and the plants; Qv is the heat gain of the air by the water evaporating; Qe is the heat given off by the fan when it is working; 01 is the heat loss through the enclosing structure; Qeh is heat stored or released by the UHES; Qd is the heat loss by the ventilation or the air infiltration. The subscripts N and Y indicate that there is not UHES or there are UHES in the greenhouse.

In these equations, the left side is the variance of the enthalpy or temperature of the inside air. Qw, Qs, Qp in the right side can be expressed as follows:

$$QW=\Sigma\ ^{5}1\alpha_{wi}F_{wi}\ (t_{wi}-t_{a})$$

$$Qs=\alpha_{s}F_{s}\ (t_{s}-t_{a})$$

$$Qp=\alpha_{p}F_{p}\ (t_{p}-t_{a})$$

where α is the convective heat transfer coefficient of each surface, and ay is greater than an because of the working of the UHES which causes the air flow in the greenhouse, tys is greater than tns due to the working of the UHES. So Qyw+ Qys+ Qyp is greater than Qnw+ Qns+ Qnp.

$$Qv = CV\frac{\delta d}{T}(R_o + C_{pw}t_a)$$

where od is the water increase of one Kg dry air caused by evaporation; R_o is the latent heat of vaporization in 0 °C; T is the working time. Since tys > tns, the transpiration of plant is strengthened and ody>odn. According to statistics, the sum of the above four heats of the greenhouse with UHES is 20-30KJ/m^2.h higher than that without UHES, so it inevitable that the inside air temperature higher than the later.

$$Ql=\Sigma\ ^{5}1\alpha_{wi}F_{wi}\ (t_{wi}-t_{r})$$

where tr is the ambient air temperature. Ql is approximately the same for these two greenhouses.

Qye=3600NeK

where Ne is the power of the electric motor of the fan; K is the load rate of the fan. Qye is the extra heating of the greenhouse, but it is much small.

The above analyses and experimental statistics indicate that the underground heal; exchange system can improve the thermal properties of the greenhouse effectively in the early spring and late autumn and can promote the utilization rate in a year and solar energy utilization rate.

9.2.3 Experimental Result Discussion

A. The UHES improves the microclimate of the greenhouse

First, it increases the air and soil temperature of the greenhouse. Shown in table 9.2.2, the air temperature and the soil temperature at 8: 00 a.m. in the experimented greenhouse is 2-3 °C and 1.88-4.66 °C higher respectively than the compared greenhouse, and the differences decreases with the ambient temperature increases. Especially the soil temperature of the planting layer soil of depth 25-30cm can be 6-10° C higher than the compared greenhouse before the middle of April. These indicate that the effect of the UHES on the interior air and soil temperature is noticeable and it is advantageous to move up the planting time. The maximum air temperature in daytime of early spring is 2-3°C lower than the compared greenhouse and need not be cooled by ventilation. So the maximum air temperature is decreased and the minimum temperature is promoted at night, and the temperature difference between daytime and night is reduced by 4-5° C which is also favorable to the plant.

Secondly, the UHES promoted the cold resistant ability of the greenhouse. Owing to the high soil temperature, i.e., great heat stored in the soil, the resistant ability of the greenhouse to the cold weather such as continuous cloudy, raining or snowing weather in the early spring. For example, it was snowing continuously from April. 10th to 21st in 1987 and became bright on Apr. 22nd with the minimum ambient temperature of - 3 ° C. The air temperature at 8: 00 a.m. was 10°C and soil temperature in the depth of 10-15cm was 11 °C in the experimented greenhouse while it were 5.5 °C and 6-7.5 °C respectively in the compared greenhouse which could damage the seedlings.

Thirdly, the UHES improves the moisture condition in the greenhouse. In the early spring and late autumn, the greenhouses are usually tightly closed and the relative humidity is 85-95% in the daytime and 95-100% at night. It is liable to cause diseases for the plant under such high temperature and high humidity. The UHES can reduce the relative humidity by condensing water in the ducts. According to the experiment, one kilogram air can condense 3 gram water at the most. The relative humidity in the experimented greenhouse can be dropped from nearly 80% at 8: 00 a.m. to 60-70% at 16: 00 p.m..

Fourthly, when the underground heat exchange system is working, air flows slowly in the greenhouse, which is favorable to the plant by the slow air flowing itself and by making the temperature and the CO_2 distribution more evenly. According to the experiment, the air flow velocity is 0.15-0.5m/s varying with the distance from the fan; and the air velocity is 0.1-0.2m/s around the plants, which does not exist in the greenhouse without the UHES.

B. The UHES promotes the growth and the production of plant

Firstly, it can move up the planting time of the fruit vegetables which can only be planted when the soil temperature in 10-15cm deep gets to more than 10 °C. The UHES started working from March 20th, 1987 and on April 5th the soil temperature of 10-15cm got as high as 14 °C at 8: 00 a.m. and 25-30cm 15°C while those of the compared greenhouse were 10°C and 9°C respectively. Based on the time of getting to the fit planting soil temperature, the greenhouse with UHES can be 10-15 days earlier than the that without the UHES. In the spring of 1988, some nonheated greenhouses in Shenyang City planted in the early March by strengthening the thermal insulation cladding, but a heavy snow afterwards frosted the seedlings in some greenhouses. Though the thermal insulating level of the experimented greenhouse was not the best, the minimum interior temperature maintained around 10°C and the seedlings grew well.

Secondly, it can accelerate the growth of the plant. The blooming time was earlier and the bloom number was more than the compared greenhouse under the same management level. The experiment shown that with one plant the fresh weight of the root in the experimented greenhouse was 56% more than that in the compared greenhouse and the stem 51% and leaf 82%, the average leaf number was 75% more and the average leaf area was 71% more.

Thirdly, it can promote the production of plant. It took 70 days for the tomato to ripe in the experimented greenhouse while 77 days in the compared greenhouse. Compared with the compared greenhouse, the production of tomato in the earlier stage increased by 138% and pepper by 141.3%, and the total production increased by more than 40% for the two vegetables. So with the UHES, the greenhouse vegetables can not only mature earlier but also can increase productions.

C. The economical benefit

The UHES increases the capital cost of the greenhouse. It cost 5400 Chinese dollar per 0.067 Ha. to build the UHES in the greenhouse in 1987 by using the clay brick ducts. Considering that the service life of the ducts and the fan are 15 years and 5 years respectively, the depreciation charge of the UHES is 111 Chinese Yuan per 0.067 ha. per growth phase. According to the experiment, the power consumption of the fan was 3Kw.hr. per day. The fan worked for 60 days approximately and the electric power was 0.09 Chinese Yuan every KW.hr., then the operation charge was 172.9 Chinese Yuans per 0.067 Ha. per growth phase. So the total cost was 283.9 Chinese Yuans per 0.067 ha. per growth season.

Since the greenhouse with the UHES can promote the production of the vegetables significantly especially the early stage production which took a proportion of 29% of total production. For the price of the tomato in the early stage was 2 Chinese Yuans per kilogram and it was 1.1 Chinese Yuans in the late stage in 1987, the output value of the experimented greenhouse was 7662.7 Chinese Yuans while that of the compared greenhouse was 4610.68 Chinese Yuans per 0.067 ha.. The output value increased by 3052.02 Chinese Yuans per 0.067 ha.. Hence, it would only take 1.78 growth phase for recovering the capital cost of the UHES and it is much shorter than its service term.

Compared with the heated greenhouse, for instance, the glasshouse of our university whose heating cost totally 600 Chinese Yuans per 0.067 ha. per growth phase, the experimented greenhouse cost was more than two times lower. The plastic film greenhouse of farmers consumed 0.3Kg/m^2 coal per day, the coal cost 100 Chinese Yuans per ton. Take the heating term as 30 days every growth phase, then total cost of coal was 599.4 Chinese Yuans per 0.067 ha. per growth phase except labour cost, which was about two times higher than the experimented greenhouse. Moreover, such supplementary heating can merely increase the air temperature of the greenhouse and do little favour to the soil temperature and the moisture condition.

Conclusion

By using the under ground heat exchange system in the greenhouse in the north cold regions, not only the solar energy using efficiency can be promoted, but also the micro - environment of the greenhouse can be improved. The planting of the fruit vegetables can be moved up by 10-20 days in the early spring and the growth phase of the vegetables can be prolonged by 10-20 days in the late autumn, so the service term of a greenhouse can be 30-40 days longer than the greenhouse without the under ground heat exchange system. Since its production promotion and the output value increases are significant, it is of great possibility to be extent widely in the north cold regions.

9.3. The benefit of vegetable production in the underground heat exchange solar greenhouse

9.3.1 Introduction

Vegetables are necessary food for humans: With the increasing living standard, the people propose higher demand on vegetable kinds, varieties and the year-round supply of palatable fresh ones. The vegetable production in protective ground has satisfied a part of the demand, but the energy consumption and high cost still prohibit the precious vegetable production in large scale, The authors have used the underground heat exchange solar greenhouse (UHESG) to solve this problem, By means of UHESG, the solar energy can be aggregated and reserved to elevate the air and ground temperature in solar greenhouse in early spring and late autumn, hence to promote early maturity and delayed production of vegetables. The harvesting date is 10 days earlier than that in the general solar greenhouse or controlled solar greenhouse (CSG) in the experiment.

In 1987 - 1988, the vegetables as tomato and chili were cultivated in UHESG for experimentation and the result was ideal.

In 1990, vegetables and flowers were also tested in such greenhouse established in the Comprehensive Energy Resource Demonstration Base.

9.3.2 The cultivation measures

A. Brief account of the cultivation measures in 1987

The soil was manured with 250kg of pig manure for each greenhouse, The tomato variety No. 401 was used as experimental material. The planting date was April 5th. when the ground temperature was 14 °C at 10-15cm below surface and 15 °C at 25-30cm below surface in the UHESG, while in the CSG was 10°C and 9°C respectively, plant spacing was 33-50cm for single plant, which was proped and irrigated after planting. Since then, watering was controlled to stunt the seedlings and the soil was kept moist only below 5cm from surface The plants were not topdressed and watered until the young fruit reached the size of 2cm in diameter. There were 6 times of irrigation in the experiment. Urea was used for Topdressing with the dosage of 3g per plant. On 20th of April, the flowers were dipped in 2-4D of 13ppm. for three times. On May 21st, the plants were topped with 3 flows clusters remained. Soil loosening and weeding was carried out for 2 times.

The early maturing NO.5 of chili was seeding on 23rd of January, 1987, The seedlings were transplanted once and the planting date was April 12th. With the spacing of 20-50c (C for single plant, irrigation was six times higher and topdressing only once with 3g of urea for each plant.

The planting area for each crop and cultivation measures in the CSG were all the same as that in the UHESG.

B. Brief account of cultivation measures in 1988

Manuring: 200kg of pig manure for each greenhouse;
Topdressing: 2.5g of (NH4)'vPO'wper plant;
Tomato variety: No.401;
Planting date: march 15th;
Spacing: 33-55c (C, proped;
Irrigation 4 times;
Spraying of tomato growth regulating hormone (25ppm) 2 times;
Soil loosening and weeding twice.

9.3.3. Crop growth situations in different greenhouses:

A. The flower bud emerging, flowering and fruiting situations of tomato and chili:

In 1987, the growth and development situations of tomato and chili cultured in the UHESG were significantly better that in the CSG. The experimental results were similar for both crops (see Tab.9.3.1).

The date of first survey for tomato plants was April 7th, 2 days after planting. The survey totalled 3 times at the interval of 10 days, In the first survey, the percentage of flower emerging plants in UHESG were less than that in CSG, which indicated that the seedlings in UHESG were worse than that in CSG. 10 days later, the plants in UHESG performed better in growth and development and the percentage of flowering plants was higher by

9%.20 days later, the plants in UHESG all flowered. The experimental results for chili were similar to that for tomato (see Tab.9.3.2)

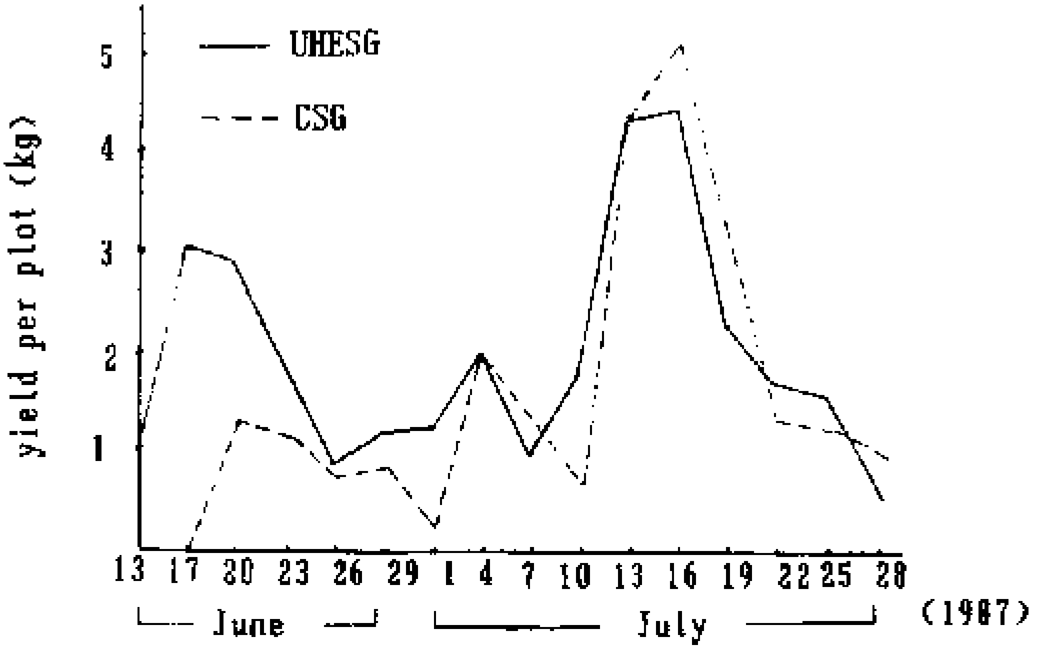
Tab.9.3.1. comparison the flower bud emerging and flowering plant percentage in different greenhouses

Item	Treatment	7/4	17/4	27/4
flower bud emerging plants %	UHESG	91	100	
	CSG	95	100	
flowering plants %	UHESG	0	14	100
	CSG	0	5	86

From the survey on the same day, it can be seen that the chili grown in the UHESG was better than that grown in the CSG according to the fruit harvested, fallen fruit, flowering and flower bud emerging situations, In the UHESG, the harvest of first Fruit on each plant began on may 28th and the second fruits on may 3rd; while in the CSG the harvest began on may 31, and the first fruits did not all harvested until June 11, 8 days later than that in the UHESG, In the Survey on June 15, 100% of the first fruits had been harvested in the UHESG, while in the CSG, only 66.7% had been harvested and the remains had fallen. The difference of 2nd fruit harvest percentage between the different greenhouses was also significant. As for the later fruiting rate, the CSG was higher than UHESG, probably because of the influence of the setting of 1st and 2nd fruits. Generally, the lower fruits are larger which influence the growth of upper fruits. Such phenomenon exists in tomato plants and particularly obvious in chili, Therefore, early harvest of 1st fruits may resolve the problem.

B. The yield of tomato and the economic benefit analysis

Fig 9.3.1 plot yield curve of tomato



The harvest date of tomato in UHESG was seven days earlier than that in CSG; and the earlier stage yield in UHESG was also higher, but the difference of later stage yield was not significant. (see Fig.9.3.1)

The yield constituting factors, such as the mean fruit number per plant, single fruit weight, yield per plant were all higher in UHESG than in CSG. The earlier stage yield (June 13-29) in UHESG was 1.3 times as high as in CSG, the later stage yield increased 12%, and the total yield increased 44% for the UHESG. Therefore, the economic benefit of Tomato crop in UHESG was significantly higher than in CSG. (See Tab.9.3.1)

According to the tomato prices of different stages from June 13 to July 29 in 1987, and the earlier stage, later stage and total output calculated, it can be seen that the tomato crop in UHESG gave about 3, 000 Yuan more than that in CSG (see Fig.9.3.2) As the investment For equipment was 8 yuan per (C or 5336 yuan per 667 (C, it could be returned within a year. If the fees for water ° electricity and human labour were also accounted, the all investment could be returned within 2 years.

C. The chili yield and the economic benefit analysis

The earlier stage yield of chili in UHESG was significantly higher than that in CSG, and the later stage yields were similar (Fig.9.3.2). From the data of fruit number per plant, single fruit weight and the yield per plant, it can be seen that the UHESG was quite better than CSG, and the earlier stage output and total output were also higher (see Tab.9.3.4). But the chili yield is rather low and people's consumption of chili is also low . Therefore, the income increased was not very high; but the crops in the UHESG grew faster, matured earlier and gave higher yield.

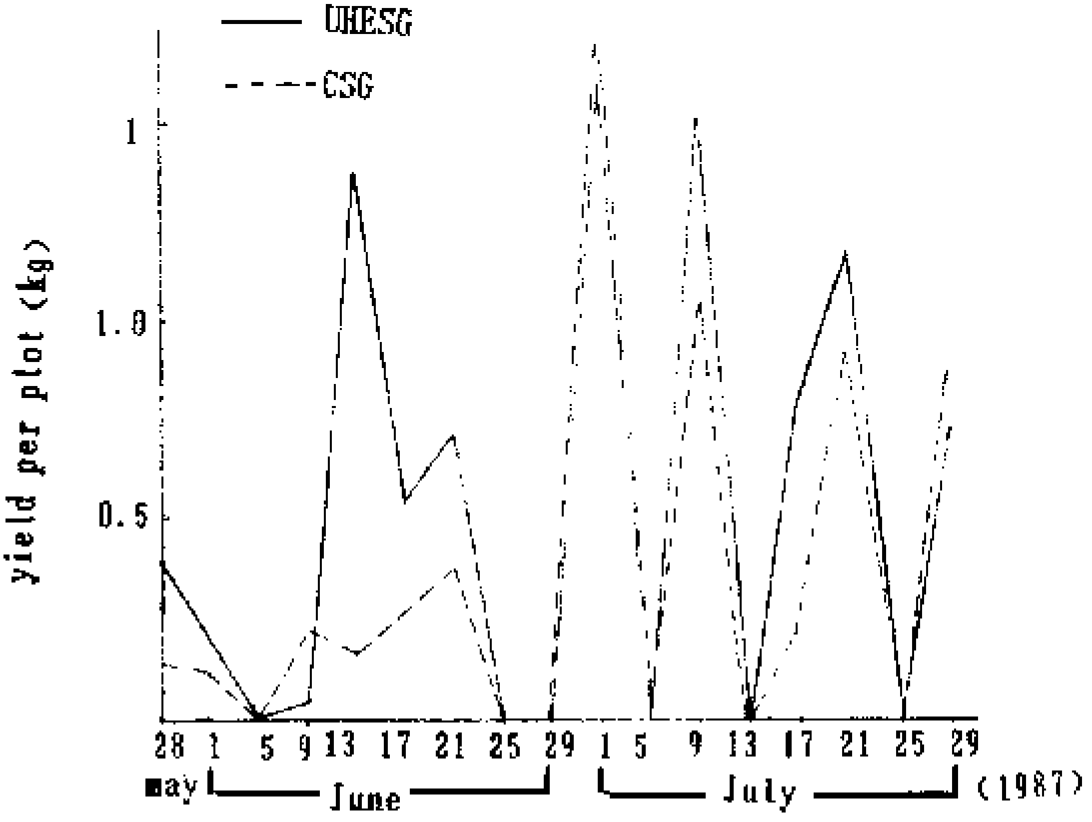
9.3.4. The cause of crop yield increase in UHESG and the nutrient balancing

A. The cause of early maturity and yield increase

Because there were underground earthenware pipes and wind blowers in the UHESG, the warm air in the day Time could be blown to the ground and the heat energy was reserved to cause the ground temperature to elevate. In the cold seasons of winter and spring, the ground temperature was the determinant factor to increase crop yield in the protective ground. In the night, the air circulation caused the room temperature to elevate about 2-5 f at the coldest time as compared with the control; but the midday highest room temperature was lowered. Thus, the elevated ground temperature made the planting earlier and the early maturity was inevitable when the other management was suitable. Because of the air circulation, the air composition around the plants changed, the Co evenly distributed and the ventilation improved.

Generally, bad ventilation caused excessive growth and diseases. Tomato is such an example if the environment is warm and humid, The ventilation in the UHESG was significantly better than that in the CSG, which was one of the main causes to promote early maturely and to increase yield.

FIGURE



Tab.9.3.1 comparison between two different greenhouses of tomato yield constituting factors and yield increase

Treatment	fruit number per plant	single fruit weight (g)	Yield per plant (kg)	earlier stage per plot*		Later stage per plot**		Yield and output per 667 (C	
				Yield (kg)	output (yuan)	Yield (kg)	output (yuan)	Yield (kg)	output (yuan)
UHESG	8.1	155	1.34	17.9	35.80	43.7	48.07	5360	7662.7
CSG	7.3	132	0.93	7.5	15.00	39.1	43.01	3720	4610.68

* earlier stage (Jane 13 - 29) price 2.00 Yuan/kg
** later stage (July 1st - 29) price 1.10 Yuan/kg.

Tab.9.3.2. Comparison of chilli fruits at different places, flowering and flower bud emerging situations in different greenhouses

Treat.	surveying date	plants surveyed	Ist fruit		2nd t fruit			3rd	
			harvested %	fallen %	harvested %	unharvested %	flowerieg %	harvested %	unharveste %
UHESG	June 15	18	100	0	52.4	11.9	35.7	0	22.9
CSG	June 15	18	66.7	33.3	0	41.9	58.1	0	38.6

Tab.9.3.4. Comparison of the chili yield constituting factors and the yield increase in different greenhouses

Treatment	fruit number per plant	single fruit weight (g)	Yield per plant (kg)	earlier stage per plot*		Later stage per plot**		Yield and output per 667 (C	
				Yield (kg)	output (Yuan)	Yield (kg)	output (Yuan)	Yield (kg)	output (Yuan)
UHESG	11.14	28.5	0.32	3.33	6.66	8.02	8.82	2112	2874.43
CSG	8.06	27.5	0.22	1.38	2.76	4.52	4.97	1452	1897.76

* earlier stage (May 28th - June 24th) price 2.00 Yuan/kg
** later stage (July 1st - August 10th) price 1.10Yuan/kg

According to the information from the National Soil Manure Station, the nutrient absorption data of several fruit providing vegetables are shown in Tab.9.3.5

B. Nutrient balancing

The growth period of vegetables is relatively short and several successive crops mature in a year. Both single crop yield and total yield are rather high. The crops take a vast amount of nutrient elements every year. Thus the soil should be applied continuously with various nutrients.

Generally, the manuring amount in the open ground is about 5000kg of organic manure per 667 (C per year, or several tons of night soil or 100kg of inorganic N. The standard of manure application should be slightly higher in the protective ground, and the organic manure is mainly used.

As for tomato, the different level of yield takes different amount of nutrients (see Tab.9.3.6)

Tab.9.3.5 The amount of nutrient absorbed by 1000kg of fruit product (kg)

crop	N	P	K	Ca	mg
cucumber	1.9 - 2.7	0.8 - 0.9	3.5 - 4.0	3.1 - 3.3	0.7 - 0.8
tomato	2.7 - 3.2	0.6 - 1.0	4.9 - 5.1	2.2 - 4.2	0.5 - 0.9
eggplant	3.0 - 4.3	0.7 - 1.0	4.9 - 6.6	1.2 - 2.4	0.3 - 0.5
chili	0.58	1.1	7.4	2.5	0.9

Tab.9.3.6. The amount of nutrient absorbed by tomato of different yield level (kg/667 (C)

yield level	N	P'vO	K'vO
2000 - 2500	7.8	2.0	7.2
2500 - 3000	10.1	2.6	8.1
3000 - 3500	11.6	2.7	11.7
3500 - 4000	15.1	3.5	14.4
4000 - 5000	16.3	3.7	13.3

In the experiment of 1987, the manuring standard was 250kg of pig manure and 200kg of horse manure for one greenhouse (62.4 (C) and 3g of urea for each plant, According to the available information, the N content in Pig manure is 0.34%, in horse manure 0.2% and in urea 45%, Through calculation, the manuring amount of N in the experiment was about 21.46kg/667 (C, much higher than the necessary amount 16.3kg/667 (C, for tomato of the 5000kg/667 (C yield level. Therefore, much nutrient was remained for the next crop, even if a part of it was evaporated or leached out. But in the experiment of 1988, the manuring amount was 200kg of pig manure for one greenhouse and 2.5g of (NH4) 'vPO'w for each plant, amounting to 9.7kg/667 (C of N. It seems much lower than the necessary amount for tomato production. If was not unexpected to see nutrient deficiency in the later period in 1988.

9.3.5 Conclusion

According to this experiment and the related information from home and abroad, it can be seen that:

The UHESG can fully use the solar energy to regulate the air and ground temperature and to promote early maturity and cause high yield of crops;

The crop yield in protective is greatly related to the nutrient balancing. Therefore it is necessary to elevate the level of fertilizer applied, particularly the organic manure;

It is possible to produce vegetables without artificial heating in winter in shenyang region, if thermal insulation is enhanced and management level elevated. At the extreme cold temperature in 1987, the room temperature in the UHESG of this experiment was above 0 f and the Chinese chive and celery could survive and recover normal growth when the weather became warmer.

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