Energy saving hydroponic greenhouse pilot project: energy aspects

L. OTTEN[1], P. G. MULLER[2], H. TIESSEN[3†], S. KHOSLA[4], F. REY[5], and H. A. JACKSON[6]

[1]School of Engineering, University of Guelph, Guelph, Ontario and Wellington Applied Sciences, Ltd., Guelph, Ontario, Canada; [2]INMARINT International Marketing & Investment Ltd., Ottawa, Ontario, Canada; [3]Department of Horticultural Science, University of Guelph, Guelph, Ontario, Canada; [4]Research Station, Agriculture Canada, Harrow, Ontario, Canada; [5]Wellington Applied Sciences Ltd., Guelph, Ontario, Canada; and [6]Engineering and Statistical Research Centre, Agriculture Canada, Ottawa, Ontario, Canada. *Contribution no. C-016[6], received 1 August 1988, accepted 1 December 1988.*

Otten, L., Muller, P. G., Tiessen, H., Khosla, S., Rey, F. and Jackson, H. A. 1989. **Energy saving hydroponic greenhouse pilot project: Energy aspects.** Can. Agric. Eng. **31**: 147–152. A semi-commercial project was undertaken for 2 yr to demonstrate the use of reduced night temperatures and rootzone heating as a means of saving energy in the production of greenhouse tomatoes. A commercial greenhouse was divided into a warm and a cold section to arrange for night temperatures of 18 and 11°C, respectively; while the day temperatures were kept the same. The project involved three types of growing media (Nutrient Film Technique, Rockwool, and Soil), heated and unheated rootzones (NFT, Rockwool), two cultivars (Buffalo and Caruso), and three replications for each treatment in both greenhouse sections. Therefore there were 60 separate modules containing about 50 plants each. Energy consumption data indicated that savings of at least 30% are possible for both the spring and fall crops with a reduction in night temperature. Yield data showed that all treatments yielded about twice the commercial average of 7.2 kg/plant, which can be attributed to the use of proper management techniques and appropriate equipment. Rootzone heating was generally not beneficial with the exception of rockwool in the early spring.

INTRODUCTION

Muller et al. (1982) presented an analysis of the technical, horticultural and economic feasibility of energy-saving methods for hydroponic greenhouse culture systems. Part of the study dealt with the use of reduced night temperatures coupled with solar-heated nutrient solutions and thermal curtains in double-polyethylene greenhouses. In the study the authors reviewed the work done on the effect of rootzone heating and reduced night temperatures on the yield of various vegetable crops and flowers. For example, they found that Moustafa and Morgan (1981a, b) observed a significant increase in the quality of spray chrysanthemums and a 60% reduction in energy use with rootzone warming and night temperatures of about 9°C. Similarly, several researchers reported increases in early yields of tomatoes but no effect on the total yield over the entire growing season when the substrate was heated (Morgan and O'Haire 1978). On the other hand, increases in the total tomato yield were reported when the heated substrate was combined with reduced night temperatures (Morgan and O'Haire 1978; Maher 1980; Moorby and Graves 1980; Orchard 1980). Most researchers also found that the selection of the cultivars had a significant effect on the results.

As a result of the feasibility study, a project was designed with the general objective of testing the horticultural, technical and economic concept of growing tomatoes using reduced night temperatures and heated nutrient solutions in a commercial hydroponic greenhouse operation. As such, the project was of an applied nature rather than being a carefully controlled scientific experiment. For example, the actual greenhouse temperatures were allowed to follow the ambient temperature so that during warm nights the cooler target temperatures were not always reached.

This paper deals mainly with the engineering work related to energy accounting and data acquisition and analysis but it also provides a summary of the tomato yields. The horticultural aspects (Khosla et al. 1989) and the economic implications (Muller et al. 1988) of the project are reported elsewhere.

PROJECT DESCRIPTION

The project was initiated in the early fall of 1984 and started with the 1985 spring crop. The results of two spring and two fall crops were evaluated separately and summarized at the end of the study. A complete description and details of the study can be found in Muller et al. (1987). The 1985 spring crop was a period of learning and fine tuning of the procedures, which were complicated by the fact that the project involved three types of growing media (Nutrient Film Technique (NFT), Rockwool, and Soil), heated and unheated root zones (NFT, Rockwool), two ambient temperatures (cold and warm sections), two cultivars (Buffalo and Caruso), and three replications for each treatment. Therefore the total number of separate growing modules was 60. The tomatoes from each module were harvested separately, graded and weighed.

Each treatment consisted of twin rows of tomato plants 1050 mm apart. The single rows were 705 mm apart and the plant spacing in the rows was 425 mm, thus providing a plant density of 2.68 plants/m^2.

After evaluating various sites, Costa's Greenhouse in Paris, Ontario was selected for the project. The greenhouse was a glass-covered, gutter-connected structure of 0.22 ha. The layout of the greenhouse and experimental equipment is shown in Fig. 1. Since the site had only one large greenhouse, it was necessary to subdivide the area into warm and cold sections. The cold section consisted of five bays at the north end of the greenhouse and was separated from the warm area by a double polyethylene-covered frame-barrier. The warm area also consisted of five bays adjoining the remaining grower's area of four bays. There was no barrier between these two areas, but guard rows of tomatoes were used to border the project.

In order to calculate the energy savings resulting from reduced night temperatures, two different target temperatures were set for the sections; namely,

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†Deceased.

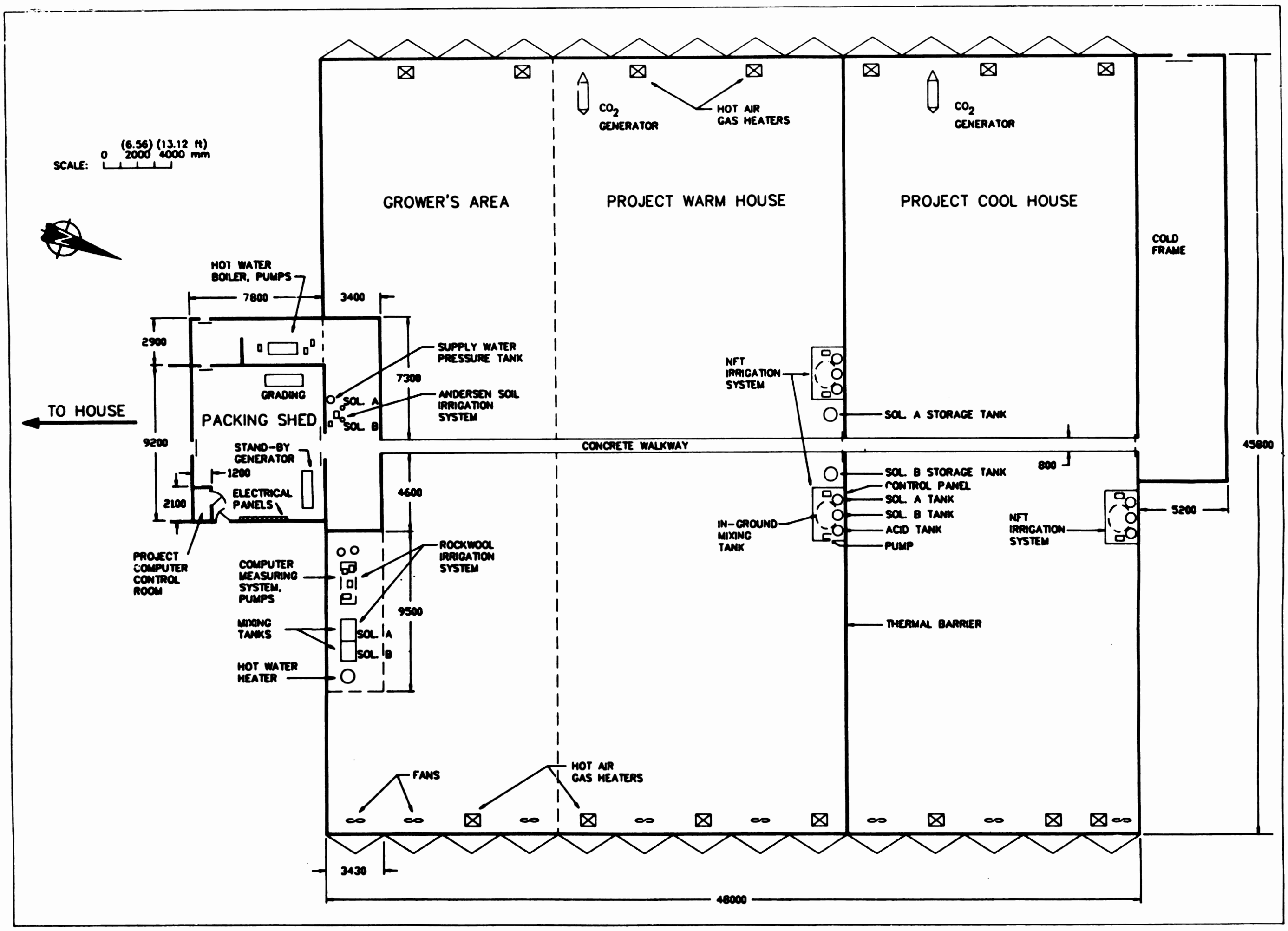

Fig. 1. Layout of grower's greenhouse.

warm section: 22°C day and 18°C night
cold section: 22°C day and 11°C night

At the same time, the rootzone temperatures for plants in the NFT and rockwool were kept at 22°C at all times for the heated media and at the prevailing ambient temperature for the unheated media.

In order to measure the amount of energy used during a given period, and hence the energy used per unit area, all significant energy flows were recorded. The major energy input was due to heating of the greenhouse space by a hot water heating system and forced air furnaces.

The second most important energy input was due to solar insolation; however, since both the warm and cold sections nominally received an equal amount of insolation, it was not included in determining the difference in energy used in the two greenhouse sections and the various cultivation systems.

The remaining energy inputs were related to specific cultivation systems and carbon dioxide generators. The heated rockwool system involved use of electric cables to maintain appropriate root temperatures, while the heated NFT system involved heating of the nutrient solution. These energy flows were monitored separately and credited to the specific system and the overall energy requirements.

GREENHOUSE HEATING

Hot water system

Both the warm and cold sections of the greenhouse were heated with a hot water system and hot-air furnaces. The hot water system included a gas-boiler, a network of pipes, and two circulating pumps. Water was heated in the 40 kW boiler and pumped through a main header along the west wall of the greenhouse. For each double row of plants, a 50-mm-diameter pipe located about 0.3 m above the ground transferred hot water across the house to the east wall. All parallel flow passages recombined in a header along the east wall. The flow direction in both headers was from the front to the back of the greenhouse with appropriate changes in pipe diameter to accommodate changes in volumetric flow rate. The fluid in the east wall header was returned to the boiler through two parallel return pipes (65 and 57 mm diameter) placed along the wall above the header.

In order to control the temperature in the cold section separately, a thermostatically controlled valve was installed in the west-wall header before it entered the cold section. If no heat was required in the cold section, the valve was closed by the thermostat and the fluid by-passed the lateral pipes in that part of the greenhouse.

Energy flow into the greenhouse from the hot water system was monitored with two Svensk (AB Svensk Varmematning SVM. Box 60, S-16391 Spanga, Sweden) energy meters. These meters recorded the volumetric water flow rate and the inlet and outlet water temperatures. The temperature difference and water flow rate were integrated over time to provide the energy consumption. The West German Testing Authority PTB (Physikalisch-Technische Bundesanstalt) determined the accuracy of the energy meters to be ± 1%.

The hot-water heating system included two pipes along the east wall and a finned-tube along the west wall through which water returned to the boiler. The lengths of the pipes running through the warm section contributed radiative and conductive heat to that section but the location of the energy meters resulted in crediting the cold section with this energy. In order to correct the energy balance, the surface temperatures of the pipes and the ambient section temperatures were monitored and averaged over four daily time periods: namely, 00:00–06:00 h, 06:00–12:00 h, 12:00–18:00 h, and 18:00–24:00 h. The average pipe temperature and the mean ambient temperature of the warm section were used for each pipe.

A check of the air temperature field around the pipes during the 1985 fall crop indicated that the convective heat loss was mainly by natural convection. Therefore, the convective heat transfer coefficient was calculated using

$$Nu_D = C\,(Gr_f Pr_f)^n \qquad (1)$$

Average daily temperature data showed that all Grashof-Prandtl products were in the range of 10^4 to 10^9 so that the corresponding heat transfer coefficients varied from 5 to 7 W/(m^2.K) (Kreith and Black 1980).

Furnaces

In addition to the hot-water system, the greenhouse was heated with hot-air furnaces; five in the cold and nine in the warm section. Heated air from a furnace was distributed throughout a bay with a 0.45-m-diameter plastic ventilation tube. After the 1986 spring crop, the seven furnaces along the east wall were removed, leaving three in the cold and four in the warm section. Each furnace was equipped with a Rockwell gas meter.

Since it was necessary to control the temperature in each section separately, a Honeywell programmable thermostat coupled to a relay and power supply was used. The thermostat of each section was programmed to control the day and night temperature at the desired levels.

Carbon dioxide burners

PRIVA burners, designed to provide complete combustion of natural gas to CO_2 and water, were used to maintain the CO_2 level in the range of 800 to 1000 ppm in each section. The amount of heat added by each burner was monitored with a Rockwell RC-415-TC gas meter.

Warm-cold section barrier

Heat transferred from the warm to the cold section through the polyethylene frame-barrier was included in comparing the energy consumption of the sections. The resistance to heat transfer through the barrier is due to the presence of boundary layers on both sides of the wall and in the air space between the two plastic layers. There is also a conductive resistance due to the plastic itself; however, since the plastic is very thin, the conductive resistance is much less than the convective resistance. With all the significant heat transfer resistances in series, the governing equation becomes,

$$q = A(T_{\mathrm{warm}} - T_{\mathrm{cold}})/(\frac{1}{h_1} + \frac{1}{h_s} + \frac{1}{h_2}) \qquad (2)$$

An examination of the daily ambient temperature data showed that only the first (00:00–06:00 h) and last (18:00–24:00 h) periods gave significant temperature differences. It was therefore decided to calculate the daily heat exchange using T_{warm} and T_{cold} for those periods only. The data also showed that the maximum temperature difference between the plastic surface and the environment was not greater than 4°C. The free convective heat transfer coefficients were calculated using a driving force of 4°C and a film temperature of 15°C. Under these conditions the heat transfer coefficient for each wall surface is given by (Kreith and Black 1980)

$$h_i = 0.59\,\frac{k}{L}\,(Gr_f\,Pr_f)^{0.25} = 2.0\ \mathrm{W/(m^2.K)} \quad i=1,2 \qquad (3)$$

For the air space between the plastic, the heat transfer coefficient correlation is

$$h_s = 0.065\,\frac{k}{b}\,Gr_f^{0.33}/(L/b)^{1/9} = 0.74\ \mathrm{W/(m^2.K)} \qquad (4)$$

DATA ACQUISITION

The ambient air temperature in each section was monitored by placing sensors in a central location, shielded from direct and reflected solar radiation. A sensor was also placed beneath the soffit of the grading house to record the outside temperature. The temperature of one module of each of the treatments was also recorded. Grounding of the senors was found to be necessary to reduce signal interference produced by electric equipment in the greenhouse.

Solar radiation, light intensities and relative humidity measurements were made and used as operating information by the grower.

The data acquisition system consisted of a TAURUS LAB connected to an IBM PC. The computer was programmed to accept thermocouple, humidity, solar radiation and light intensity sensor signals at 3-min intervals for display on the screen. Ten sets of data were averaged to give half-hour averages which were also shown on the screen and recorded on the data disk. These averages were sent to a printer for a hard copy output.

A program was written to produce daily plots of temperature data which were used by the greenhouse staff to control the operation of the treatments.

RESULTS AND DISCUSSION

Since the 1985 spring crop was a learning period and some of the monitoring systems were delivered after the crop had been started, the results reported in this paper are for the 1986 spring and fall crops only.

Energy data

Hot water system efficiency. The hot water meters measured the amount of energy flowing from the pipes to the greenhouse and therefore recorded energy output. In contrast, measurements of gas consumption of the furnaces and CO_2 burners represented energy input. In order to be consistent, the energy output obtained from the hot water meters, including the return pipe correction, had to be converted to an equivalent input using a hot water system efficiency value.

The efficiency rating was calculated during the 1986 spring and fall crops after another gas meter was installed to provide the gas input to the boiler. The efficiency or effectiveness was determined to be 68 and 64% for the 1986 spring and fall crops, respectively. The calculated values compare well with a typical efficiency of 70% and a maximum one of 80% for gas-fired boilers, especially as the project boiler was used intermittently during part of the season and was kept operating in a recirculating mode to prevent shocking of the boiler tubes.

Heat transferred from return pipes. As mentioned, the energy meter readings were corrected to account for the heat flow from the return pipes and finned-tubes to the warm section. Table I shows the corrections for the 1986 spring and fall crops. In each case the magnitude of the correction was significant, especially as the amount was subtracted from the cold house energy use and added to the warm house use.

Table I. Overall energy consumption to heat cold and warm sections of the greenhouse, 1986 crops

	Spring crop		Fall crop	
	Cold	Warm	Cold	Warm
Gas furnaces (GJ)	294.17	502.07	46.18	122.68
Warm system (GJ)	555.95	1418.61	262.52	697.89
Carbon dioxide burners (GJ)	29.18	54.76	14.59	14.51
Rootzone heating (GJ)	26.94	31.52	14.23	3.06
Total (uncorrected)	906.23	1988.96	337.53	838.14
Corrections:				
(a) Return/Pipes (GJ)	−80.31	80.31	−39.45	39.45
(b) Barrier (GJ)	0.11	−0.11	0.04	−0.04
Total (corrected)	826.03	2069.16	298.12	877.55
Specific energy consumption (MJ/m^2)	1050.5	1463.4	379.5	620.7
Savings (%)	28.2	–	38.9	–

Heat flow through the barrier. Table I also shows the total heat flow through the barrier between the two sections. In contrast with the return pipe corrections, the exchange of heat through the barrier was insignificant. The main reasons for this small heat flow were the small average temperature differences between the two sections and the high thermal resistance of the barrier. Even though the heat transfer coefficients were estimated using a number of assumptions, errors of 100% or more would not affect the final conclusion that this flow of heat was insignificant.

Heat flow from media heating. The heat contributed to each section by rootzone heating was also included in the energy consumption analysis. As shown in Table I, the amount was similar in magnitude to that supplied by the carbon dioxide generators but small in comparison with the total energy consumption.

Weekly energy data

Graphical histories of the weekly energy consumption for heating of both sections were prepared for each crop. Figure 2 illustrates the plot obtained for the first half of the spring crop. The energy consumption is presented on a per-unit-area-per-day basis for each period or week and includes the hot water system efficiency but not the return pipe correction.

The figure indicates that the cold section used less energy than the warm section during each of the test periods. It also shows the effect of the weather. For example, as shown in Fig. 2, there was a decrease in energy consumption as the weather became warmer in the spring. Of course, the reverse was observed for the fall crop.

Weekly temperature data

Starting with the 1986 spring crop the temperature data were analyzed on a weekly basis, as well as checked daily by the greenhouse staff. The temperatures of greatest interest in terms of energy use are the average night (00:00–06:00 h) temperatures of the two sections and the ambient environment. Figure 3 shows the temperature histories recorded for the first half of the 1986 spring crop with the abscissa representing the number of days elapsed since the start of the crop.

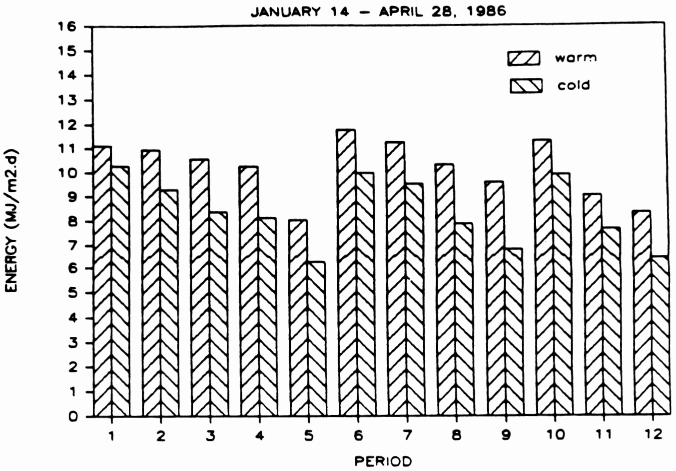

Fig. 2. Weekly energy consumption results for first half of Spring 1986 crop.

The plot shows a significant difference in the average night temperatures of the two sections. In most instances the difference was in the range 5 – 7°C, which was less than the design target of 8°C. Although much of the data exhibited uniform temperatures in each section, the observed fluctuations indicate that at times there was a temperature control problem.

The bottom plot of the figure shows the change in average ambient temperature as the crop progressed. This plot is important in that it indicates the potential of achieving the desired night temperatures of 11 and 18°C in the cold and warm sections, respectively. Clearly, there was no difficulty in reducing the night temperatures during the winter months; however, starting in April it became more and more difficult to get the cold section down to 11°C. With the exception of a few cold nights in June, the night temperature stayed well above the target temperature after the middle of May.

A similar pattern was observed for the fall crop. On only 27 d did the ambient night temperature drop below 11°C so that it was difficult to achieve the target of 11°C for the cold section. Furthermore, because of the thermal inertia of the greenhouse, the cold house reached an average night temperature of 12 – 14°C on only 14 out of 106 d. In the same period, the warm house recorded an average night temperature of 18 – 20°C on 41 occasions and 18°C or less on nine occasions.

Although it is obvious that one cannot obtain the target temperatures without sufficiently low ambient temperatures, there was no reason for both houses not to reach the same minimum value, albeit above 18°C, on any one day. However, the fall data indicated that while the cold house regularly dropped to 18°C or less, the warm house was 20°C or higher. This again suggests inadequate and inconsistent control of the temperatures in both houses during the 1986 fall crop. In part, this condition appeared to be due to the programmable thermostats which had a tendency to malfunction in the high humidity environment. However, since most of the heat was supplied by the hot water system (see Table I), lack of control of the boiler by the grower was also a factor.

Growing media temperatures

The temperature recordings of the individual media treatments showed that the NFT solution reached temperatures well above

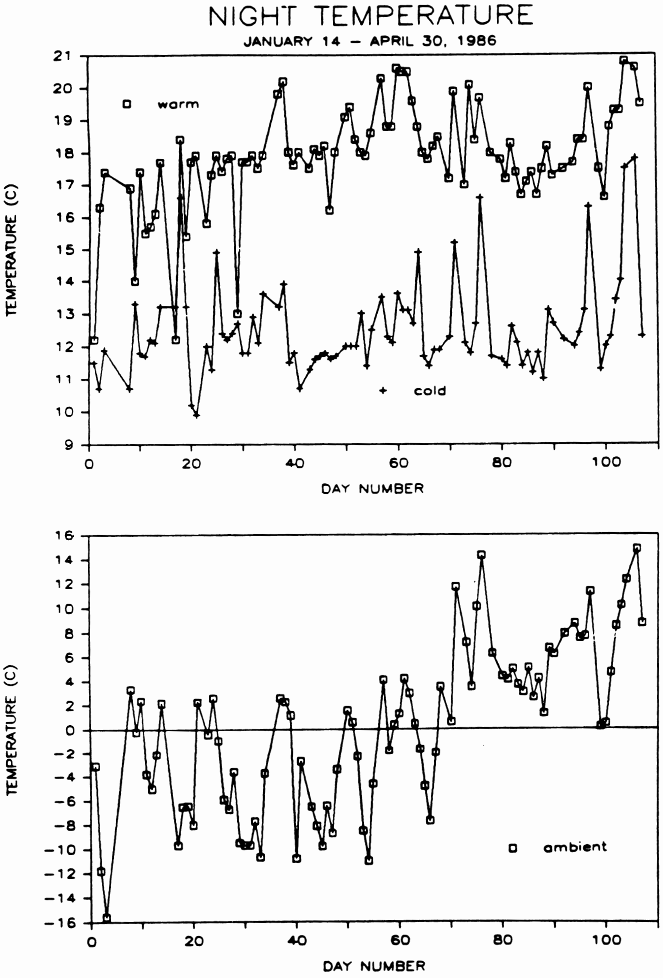

Fig. 3. Temperature data for warm and cold sections, and ambient environment for first half of Spring 1986 crop.

30°C during the summer months. The NFT troughs acted as solar collectors even though the white side of the polyethylene film was put on the outside. As a result the plants were subjected to considerable stress, thus reducing the yield. The overheated solution had to be dumped frequently and replaced with cool ground water mixed with fresh nutrients. The same observation was also made regarding the rockwool solution which was stored in a tank above the ground; however, the condition was not as serious.

It is recommended that provisions be made to cool the nutrient solutions using an appropriate cooling or refrigeration system. This would eliminate plant stress and the high cost of preparing new solutions.

Overall energy consumption

The energy consumed by furnaces, boiler and carbon dioxide burners is summarized for the crops in Table I. After making the corrections for the heat loss from the return pipes and finned tubes and for the heat exchange through the barrier, the energy per unit area of section was calculated based on 785.47 m^2 and 1413.85 m^2 for the cold and warm sections, respectively.

The table shows that even though the hot water system and furnaces accounted for the major energy flows in the greenhouse, the contributions by the CO_2 and rootzone heating system were significant. The results also show that the correction to account for the return pipes was necessary.

Although the savings of 39% for the 1986 *fall* crop was substantial, it must be recalled that the temperature control was inadequate. Some of the savings were made possible because an unnecessary temperature difference was maintained between the two sections on occasions when the ambient temperature allowed both sections to drop to 18°C or less. Hence, the specific energy consumption of each section, but especially the warm one, was higher than necessary.

In view of the above discussion it may be concluded that reducing the night temperatures resulted in energy savings of about 30% in both the spring and fall crops. Also, better control of the temperature by the grower would result in greater savings.

Crop yield

Although details of the horticultural results, including grade distribution and disease information, are published elsewhere (Muller et al. 1987; Khosla et al. 1988), a summary of the total yields is given in Table II. The yield obtained for the complete spring/fall season for all growing media was more than twice the commercial average of 7.2 kg/plant. The corresponding revenues per plant ranged from $30 to $37 for the spring crop and from $9 to $10 for the fall crop.

The results also showed that plants grown in good soil at cool night temperatures and fertilized through a drip irrigation system can produce similar yields to those obtained with NFT and rockwool systems but with a lower percentage of large fruits.

The crop yield results suggest that the NFT system gave optimum yields when the night temperatures were lowered and the nutrient solution was not heated. This system produced the highest yields and the highest percentage of extra large fruits so that the revenue averaged $37.44/plant for the spring crop. The yields from this NFT treatment over a 12-mo period of spring and fall production was over 440 000 kg of marketable tomatoes per hectare. In addition, this NFT treatment required the least amount of energy.

Although rootzone heating did not improve the performance

Table II. Summary of 1986 tomato yields

		1986 yield (kg/plant)							
		Spring				Fall			
		Buffalo		Caruso		Buffalo		Caruso	
Growing system	Rootzone	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold
NFT	Unheated	11.1	12.2	11.1	13.1	4.2	4.1	5.0	4.9
	Heated	11.6	10.8	11.3	11.6	4.2	4.8	4.8	5.6
Rockwool	Unheated	11.4	10.9	11.3	10.6	disease problems			
	Heated	11.6	12.1	11.6	12.7	(Koshla et al. 1989)			
Soil		10.7	10.9	11.8	11.4	4.1	4.0	4.6	5.0

of the NFT system, it did prove to be beneficial for rockwool in the cold section during the spring crop. A gradual decrease in the rootzone temperature in the unheated rockwool slabs was recorded overnight. This decrease probably results in a reduced uptake of water and nutrients by the plants and therefore decreased the yields.

CONCLUSIONS AND RECOMMENDATIONS

The energy and yield data show that energy savings of at least 30% are obtained by reducing the night temperature to about 11°C in the production of greenhouse tomatoes without adversely affecting the yield. In fact, both the yields and grades were improved when the tomatoes were grown with the NFT at reduced night temperatures without rootzone heating. As a result, the cooperator has now converted his entire operation to this system.

Temperature and energy data suggest that additional energy savings are possible if better control of the heating system is achieved.

Control of the nutrient temperature in NFT and rockwool is necessary to prevent overheating of the nutrient solution during periods of high insolation and ambient temperatures.

ACKNOWLEDGMENTS

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LIST OF SYMBOLS

A = barrier wall area = 104.5 m^2
b = thickness of airspace [m]
C = empirical constant = $f(Gr_f Pr_f)$
D = pipe diameter (m)
g = gravitational constant [$\mathrm{m/s}^2$]
Gr_f = Grashof number based on the film temperature.
$= \beta \frac{g}{\gamma^2} (T_s - T_w) D^3$
h = convective heat transfer coefficient [$\mathrm{W/(m^2.K)}$]
k = thermal conductivity of air [W/(m.K)]
L = height of barrier (m)
n = empirical constant = $f(Gr_f Pr_f)$
Nu_D = Nusselt number
Pr_f = Prandtl number based on the film temperature
T = temperature (°C)
T_s = average surface temperature of pipe (K)
T_w = average temperature of warm greenhouse section (K)
q = heat flow (MJ)
β = coefficient of thermal expansion of air (1/K)
γ = kinematic viscosity of air (m^2/s)

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