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SIMULATION AND MEASUREMENT OF ENERGY PARTITION IN A FLUID-ROOF GREENHOUSE

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ABSTRACT

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A 22-m^2 greenhouse was fitted with a hollow, channeled plastic roof through which a 3% solution of $CuCl_2$ was pumped. This roof was a spectrally discriminating filter that transmitted 50—60% of photosynthetically-active radiation and 0—13% of nonactive radiation. During 5 periods of 1—4 days from September, 1979, to July, 1980, data were collected on environmental conditions: solar irradiance, air temperature and humidity, and windspeed; and on greenhouse conditions: temperature and humidity of the air, temperature of the crop, the roof, the fluid storage tank and at four depths in the soil, and net radiation both above the greenhouse and above the crop in the greenhouse.

The environmental conditions were used as boundary value inputs in a deterministic, mechanistic, and dynamic simulation model of the greenhouse system. To test the model, its outputs were compared to the corresponding measured values. The model simulated the various temperatures to within 2—3°C and the net radiation to within 20—30 W m^{-2}. For one of the five tests, the humidity was simulated almost exactly, but the reliability of the humidity data in the other tests was inadequate.

The greenhouse tanks stored energy equivalent to 32% of the daily total of solar radiation. Among the 12 test days, this ratio ranged from 23 to 43%. This contrasts with a figure of 15% for energy storage by a conventional greenhouse, which we have found by simulation of the test structure with an empty roof.

INTRODUCTION

The purpose of a greenhouse is to protect plants from adverse environments, allowing economic crop production in areas that would otherwise be less suitable. During clear sky conditions, however, the climate inside a greenhouse will likely have a wider temperature range than the outside environment, with temperatures above ambient during the day (Waggoner, 1958) and possibly below ambient during the night. A cold, clear night requires heating, usually with fossil fuel, and a clear, sunny day requires cooling, usually by ventilation and aided by evaporative cooling if necessary. Ventilation with fans requires electricity, an expensive form of energy. Cooling can also be done by neutral shading of the crop, but this is at the expense of light required in crop production.

A greenhouse design that provides a more efficient means of cooling and

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heating during clear weather would clearly be of benefit to the greenhouse industry. Such a design was proposed by the French Institut National de Récherche Agronomique (INRA) in Avignon, France (Damagnez et al., 1975). It utilized a spectral filter to trap the approximately 50% of solar radiation that the crop cannot use in photosynthesis. This radiation was converted to heat in the roof rather than allowed to pass through and heat the crop and the greenhouse air.

In the INRA greenhouse, and in the one used in the tests reported here, a 3% solution of copper chloride was pumped through a hollow plastic roof. This made the roof a longwave cutoff filter at 700 nm (Morris et al., 1958). The flowing solution also served as the heat transporter to a storage facility such as an underground tank. A later INRA design used a blue-green glass panel as the filter; water running over the panel was the working fluid, and a second glass layer covered the system (Chiapale, 1981).

Concurrent with physical tests of the feasibility of the fluid-roof concept in Avignon, France, theoretical studies were conducted at Texas A&M University in College Station, Texas. The objectives were to assist engineering feasibility studies and, later, to optimize sizing of the greenhouse components and refine the management strategy. The principal tool in this theoretical work was a dynamic simulation model of the physics of the fluid-roof greenhouse. The model was based on physical relationships, but nevertheless required verification before application. The model tests reported here were conducted concurrently with experiments in Avignon (Chiapale et al., 1983). They differ from the Avignon tests in that the radiation was absorbed by the fluid, $CuCl_2$ in water, rather than by the tinted glass. Also, the current tests represent an independent verification of the model in a different climate.

Theoretical analyses of the climate inside a fluid-roof greenhouse have shown it to be more moderate than in standard glass or plastic enclosures. Radiant load on the crop, temperatures of the air and the crop, crop water use, and water stress of the crop are all reduced. The price of these improvements is a slightly reduced photosynthetically active radiant flux and a somewhat higher humidity (Van Bavel et al., 1981; Chiapale et al., 1983). Because the temperature regime is more moderate, less day-time ventilation is required in a fluid-roof greenhouse, so that eventual carbon dioxide fertilization would be more efficient.

METHODS

The theoretical analysis used a computer model to simulate the effect of environment, structure, and control methods on the climate inside the greenhouse. This model was developed using established physical relationships to describe the flow of energy and mass in the greenhouse system. The model, SG79, has been described briefly in Van Bavel et al. (1981) and Chiapale et al. (1983), and in more detail by Sadler (1983). A summary will be given here. For more information about SG79, a detailed user's guide is available from the authors.

The model was designed for use on an Amdahl 470 V/6II or V/8 computer with IBM operating system MVS/JES3. It was written in IBM's Continuous System Modeling Program (CSMP III; IBM, 1975, and Speckhart and Green, 1976), which is a statement-oriented special-purpose language for the simulation of time-dependent systems.

SG79 was developed with the assumption that a greenhouse could be described as a system of connected, homogenous components: the roof, the crop, 15 soil layers, the air inside, and a storage tank. SG79 was a one-dimensional model; flux of energy and mass were assumed to occur in the vertical direction only. The cross-flow of air in ventilation has been described as adding a quasi-second dimension to the analysis (Seginer and Levav, 1971), but it did not add complexity to the model. The same was true for the flow of fluid through the roof. A recent review of related greenhouse modeling studies can be found in Sadler (1983).

The energy content of each compartment in the greenhouse was characterized by its temperature; the crop was assumed to have negligible heat capacity, so that its temperature then reflected thermal equilibrium. The surface of the soil also was assumed to have negligible heat capacity. The transfer of heat from the tank to the surrounding soil was simulated using a separate soil compartment around the tank. A water balance was kept for the air and for condensation on the roof surface.

Energy was assumed to move by way of short-wave radiation, long-wave radiation, sensible heat of convection in air, latent heat of evaporation to air, by conduction in solids, and with mass flow of air in ventilation and of fluid in flow through the roof and storage tank. Short-wave radiation was considered separately in two wavebands: photosynthetically-active radiation (PAR; 400—700 nm) and non-active radiation (NAR; 700—3000 nm). The transmission, reflection, and absorption of short-wave radiation depended on the optical properties in each waveband of the roof, crop, and soil. Long-wave radiation was assumed to depend on the temperature and emittance of the roof, crop, and soil according to the Stefan—Boltzmann relationship. Sensible heat flux depended on the temperature difference between a surface and the air by a resistance form of Newton's law of cooling. Latent heat flux was found from the product of the latent heat of evaporation and the water vapor flux rate; the latter was found from the difference between the humidity of the air and of the surface under consideration using a resistance form of Fick's law of diffusion. Conduction of heat in the soil was calculated using Fourier's law following the example of Wierenga and De Wit (1970).

The crop was assumed to be a horizontal plane of unit leaf-area index and negligible heat capacity. Further, it was assumed to be homogenous regarding temperature, internal humidity, and internal carbon dioxide concentration. The optical properties of the crop depended on leaf area index and were found using the radiation routines from a complex canopy model

(McCree and Van Bavel, 1977). Evaporation from the crop was controlled by the resistance of the leaf in series with the resistance of the aerodynamic boundary layer above the leaves. The leaf resistance depended on the more limiting of two factors: leaf water potential and absorbed PAR. The humidity of the leaf interior was assumed to be that of saturation at the leaf temperature.

The model included simulation of the carbon balance, including carbon dioxide assimilation and respiration, as well as the effect of the internal carbon dioxide level. However, no measurements of the simulated variables were made and its was assumed that the carbon dioxide balance has a negligible effect on the energy fluxes.

The greenhouse used for the tests was located on the Texas A&M University Research Annex, 10 km west of Bryan, TX. The structure measured 4.88 × 4.88 m; wall height increased from 1.59 to 1.92 m from eave to peak. The walls of the greenhouse were 0.15 m thick, insulated, and covered with polished aluminum foil on the inside and white paneling on the outside. The reduced height, nearly flat roof, and reflective, insulated walls were used to reduce the horizontal flux of heat out of the greenhouse. To reduce horizontal flow of heat below the wall in the soil, the soil beneath the greenhouse was insulated from the surrounding soil by 0.05 m of styrofoam insulation to a depth of 0.3 m. A sod of St. Augustinegrass (*Stenotaphrum secundatum* [Walt.]) was established inside the greenhouse to provide an easily-maintained, permanent crop during the tests.

The roof was constructed of channeled, hollow polycarbonate panels (Tuffak Twinwall, Rohm and Haas Co., Philadelphia, PA, USA) in 6 mm thick 1.22 × 2.44-m sheets. Each panel was fitted with supply and return manifolds made of 30-mm PVC pipe. Two 1.5-m^3 fluid storage tanks were buried outside the greenhouse. The tanks were filled with 3% $CuCl_2$ in waters; concentrated HCl was added to maintain the pH between 2 and 3, thus preventing precipitation of copper compounds. The fluid was circulated by a magnetically-driven, nylon-impeller pump (Model AC-5C-MD, March Mfg. Co., Glenview, IL, USA). Connecting plumbing was PVC pipe or flexible tubing throughout because the fluid was corrosive.

During the tests, measurements were made to characterize the environment both outside and inside the greenhouse. Solar irradiance was measured with a pyranometer (Model CM-2, Kipp en Zonen, Delft, Holland). Outside air temperature was measured with a ventilated, shielded thermocouple (Type T, 0.5 mm) as an average of two measurements at 1 m height. Dew-point temperature was measured with a LiCl dew cell (Model SSP129B, Minneapolis-Honeywell Regulator Co., Minneapolis, MN, USA) at a sample height of 1 m. Wind speed was measured with an analog cup anemometer (Model: Windscope, Taylor Instruments, Arden, NC, USA) at a height of 10 m. Two additional environmental conditions were not measured: the sky long-wave irradiance was calculated from ambient temperature and humidity by the method of Idso (1981), and the temperature of the deepest layer (2 m) of the soil below the greenhouse was assumed constant at the initial value.

Greenhouse air and dewpoint temperatures were measured at three points near the center of the greenhouse using the same methods as were the outside conditions. Greenhouse crop temperature was measured with an infrared thermometer (Model IT-3, Barnes Engineering Co., Stamford, CN, USA). In addition, in two of the five tests, the leaf temperature was measured with a fine thermocouple (Type T, 0.05 mm). The roof temperature was taken as the weighted average of 3 thermocouples, two in the supply and one in the return manifold. These were 0.5-mm, type T thermocouples coated with silicone-based caulk to prevent corrosion or electrical effects from reactions with the fluid. Tank temperatures were measured with similarly-treated thermocouples that were weighted and suspended at the center of the tanks. The soil temperatures were measured with four thermocouples at 0.08 m, four at 0.18 m, four at 0.40 m, and one at 1.6 m. The net radiation between the roof and crop was measured with a Fritschen-type net radiometer (Micromet Inst., Bothel, WA, USA) as was the net radiation between the roof and sky. The operation of the ventilators was monitored with the event recorder of a strip chart recorder (Model 680M, Hewlett-Packard Co., Corvallis, OR, USA). For the test periods in which supplementary heat was required, a 1500-W electrical heater was suspended from the roof; the time of operation was recorded manually.

During the tests, data were collected at 15-min intervals with a microprocessor-based data collector (Model PD2064, Esterline Angus Corp., Indianapolis, IN, USA) and were printed on a paper tape and a magnetic cassette tape (Model 817TI, Techtran Co., Rochester, NY, USA). These data were transferred to a computer for processing.

Tests were made during five periods of 1—4 days each over a period of 1 year, as shown in Table I. The first test period had clear late-summer weather; the next two, cold, clear winter weather; and the last two, hot, dry summer weather.

TABLE I

Test periods for the fluid-roof greenhouse tests

Abbreviation	Start		End	
	Time	Date[a]	Time	Date[a]
SEP 79	0000	09/27/79	0815	09/28/79
NOV 79	1445	11/28/79	0500	12/03/79
FEB 80	0000	02/20/80	1400	02/24/80
JUN 80	0000	06/20/80	1300	06/22/80
JUL 80	0900	06/30/80	1300	07/02/80

[a] Month/day/year.

TABLE II

Parameters measured in the fluid-roof greenhouse tests

Parameter	SEP 79	NOV 79	FEB 80	JUN 80	JUL 80	Units
Roof optical properties						
Reflectance						
PAR	0.14	0.14	0.14	0.11	0.11	
NAR	0.08	0.08	0.08	0.05	0.04	
Transmittance						
PAR	0.51	0.50	0.51	0.53	0.58	
NAR	0.06	0.00	0.06	0.06	0.13	
Heater power	0.0	67.00	67.0	0.0	0.0	$W\ m^{-2}$
Instrument power	6.4	6.4	6.4	6.4	6.4	$W\ m^{-2}$
Ventilation rate	0.0065	0.0065	0.0065	0.0065	0.0065	$m^3\ m^{-2}\ s^{-1}$
set point	26.0	26.0	26.0	26.0	26.0	°C
dead band	±1.5	±1.5	±1.5	±1.5	±1.5	°C
Tank volume	0.069	0.0563	0.137	0.147	0.147	$m^3\ m^{-2}$
Roof volume	0.004	0.004	0.004	0.004	0.004	$m^3\ m^{-2}$
Fluid flow rate	1.83E-5	1.70E-5	1.82E-5	1.70E-5	1.88E-5	$m^3\ m^{-2}\ s^{-1}$

The environmental inputs for the model were the actual measurements made during the tests. Initial conditions were taken as the measured greenhouse conditions at the start of each test. Parameters were taken from the literature or measured for each test if appropriate. Those that were measured are shown in Table II. Parameters invariant over the test series were the greenhouse geometry and the properties of the crop. The heater energy output was used as an input to the model.

The optical properties of the fluid roof are of special interest. They were calculated from measurements made with the pyranometer and a photon flux meter (Model LI180, Li-Cor Inc., Lincoln, NB, USA). Three measurements were made with each sensor: upward above the roof, inverted above the roof, and upward immediately below the roof. A black shield was suspended below the roof to eliminate reflection from the crop. The pyranometer measurements were used to determine the optical properties of the roof for total solar radiation; the photon flux measurements were used for the photosynthetically-active waveband. The properties of the roof for non-active radiation were calculated from these data and the assumption that solar radiation is 47% PAR and 53% NAR. Reflectance was calculated as the ratio of the inverted sensor reading above the roof to the reading in the upward position. Transmittance was calculated as the ratio of the upward reading below the roof to that above the roof. Transmittance of the clear panel was reduced by 10% to account for the area of opaque structural members.

RESULTS AND DISCUSSION

In all, tests were conducted during five periods. Because of limitations of space, we have selected the NOV79 and JUN80 test periods for a detailed data presentation. These are representative of winter and summer performance of the model. The results of the simulations are plotted along with the measured values of each test variable.

The environmental conditions used to drive the model for the two tests are given in Figs. 1a and 1b. The NOV79 test had weather typical for the area after a cold front passage: clear skies and a cold, dry airmass. The JUN80 test period had conditions warmer and drier than normal for the date and area. The sharp drop in air and dewpoint temperatures and the increased wind speed in the early morning of the second day correspond to the passage of a cool dry front that resulted in fewer clouds the second day.

The air temperature was usually simulated within 2°C during the NOV79 test (Fig. 2a), and during the JUN80 test (Fig. 2b), except in late afternoon, when the error reached 3°C. The interior humidity is shown in Figs. 3a and 3b. The NOV79 test had agreement within 1.5 $g\,m^{-3}$ for all but the first day, but the JUN80 test had reasonable agreement only at night and up to 3 $g\,m^{-3}$ overestimation during the day. The NOV79 test was the only period

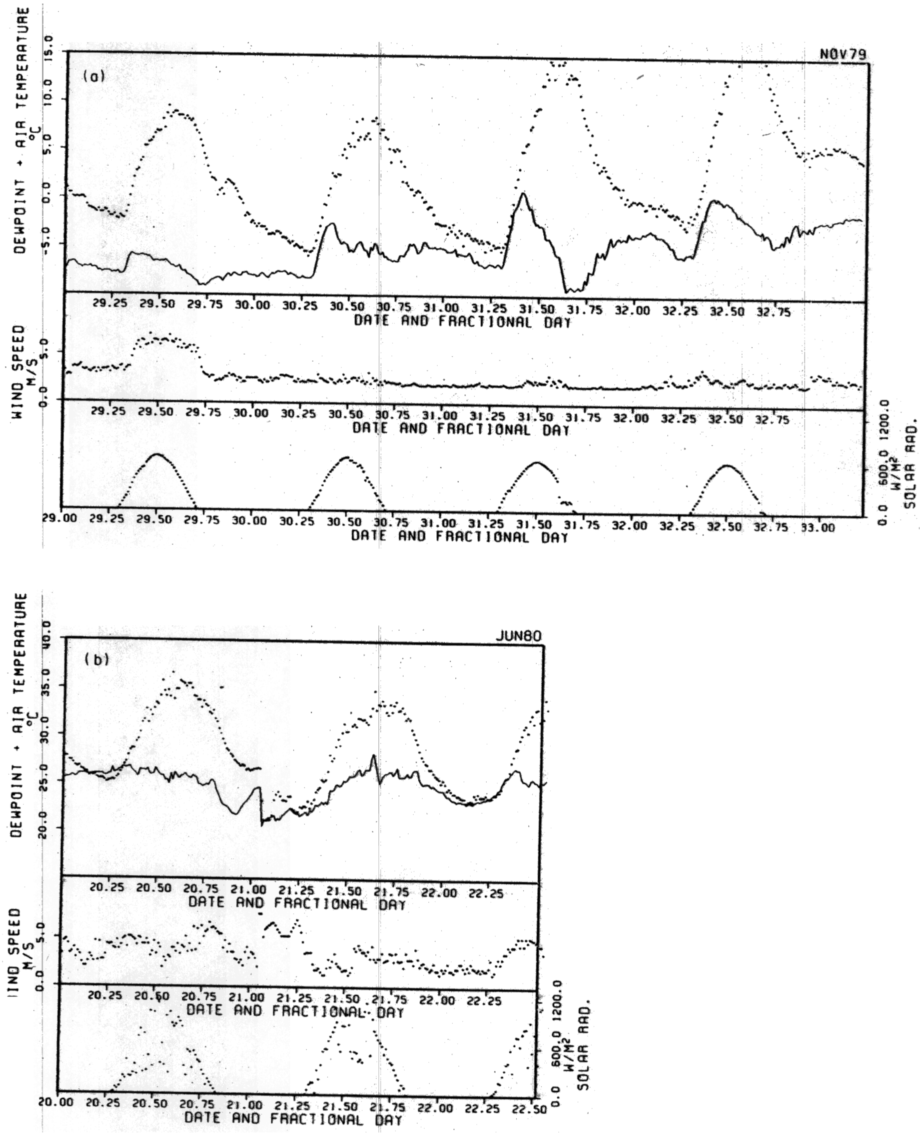

Fig. 1. Environmental conditions for the NOV79 test (a) and the JUN80 test (b).

with satisfactory simulation of humidity. Later supplementary measurements of humidity with wet/dry bulb psychrometers indicated that the dew cells may not always have functioned reliably, however.

The roof and tank temperatures were both simulated fairly well with essential agreement during the day and overestimation by 2—3°C during the night in the NOV79 test. The overestimation of the diurnal wave is shown

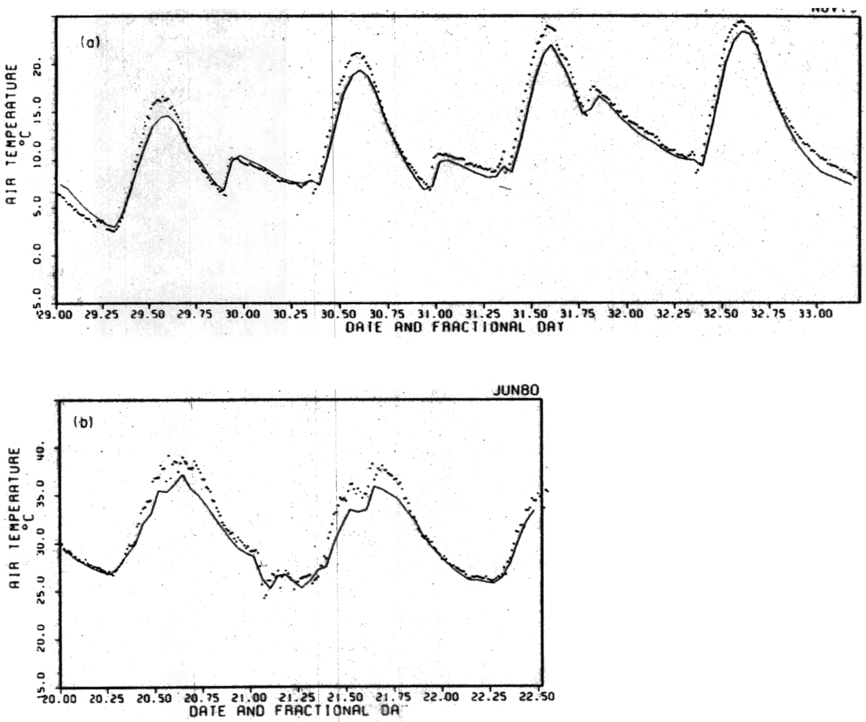

Fig. 2. Comparison of measured and simulated greenhouse air temperature in the NOV79 test (a) and the JUN80 test (b). The measured values are individual points; the simulated values are solid lines.

for the tank temperature in the JUN80 test (Fig. 4). In this test, the daily average is nearly correct, but the amplitude of the wave is about 1.5°C too large. Results for the roof temperature are similar. This contrasts with the NOV79 test, in which the overestimation of the amplitude was accompanied by a 1—1.5°C overestimation of the daily average.

The net radiation between the roof and crop was simulated generally within 20 W m^{-2}. That between the roof and sky was simulated to within about 30 W m^{-2} except for the middle of the first day in the NOV79 test (Fig. 5a). The agreement was similar for the JUN80 test (Fig. 5b), and also for the other three tests. The scatter of the measurements about the simulation line results from the simulated values being hourly averages, whereas the measurements were instantaneous, taken at 15-min intervals.

In the introduction, it was stated that the rationale for the fluid-roof design was the objective of diverting solar energy to storage. The amount so stored by the experimental structure is readily computed by the SG79 model; it can also be calculated from the measured temperature of the water in the storage tank. In Table III, the results of this test of the model are

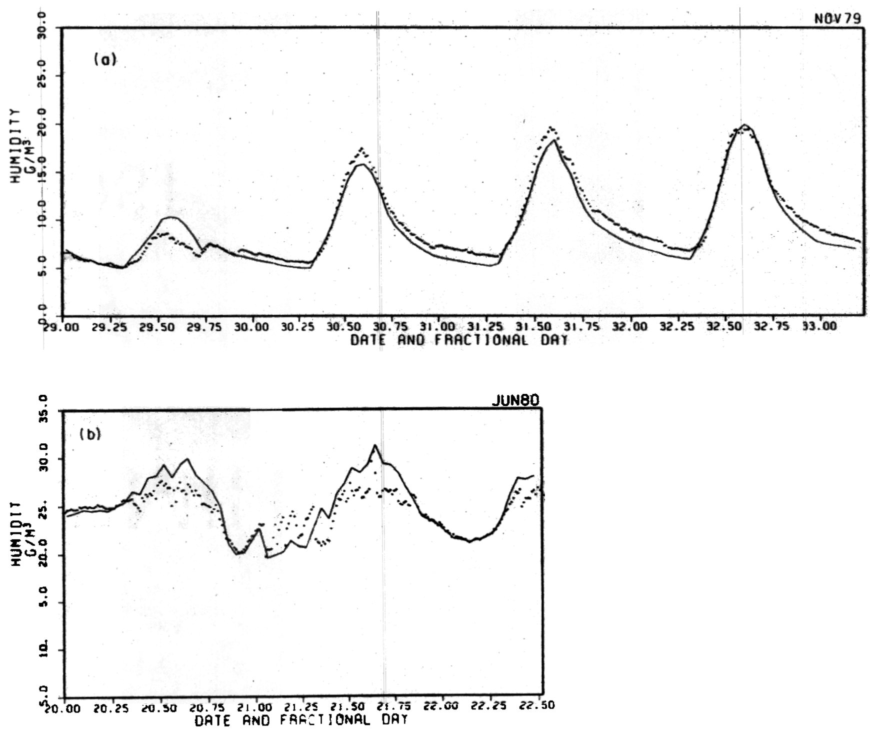

Fig. 3. Comparison of measured and simulated greenhouse air humidity in the NOV79 test (a) and in the JUN80 test (b). The measured values are individual points; the simulated values are solid lines.

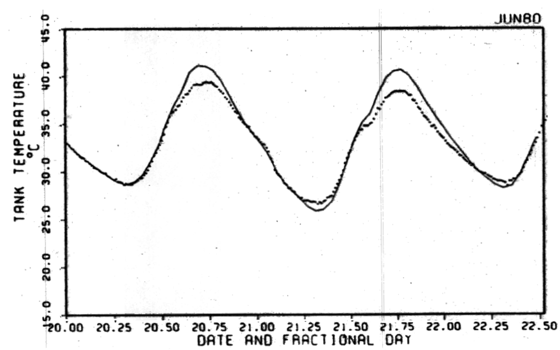

Fig. 4. Comparison of measured and simulated tank temperature in the JUN80 test. The measured values are individual points; the simulated values are solid lines.

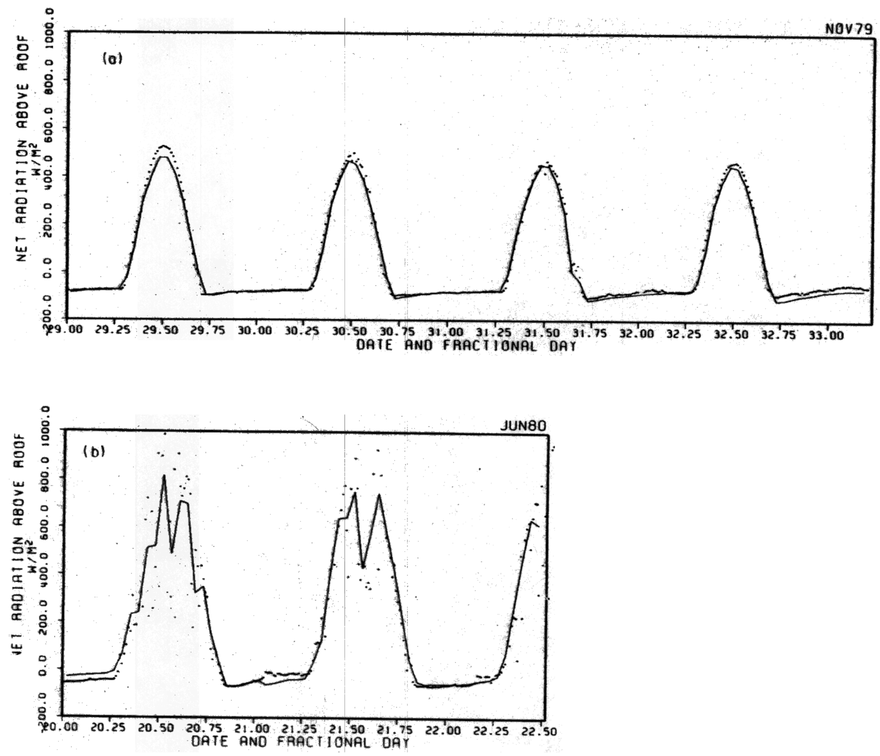

Fig. 5. Comparison of measured and simulated net radiation between the greenhouse roof and sky in the NOV79 test (a) and in the JUN80 test (b). The measurement of values are individual points; the simulated values are solid lines.

given for all five test periods. This table shows, for each day of record, the incident global solar radiation, the measured and the computed (simulated) storage, and the ratio between the latter. The average ratio over all days was 1.09, indicating a slight underestimation by the model. Of further interest is the collection efficiency of the fluid-roof greenhouse as a translucent solar energy collector. This efficiency was defined as the measured energy storage divided by the daily total of solar radiation. The average figure was 32%, somewhat higher results were obtained in the cool season than in the warm season.

CONCLUSIONS

The greenhouse model simulated the inside air temperature to within 2°C in most cases, as did the roof and tank temperature. The humidity was simulated well in one of five tests; some of the discrepancy in the other tests was attributed to measurement error. The net radiation between

TABLE III

Comparison of measured and simulated daily energy storage in the fluid-roof greenhouse system. Both values are derived from daily temperature increase and the heat capacity of the storage tanks. Daily global radiation is abbreviated DGR

Test	Date[a]	DGR ($MJ\,m^{-2}$)	Storage		Ratio S/M	Collection efficiency Meas/DGR
				Sim. ($MJ\,m^{-2}$)		
SEP79	9/27	20.6	6.18	5.63	0.91	0.30
NOV79	11/29	14.6	3.35	3.56	1.06	0.23
	11/30	14.2	4.08	4.29	1.05	0.29
	12/01	13.5	4.29	4.85	1.13	0.32
	12/02	13.5	3.86	4.76	1.23	0.29
FEB80	02/20	14.8	6.36	6.88	1.08	0.43
	02/21	18.9	6.54	6.82	1.04	0.35
	02/22	18.4	7.57	8.43	1.11	0.41
	02/23	18.4	5.68	6.77	1.19	0.31
JUN80	06/20	22.4	6.52	7.20	1.10	0.29
	06/21	24.5	7.14	8.55	1.20	0.29
JUL80	07/01	28.0	8.37	8.49	1.01	0.30
				Mean	1.09	0.32

[a] Month/day.

the roof and sky, and between the roof and crop were simulated within 20--30 $W\,m^{-2}$. The total energy collected by the greenhouse structure and stored in the tank was computed with an accuracy of about 10%, as determined on 12 separate days of record. These agreements approach the tolerances expected in the design of greenhouse systems.

In sum, we conclude that the model is adequate for making predictions of the conditions in a fluid-roof greenhouse for horticultural applications; improvements may be possible, however. From an engineering viewpoint, the simulation model should be adequate in computing solar energy storage, supplementary heating requirements, and ventilation requirements. Thus, it can be used to size tanks, heaters, ventilators, and circulation pumps.

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