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SIMULATION OF GREENHOUSE FLOOR HEATING WITH A COGENERATION UNIT

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SUMMARY: Computer simulation is being used to determine management strategies and the economic feasibility of providing energy to greenhouses with a cogeneration unit. This paper focuses on the development and accomplishments of such a model to study these questions in depth.

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SIMULATION OF GREENHOUSE FLOOR HEATING WITH A COGENERATION UNIT

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INTRODUCTION

Computer simulation is being used to model greenhouse heating utilizing a cogeneration unit providing energy through a floor heating system. Simulation was used as a design tool for the development of a 1.1 hectare commercial greenhouse installation using reject heat from a utility (Manning and Mears, 1981). Simulation is an important tool for examining the concept of cogeneration as there are many design variables. These include: The insulation system for the greenhouse, the heat delivery system, the size of the cogeneration unit relative to the greenhouse and the management strategy for the cogenerator and the back-up system. Economical use of a cogenerator will be determined in part by the capital cost of the unit and the relationship between fuel cost and the value of the heat and electricity produced. The value of the electricity depends upon the avoided retail costs and the purchase price of surplus power sold to the grid. The rates for both of these vary with the time of day including peak, off peak and intermediate rates.

This study focuses on the development of a model to study this question in depth, including options for various control strategies for the system. The major accomplishment to date is the development of the model and its calibration to real data from an actual research greenhouse heated by a cogeneration unit (Giniger et al, 1983). Also, the simulation model developed by Manning and Mears (1981) is used to examine the contribution to the heating load that could be made with a cogeneration unit coupled to a floor heating system.

THE COGENERATION RESEARCH FACILITY

The greenhouse cogeneration heating system used to calibrate this computer model has been described by Giniger et al (1983). The major heat inputs to the greenhouse air are from the heated floor, a back-up overhead heating system, and from carbon dioxide generators and supplemental horticultural lights when they are running. The flooded floor normally receives heat through a pipe loop heat exchanger coupled to the cogenerator but the floor heat exchanger can be switched to the back-up boiler.

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In order to evaluate the cogeneration system and to gather data to calibrate this model a computer based data acquisition system was developed and installed. The hardware specifications for this system are outlined in Table 1.

TABLE 1. Hardware Specifications for the Data Acquisition System

Doric Digitrend 235 Data Logger:*

- Manufactured by Doric Scientific
- San Diego, California
- 8-bit NMOS microcomputer chip
- serial I/D port of the RS-232 type
- 100 analog imput capability - scanned every seven seconds
- Alphanumeric thermal printer.

Northstar Horizon Microcomputer:

- 2 double-sided, double-density ("quad") disk drives
- 5.25-inch floppy disks
- 64k RAM
- RS 232 serial and parallel interface
- S-100 Bus
- Z80A CPU
- 8-bit chip
- 4 MHZ time clock

DESCRIPTION OF THE MODEL

The computer model developed to simulate the functioning of the cogeneration research greenhouse was written on a Northstar Horizon microcomputer in Microsoft BASIC.

An energy balance for the greenhouse including the floor storage corresponds to the following equation:

$$QSLR + QPRESP + QGEN + QLIT + QCOW + QOVHD = QPSYN + QVENT + QGH + QGRD + QSTRG$$

QSLR is the solar heat gain, watts.
QPRESP is heat gained from the respiration of plants, watts
QGEN is heat gain from the cogeneration unit, watts
QLIT is heat gain from artificial lighting used for plant growth, watts
QCOW is heat gained from carbon dioxide generation unit, watts
QOVHD is heat gained from the overhead-in-air back-up heat

*Reference to commercial products or trade names is made with the understanding that no discrimination and/or endorsement is intended or implied.

supply for the greenhouse, watts.
QPSYN is energy used by plants during photosynthesis, watts
QVENT is heat lost through the ventilation system, watts
QGH is heat lost from the greenhouse air through the double-poly covering to the outside environment, watts
QGRD is heat lost from the warm flooded floor to the ground below the floor, watts
QSTRG is the energy stored in the greenhouse floor, watts

Several of the terms in the energy balance, QPRESP and QPSYN, are very small compared to the others and can be neglected. In the first stages of this study, efforts are being concentrated on the calibration of the model to night heating requirements so QSLR and QVENT are not involved. The remaining terms are:

QFLR, or heat gained by the greenhouse air from the flooded floor, is the product of the floor's heat transfer conductance (UFLR, W/M^2K) times the area (AFLR, M^2) times the difference in greenhouse ambient air temperature and flooded floor temperature (TFLR-TAMBIN,K).

$$QFLR = UFLR*(AFLR)*(TFLR - TAMBIN)$$

The QGEN term is the heat input from the cogeneration unit to the flooded floor. In the program it is input as the average hourly output on a daily basis, in watts.

Certain plant growth studies in the greenhouse utilized supplemental lighting to extend the day length. These growth lights, considered by the variable QLIT, supplied about 14 kW when on.

QOVHD is the heat input from the back-up overhead steel pipe heat system (boiler) and can be up to 145 kW. The 145 kW boiler heat can be input heat either to the overhead heat exchanger or to the flooded floor. In the period used to calibrate this model it was not used to heat the floor, only to touch up the air.

The QGH term is the heat loss from the greenhouse to the outside environment.

$$QGH = UGH*(AGH)*(TAMBIN - TAMBOUT)$$

Where UGH is the greenhouse heat transfer coefficient in W/M^2K, AGH is greenhouse surface area, M^2, TAMBIN is the inside ambient temperature of the greenhouse, and TAMBOUT is the ambient outside air temperature.

QGRD is the heat loss from the flooded floor to the ground beneath.

$$QGRD = UGRD*(AGRD)*(TFLR - TGRD)$$

Where UGRD is the heat transfer conductance value between the warm, flooded floor and the soil beneath the floor, AGRD is the same as AFLR, and TGRD is assumed to be a constant deep soil temperature value.

The QSTRG term represents gains or losses in the energy storage of the greenhouse floor system. The energy balance on the floor storage is:

QGEN = QFLR+QGRD+QSTRG

Primary data input to the model are outside ambient air temperature and initial floor temperature. An option exists in the program to use either the actual outside air temperature or a simulated pattern. A similar option exists for floor temperature. Outside air temperature and flooded floor temperature can be input on an hourly basis from actual data. At the start point for each period of simulation the program uses an outside air temperature value and an initial floor temperature value to estimate the initial inside ambient air temperature of the greenhouse for time zero. Thereafter, the greenhouse air temperature estimate is used to calculate an estimate of floor temperature and the cycle begins anew. Thus the simulation program contains the following primary options: a) either actual or simulated outside hourly air temperature data can be used b) either actual or simulated floor temperature data can be used as a basis for the computations; or c) either greenhouse ambient air temperature or floor temperature can be simulated or both can be simulated.

The simulation program in its present form outputs the following information in tabular form: the "day", the hour of the day (military time), hourly outside ambient air temperature, hourly greenhouse ambient air temperature - both real and simulated, hourly cogenerator heat output to the floor, and the energy balance in the greenhouse for that hour.

SIMULATION RESULTS AND CALIBRATION OF THE MODEL

In order to establish a calibration procedure for the simulation one of the simplist cases was studied. Ten days of actual data were collected for the greenhouse under the following conditions: 1) there were no plants in the greenhouse 2) the insulating curtain system was open; and 3) there were no plant growth lights or carbon dioxide generators in use. Only the nighttime hours, between 7 p.m. and 7 a.m. (1900-0700) hr.) were used as the calibration basis. There was no utilization of the back-up heat system. The cogeneration unit supplied constant heat input to the floor each night for the hours for which it was actually running at 44 kW. Hourly actual outside ambient air temperature and floor temperature were used. The ventilation system for the greenhouse was "locked out" so that during the nighttime hours the only air-exchange in the greenhouse would be due to infiltration.

Figure 1 shows the mean and extreme outside ambient air temperature for each of the ten nights studied. Two relatively warm nights had air temperatures between 12 and 18°C range. Two colder nights had mean outside air temperatures below 0°C. The mean outside air temperature for all ten nights was 4.7°C.

The following scheme was used to assess the accuracy of the resultant predictions of greenhouse air temperature by the simulation program: 1) the difference between the actual greenhouse air temperature and the simulated estimate was computed for each hour of each night 2) the statistical parameter of mean and standard deviation for these temperature differences for each individual night and for the composite of all ten nights were computed. When all of the heat for the greenhouse air is being provided from the floor, the accuracy of the air temperature prediction depends upon the ratio of the heat transfer coefficient coupling the air to outside and the floor to the air. In order to find the ratio of these two coefficients, UGH/UFLR, that best predicts greenhouse air temperature over the entire ten-day test period simulations were run at a number of coefficient levels. Figure 2 shows the mean temperature difference between predicted and actual air temperatures over the ten day period for 34 different combinations of UGH and UFLR. Fitting an exponential curve to the data in figure 2 indicates that the best prediction of greenhouse air temperatures is for a ratio of UGH/UFLR of 0.72.

Having determined the ratio of UGH/UFLR that predicts greenhouse air temperature most satisfactorily a number of runs made at that ratio were studied to find out that level of UGH and UFLR that best predicted actual floor water temperatures over the entire ten-day test period. It was found that values of 4.35 W/M^2K for UGH and 6.05 W/M^2K for UFLR minimized the differences in simulated and actual air and floor temperatures. These figures agree very well with the direct measurements reported by Giniger et al (1983). Plots of the actual and simulated air and floor temperature at the end of each day in the test period are shown in figure 3.

It should be noted that UGH will actually vary significantly from one night to the next. This is shown clearly in direct measurements of greenhouse heat transfer coefficients over many nights by Roberts et al (1981) and in other references. This is because heat transfer is determined in significant measure by radiation conditions, outside air temperature, wind conditions and humidity as well as the greenhouse glazing, heating system and insulation system. Using a single average value for UGH will produce reasonable total energy transfer predictions over long time periods but will under and overpredict on hourly or even nightly periods. This is clearly shown in figure 3. If more precise predictibility over short time spans is needed it will be necessary to determine UGH as a function of known environmental parameters.

PRELIMINARY PREDICTIONS OF COGENERATION SYSTEM PERFORMANCE

To predict seasonal energy contributions from a cogeneration unit it is necessary to decide the system's physical design and operating strategy. Then a computer simulation run operating under these parameters can be made and the results analyzed. For a first run on a possible cogeneration utilization concept the simulation for waste heat utilization developed by Manning and Mears (1981) was run for six different cases. The model was set up for a 0.4 hectare (1 acre) greenhouse block with a night insulating curtain and primary heat from the floor and secondary heat added through an overhead pipe system. The weather data used to drive the model was the same as used in the 1981 study.

The first run was made with no floor heat used at all so the total heat requirement for the season could be determined. This total requirement of 752,000 kWh is shown in the first row of Table 2. For each of the other runs it was assumed that the cogenerator was hooked through a heat exchanger to a floor and was operated to maintain the floor temperature at a predetermined set point. These set points were run at five equally spaced increments from 21°C (70°F) to 32°C (90°F). In each case the cogeneration unit was sized to keep the floor at the desired temperature when the greenhouse ambient air was 16°C. The size of the cogeneration unit required is shown in column two. This is based on a thermal output twice as great as the electrical output. The seasonal electric and thermal energy outputs are shown in the next two columns and the seasonal operating time for the unit in the last column.

The fifth column shows the heat needed from the overhead back-up source during those hours when the floor is not delivering enough heat to maintain the desired air temperature. At the lowest floor temperature run, 21°C, the floor provided over half the needed heat and there was virtually no oversupply of heat. As the floor temperature is increased, the needed overhead heat is markedly reduced, but the heat oversupplied does increase. This simulation model was run as if the greenhouse were vented to maintain desired night air temperatures when the floor was capable of overheating.

Clearly the most effective use of the heat from the cogeneration system is associated with a smaller unit maintaining relatively low air temperatures. The economic penalty of running a larger unit which would dump significant amounts of surplus heat would depend on the relative value of electricity produced and the cost of fuel and other engine operating costs. Heat oversupply could be reduced by operating the floor at lower temperatures and running the unit less hours in milder weather. The operating system and control strategy simulated here is only one of many possible systems and much remains to be done before an optimum strategy is developed.

CONCLUSIONS

Simulation models have been developed which can be used to study the effectiveness of using cogeneration to provide heat and electricity for greenhouses. Such models can be used to optimize designs and control strategies for a given set of economic parameters.

REFERENCES

Giniger, M., and D. Mears, 1983, Cogeneration for heating greenhouses. ASAE Paper 83-4019.

Manning, T. O. and D.R. Mears, 1981, Computer aided design of a greenhouse waste heat utilization system. Energy in Agriculture;1:5-20.

Roberts, W.J., D.R. Mears, J.C. Simpkins and J.P. Cipolletti, 1981. Progress in movable blanket insulation systems for greenhouses. Agricultural Energy. ASAE Pp. 558-561.

FIGURE 1 - MEAN OUTSIDE AMBIENT AIR TEMPERATURES FOR TEN SIMULATION NIGHTS

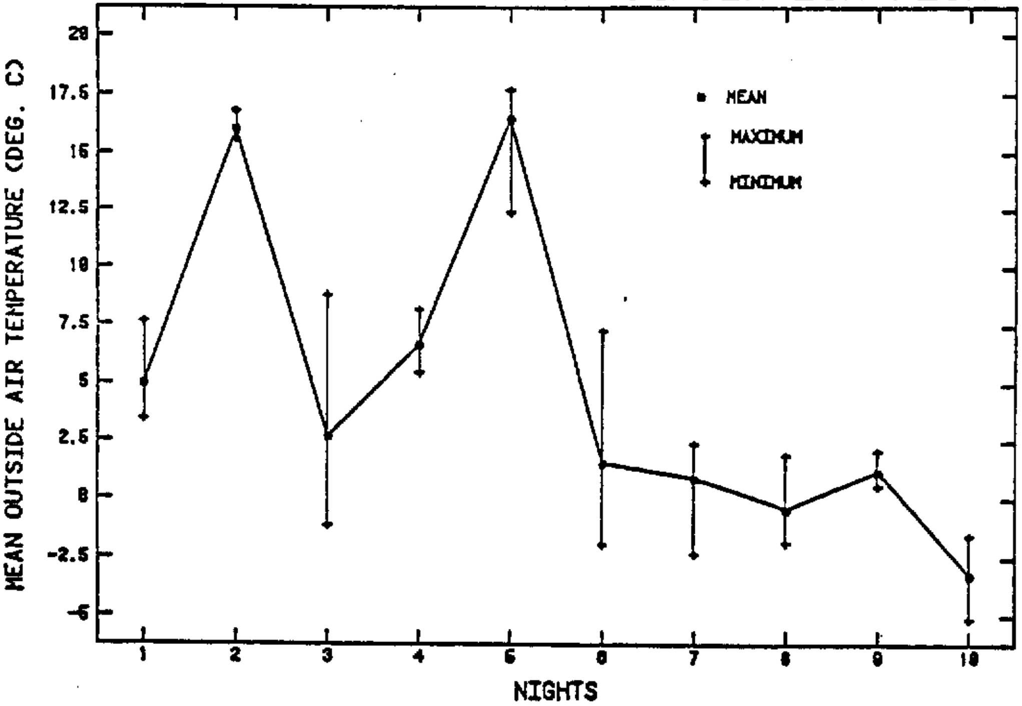

FIGURE 2 - PREDICTION OF GREENHOUSE AIR TEMPERATURES BASED ON HEAT TRANSFER RATIO

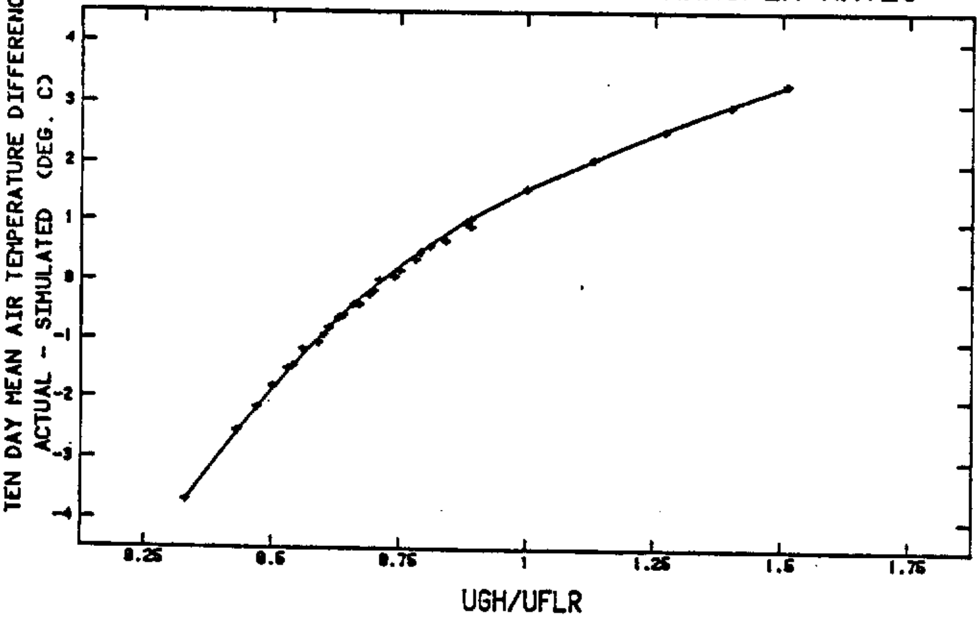

FIGURE 3 - COMPARISON OF TEMPERATURES FOR TEN NIGHTS OF SIMULATION (UGH=4.35,UFLR=6.05)

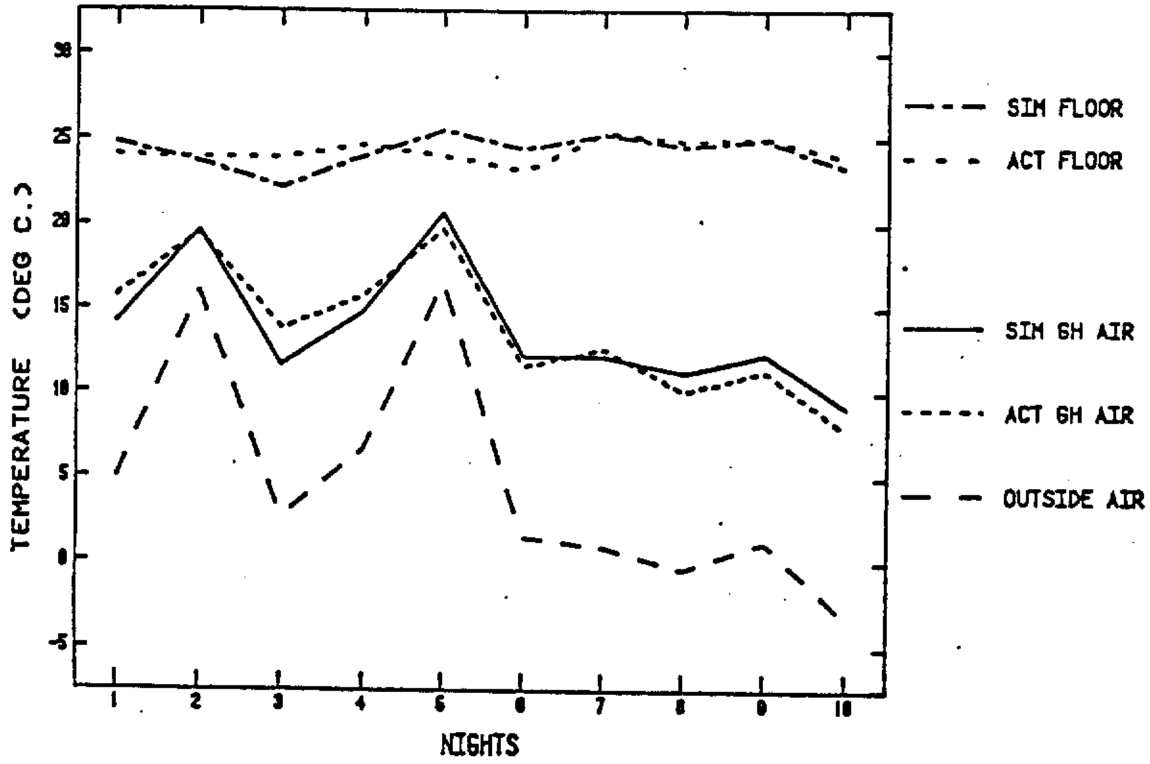

TABLE II

Seasonal Energy Outputs for Cogeneration on Floor Heated 0.4 Hectare Greenhouse

Floor Temperature oC	Cogenerator Size (KW)	Total Electric Production (1,000 KWHR)	Total Heat to Floor (1,000 KWHR)	Total Overhead Heat (1,000 KWHR)	Total Seasonal Oversupply (1,000 KWHR)	Cogenerator Seasonal Running Time (HR)
No floor Heating	0	0	0	752	0	0
21	63	218	437	315	0.6	3,454
24	103	322	644	167	59	3,128
27	142	425	853	86	188	2,995
29	182	537	1,073	38	360	2,948
32	222	656	1,309	14	571	2,954