Greenhouse Floor Heating, Preliminary Results from the 2003-2004 Heating Season

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Abstract

Making use of the synergy of both bottom heat and bottom watering, many greenhouse growers are utilizing heated ebb and flood floors as their main plant productions system. While the typical design and control strategies that are implemented for these systems work well, they still may not be optimized for energy efficiency or crop benefit. Accurate and flexible computer models can be extremely valuable design tools when applied to the study of greenhouse environmental control systems and can answer many questions without the time and expense associated with experimental research. This paper describes the first attempt to develop and verify a model of a floor heating system that is installed in a research greenhouse located at Cook College, Rutgers University in New Brunswick, NJ. This model considers the simple case of a heated ebb and flood floor without a crop, and will be used to develop more complex models. The model's output under predicted the average floor surface temperature measured in the greenhouse by an average of 3.20^{o}C (5.76^{o}F), for eight combinations of pipe water temperature and greenhouse air temperature considered, with a standard deviation of 0.28^{o}C (0.49^{o}F). By raising the external radiation temperature used as input to the model by an average of 8.63^{o}C (15.53^{o}F), the models predicted average surface temperature matched the measured average surface temperatures for all eight cases considered. In order to confidently verify the model's output, a better method for determining the external radiation environment is necessary. More complete models need to be developed that include the soil below, the crop above, and all the thermal relationships that exist between them and the greenhouse. With such models, the thermal performance of these systems can be better understood, and the effects of changing design parameters as well as control strategies can be determined.

Introduction

The benefits of a warm root zone on the growth of plants have been well established, and many techniques have been employed over the years to warm the media surrounding the roots of plants grown in greenhouses. Typical approaches include floor and bench heating systems. This article focuses on a floor heating system that is heated by circulating warm water through pipes embedded in the floor. This heat is transferred to the growing media and plant roots, the aerial portion of the plants, and directly to the greenhouse environment. Bottom watering (sub-irrigation) has also been found to be very beneficial to greenhouse crops and an economical way to provide sub-irrigation to greenhouse grown crops is with an ebb and flood system. It was a natural progression to incorporate both bottom heat and bottom watering into one system, and today increasing numbers of growers are installing heated ebb and flood floors in their new plant production systems because of the significant advantages this growing system provides. Heated ebb and flood floors typically consist of plastic heating pipe embedded in a 10.2 cm (4 in) concrete slab. The pipe size is typically 13 mm (0.5 in) or 22 mm (0.87 in) inside diameter, with a horizontal pipe spacing (center to center) of 25 cm (10 in) and

30.5 cm (12 in), respectively. Warm water ranging from 27^{o}C (80^{o}F) to 60^{o}C (140^{o}F) is circulated through the pipes, while the temperature of the water delivered to the pipes is controlled by three-way or four-way mixing valves (Roberts, 1996).

Floor heating is also used in residential and industrial applications. The control of all floor heating systems is more challenging than forced air or radiant heating because of the large thermal mass of the concrete floor. This large thermal mass causes the floor to respond relatively slowly to changes in heat input. Heat may not reach the surface of the floor for hours after it is introduced to the floor and until that heat reaches the surface it cannot affect the environment above it. Therefore, some type of anticipatory or predictive control is useful. In addition, certain design parameters such as pipe size, spacing, and vertical position in the concrete slab can have a significant impact on the performance of the floor, and the best floor design may vary from one application to another.

Considerable research has been conducted on optimizing the design of, and control strategies for these systems. Zaheeruddin *et al*. (1997) developed a dynamic model of a typical residential floor heating system. This model applied the energy balance method at each of four nodes in the system represented by the boiler, the water inside the heating pipes, the floor surface, and the zone air. The purpose of this model was to find the optimal sequence of firing the boiler and operating the three-way valve so that the zone temperature remains close to its set point and the energy use by the boiler is minimized.

In another study Cho and Zaheeruddin (1997) built an experimental facility consisting of two identical side-by-side rooms to simultaneously test two control strategies. Later, Cho and Zaheeruddin (2002) incorporated a model of a radiant floor heating system into the TRNSYS computer program (a transient systems simulation program) developed by the Solar Energy Laboratory at the University of Wisconsin. They were able to simulate a predictive control strategy and compare it with a conventional feedback control system.

While these were all useful studies for residential and industrial floor heating systems, the heat loss and the corresponding heat loads associated with these applications are significantly different, (much greater per unit area), from those in greenhouses. In addition, the construction of residential and industrial floor heating systems differs considerably from the typical greenhouse systems that are installed today. Furthermore, the large solar heat load (especially on sunny days), the comparatively poor insulation, and the crop canopy covering the floor will significantly change the performance of greenhouse floor heating systems compared to typical residential and industrial systems.

There have been several research projects conducted investigating the early floor heating systems designed for greenhouses (James, 1980; Roberts and Mears, 1980; Giniger *et al.*, 1985; Takakura and Manning, 1994). These research projects focused on both optimizing the performance and control of these early systems by direct experimentation in the greenhouse, in experimental set-ups, or by utilizing computer simulations.

Parker *et al.* (1981) developed a simulation model using a finite difference analysis to predict transient heat and moisture transfer in soil when it was heated by a buried warm water pipe system. The purpose of this model was to investigate the feasibility of using “low quality” waste energy, from cooling water used in electrical power generation, to heat greenhouse crops. Computer simulations were performed for three model cases: without buried pipes, buried pipes with 25^{o}C (77 ^{o}F) water, and buried pipes with 35^{o}C (95 ^{o}F) water, and each case was evaluated using the same weather data.

Kurpaska and Slipek (2000) developed a computer model to investigate design parameters for two different greenhouse substratum heating systems: heating pipes buried in the soil below the crop, and pipes laying on the surface of the soil. The specific design parameters that were investigated included water temperature and pipe spacing. In the case of the buried pipe system, the depth of the pipe was also investigated. They used two optimization parameters in the model: heat loss to the soil below the crop, and the uniformity of the temperature gradient around the crop's roots.

The above described research projects aimed to optimize both residential/commercial and horticultural floor heating systems. While the conclusions from this research may not have direct application to the typical greenhouse floor heating systems installed in new greenhouses today, the reasons for conducting the research are equally valid and important to the new systems. That is, while the typical design and control strategies that are implemented for new floor heating systems work well, they still may not be functioning optimally. For greenhouse applications, the important optimization parameters include installation cost, energy use, and, most important, temperature uniformity within the plant growing environment. The design criteria that influence these parameters are pipe size, pipe spacing and depth, pipe water temperature, and the use or absence of insulation below the concrete floor. Different control strategies can also have an impact on energy efficiency and temperature distribution through the root zone and crop canopy. Comparing different control strategies can be challenging in a greenhouse because weather conditions and heat loads can vary so much over time. Changing design parameters in the field or in experimental set-ups in order to compare performance can be expensive and time consuming. Accurate and flexible computer models can be extremely valuable design tools when applied to the study of greenhouse environmental control systems and can answer many questions without the time and expense associated with experimental research. To the authors' knowledge, no models have been developed for the typical floor heating systems found in modern greenhouses. Therefore, the development of an accurate computer model to investigate and quantify the performance of greenhouse floor heating systems is warranted. With such a model, the thermal performance of these systems can be better understood, and the effect of changing design parameters as well as control strategies can be determined. This paper describes the first attempt to develop and verify a model of a floor heating system that is installed in a research greenhouse located at Cook College, Rutgers University in New Brunswick, NJ. This model described here considers the simple case of a heated ebb and flood floor without a crop, and will be used to develop more complete models that represent the floor, the soil below, the crop above, and all the thermal relationships that exist between them and the greenhouse.

Materials and Methods

The floor heating system that was used to develop the simulation model was installed in a 17.7 m (58 ft) by 18.3 m (60 ft) open-roof greenhouse manufactured by Van Wingerden Greenhouse Company (Model MX-II), and is located at one of the Cook College research farms in New Brunswick, NJ. The design of the floor heating system is typical for the greenhouse industry today (Roberts, 1996). The system consists of 22 mm (0.87 in) (inside diameter) polypropylene pipes, spaced 30.5 cm (12 in) apart (center to center) and embedded in the lower third of a 10.2 cm (4 in) concrete slab. Figure 1 shows a generalized cross section (not to scale) of a typical heated ebb and flood floor (Both *et al.*, 2001). Water is heated by a gas-fired hot-water boiler and circulated throughout the system while a three-way mixing valve controls the temperature of the water entering the pipe loops. A greenhouse environment controller (Argus Controls, White Rock, British Columbia) controlled the air temperature and position of the mixing valve. A poinsettia crop was grown in the greenhouse during data collection.

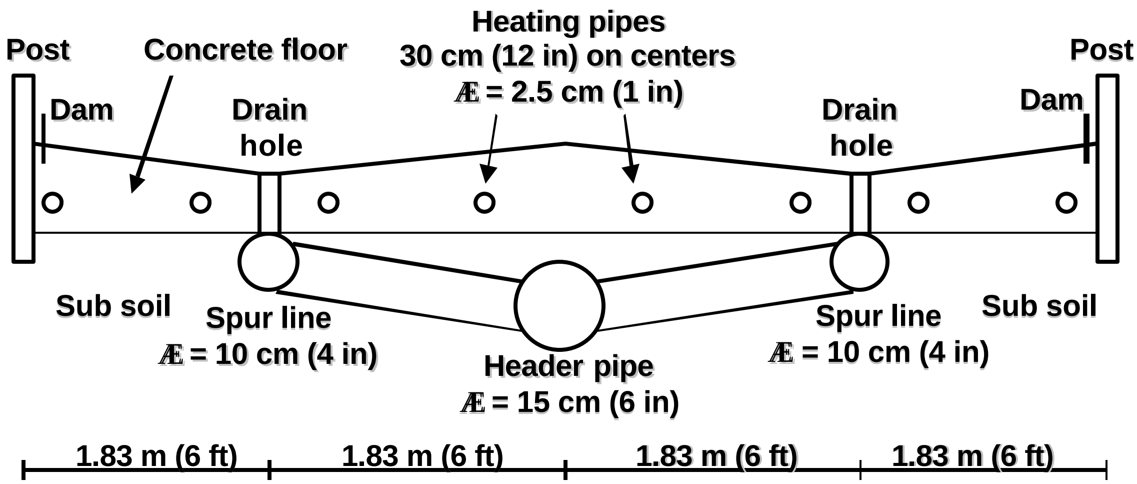

Figure 1. Generalized cross section (not to scale) of a typical heated ebb and flood floor.

Outside and inside environmental data was collected with a Campbell Scientific (Logan, UT) data logger (Model 21X) and stored as one-minute averages. The following environmental parameters were collected and used directly as inputs for the model, to determine model inputs, or to verify the output of the model. The greenhouse air temperature, for example, was used directly as the free stream air temperature input in the model, the net radiation was used to calculate a mean radiant temperature that was then used as an input for the model, and the floor surface temperatures were used to calibrate and verify the model. Note that some of the parameters shown below were not used in the simplified model but will be used in subsequent models.

1. Temperature of the water supplied to the mixing valve
2. Temperature of the water supplied to the heating pipes (after passing the mixing valve)
3. Temperature of the water returning from the heating pipes
4. Flow rate of the water returning to the boiler to be reheated
5. Floor surface temperatures at 15 locations
6. Four root zone temperature locations in each of two representative plant pots
7. Greenhouse air temperature above the crop canopy
8. Greenhouse air temperature just below the crop canopy
9. Inside net radiation from and to the crop
10. Inside and outside photosynthetically active radiation
11. Inside and outside total solar radiation
12. Outside temperature
13. Outside wind speed and direction

Since the greenhouse floor consisted of a repeating pattern of pipe loops, with each loop having the same water temperature supplied to it, the entire floor did not have to be modeled. A section of the floor was chosen where the environmental parameters needed for the model would be collected, and it is this section that the model represents. Data collected at this location was used to calibrate and verify the model. The floor section is 155 cm (61 in) wide and includes five pipes as shown in Figures 2 and 3. These five pipes are a return pipe (R), and four successive supply pipes (S, S-1, S-2, and S-3). As the warm water travels through the pipe loops it cools slowly as heat is transferred from

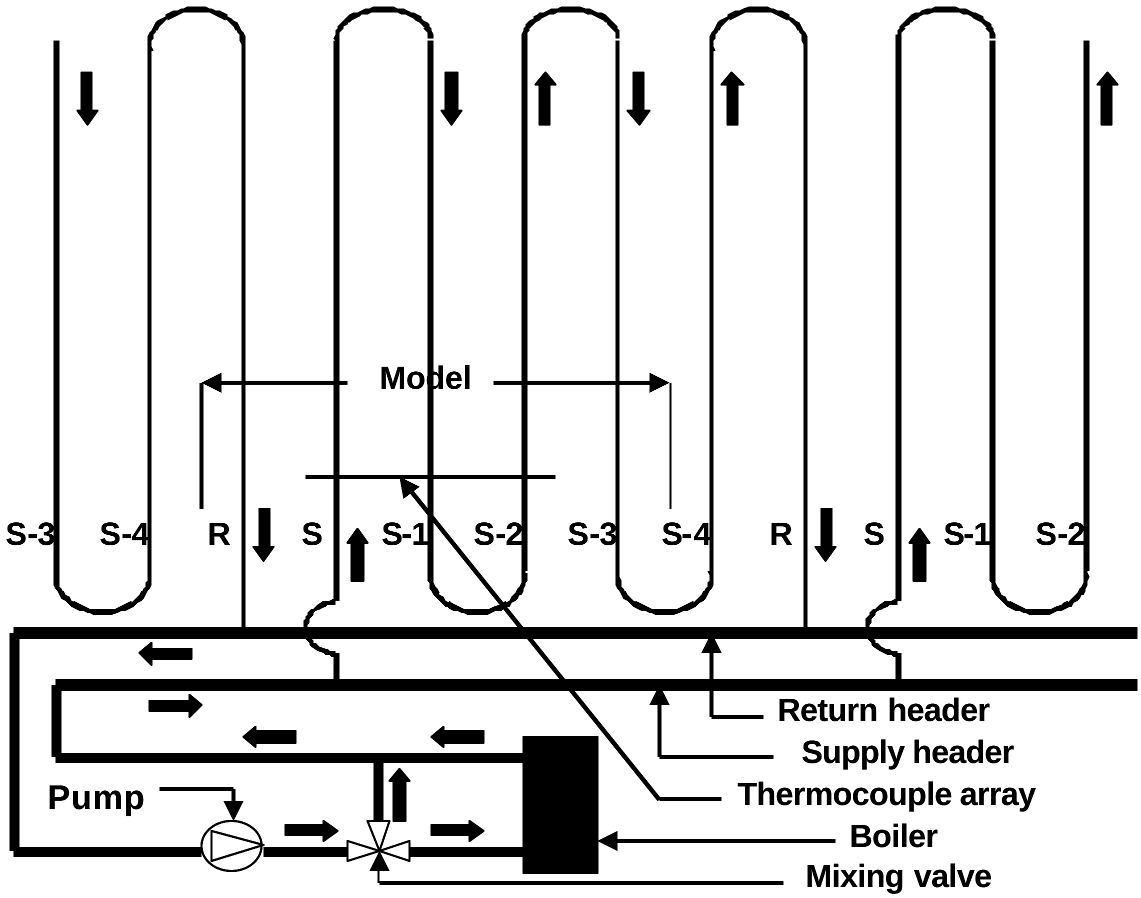

Figure 2. Generalized representation (not to scale) of the repeating pattern of the floor heating pipes considered in the model, and location of the 15 thermocouples.

the water to the concrete floor. At steady state conditions, the water temperature differences between adjacent pipe sections S-3 and S-4 and between S-4 and R were relatively small. In addition, the temperature differences between pipe sections S and R were relatively large. Therefore, with the model's boundaries chosen as indicated in Figure 2, the model is in a region of the floor with little heat flux to the sides because of the small temperature gradients at the boundaries, thus simplifying the simulation model.

In the simplified model, the surface temperature of the floor is the model output, using pipe water temperature, greenhouse air temperature, and convective heat transfer coefficient for the floor surface as inputs. In order to model the radiation heat loss from the floor, the external radiation temperature (the temperature of the inside of the greenhouse structure that the floor radiates to and receives radiation from) and emissivity of the floor were also used as inputs. The floor's surface temperatures (15 locations) were collected for a portion of the floor section being modeled so the model's output (floor surface temperature) could be verified.

In order to measure the floor surface temperature, copper-constantan thermocouples were constructed with the copper-constantan union approximately 2.4 mm (3/32 in) long. The union and about 5 cm (2 in) of the adjacent shielded wire were coated with a thin white dielectric material in order to separate the dissimilar metal union from the concrete, and to protect it from the slightly acidic nutrient solution that was regularly delivered to the crop. The white coating also reduced the potential for heating from solar radiation reaching the thermocouple wire through the crop canopy. A 3.2 mm

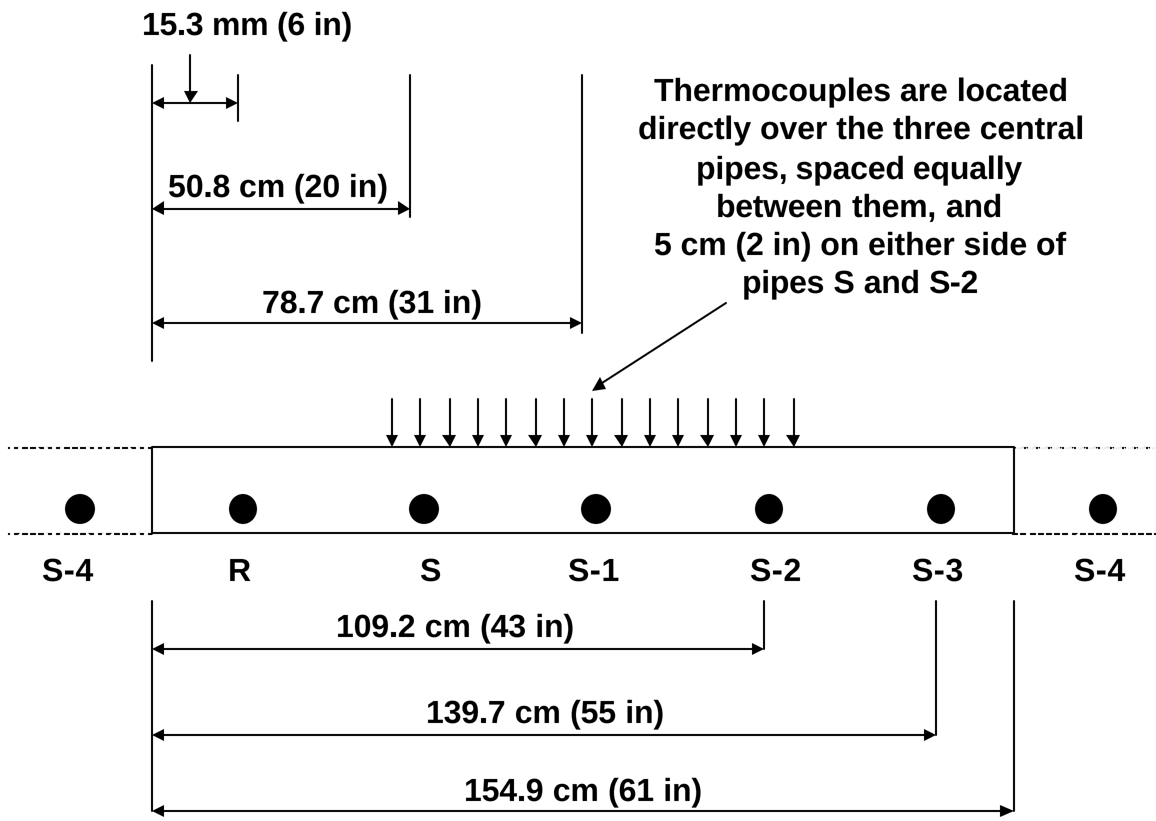

Figure 3. Cross section of the floor section used for the model (including heating pipes R through S-3), and the location of the 15 thermocouples over the three center heating pipes.

(0.125 in) diameter hole was drilled into the concrete to a depth of approximately 3.2 mm (0.125 in) at the locations where the thermocouples were to be installed, and a small amount of gray epoxy was used to secure the copper-constantan union just below the surface.

In order to accurately model the heat transfer and resulting surface temperature of floor section under investigation, it was important to know the exact position of the heating pipes in the floor relative to the thermocouples installed near the surface. This information allowed for the same pipe position to be generated in the model so the surface temperatures generated by the model could be compared with the measurements taken with the thermocouples. During installation, the thermocouples were placed directly above the pipes and evenly spaced between them (Figure 3). In order to determine the exact location of the heating pipes, an infrared temperature sensor (IRTS) was used to measure the surface temperature of the floor every 1.3 cm (0.5 in) in the direction perpendicular to the heating pipes. These measurements were performed at the location where the thermocouples would be installed. By plotting the measured surface temperatures versus position, the position of each heating pipe could be determined by noting the temperature peaks in the plot. Following this method it was found that the distance between pipes R and S was 35.6 cm (14 in), between S and S-1 27.9 cm (11 in), and between S-1 and S-2 and S-2 and S-3 30.5 cm (12 in). The thermocouples were then positioned in the floor as shown in Figure 3. Although the vertical position in the floor could not be exactly determined, it was assumed that all pipes, with the exception of the supply pipe S, were located at a distance of 1.3 cm (0.5 in) from the bottom of the pipe to the bottom of the concrete slab. From an evaluation of the surface temperature versus position plot, it was determined that the supply pipe S was likely positioned slightly higher than the other pipes, and therefore was determined to be located at a distance of 2.5 cm (1.0 in) from the bottom of the pipe to the bottom of the concrete slab.

Four different supply water temperatures were used during the data collection, 32°C (90°F), 38°C (100°F), 43°C (110°F), and 49°C (120°F). For each of these supply temperatures, the ambient greenhouse air temperature was maintained as close as possible to either one of two target air temperatures: 16°C (61°F) and 19°C (66°F). For each of these eight temperature combinations the crop was positioned in four different configurations around the 15 thermocouples. For the first configuration, several plants were removed so that there was a clear floor area centered on the thermocouples and measuring 2.1 m (7 ft) by 2.1 m (7 ft). This configuration would allow for the verification of the simplified model that did not include the presence of a crop. For the second configuration, two pots each with four thermocouples placed throughout the root zone were placed in the same open area but well away from the thermocouples. This configuration will allow for the calibration and verification of another model that simulates the heat flow through a pot placed in an open area (a simplification of a model that would simulate the presence of an entire crop). For the third and fourth configuration, a full crop canopy was arranged in a typical poinsettia crop spacing with and without the pots covering some of the thermocouples. These configurations will allow for the calibration and verification of the final model that should be able to show the heat flow through the floor to the greenhouse air as well as through the crop to the air above.

All data used as inputs and for verification of the simplified model (without a crop canopy) were collected during the night when conditions could be kept as steady as possible without the influence of solar radiation.

Model Description

The model was developed using the Gambit and Fluent computational fluid dynamics software programs (Fluent, Inc., Lebanon, NH). The model's geometry is two-dimensional and represents a 155 cm (61 in) wide section of the10.2 cm (4 in) thick concrete floor. Within this section, five pipes were represented: a return pipe (R), and four supply pipes (S through S-3) as shown in Figure 3. In the model, the inside volume of the pipes is filled with water, and the properties of concrete, polypropylene pipe, water, and the air above the concrete are defined and their values used are shown in Table 1. The values listed are for standard temperature and pressure with the exception of water. The values chosen for water are average values for the range of temperatures used in the model.

Table 1. Material properties used in the model.

Material	Density kg/m^3 (lb$_m$/ft^3)	Specific heat J/kg-K (BTU/lb$_m$-°F)	Thermal conductivity W/m-K (BTU/hr-ft-°F)
Air	1.1614 (0.0725)	1007 (0.214)	0.0263 (0.0152)
Concrete	2300 (143.58)	880 (0.210)	1.4 (0.8089)
Polypropylene	901(56.26)	1800 (0.430)	0.13 (0.0751)
Water	992 (61.93)	4178 (0.998)	0.631 (0.3646)

The conditions of the four model boundaries are defined as follows. In the simplified model (without a crop canopy) it is assumed that there is no heat flux (i.e., adiabatic conditions) to the soil below the slab and no heat flux through the sides of the slab section. The assumption that no heat flows to the soil below is an oversimplification but may be justified if the soil underneath the floor slab remains sufficiently dry and the floor heating system has been running for a long time. The assumption that no heat flows through the sides of the slab section appears justified considering the fact that the side boundaries of the concrete slab are located at an equal distance between two pipes, and the temperature difference between these two pipes is small. In addition, the temperatures of the 15 surface locations being simulated are a reasonable distance away from the slab's side boundaries. This will be verified in subsequent models by expanding the width of the simulated slab and adding additional heating pipes in the model.

At the top surface of the concrete slab, a thermal boundary was chosen where both convective and radiative heat loss occurs. In the simplified model, the convection coefficient must be supplied as input. The simplified model simulates the floor surface without a crop, so the concrete surface is considered as a heated flat plate facing upward. Simplified equations for convective heat loss from horizontal plates in air have been developed (ASHRAE Handbook, 1985). First it must be determined whether the boundary layer heat flux is turbulent or laminar. If the product of the Grashof Number (*Gr*) and the Prandtl Number (*Pr*) is between 10^4 and 10^8, the heat flux is considered to be laminar. If *Gr**Pr* falls between 10^8 and 10^{12}, the layer is considered to be turbulent. For air:

$$Gr*Pr = 1.6 \times 10^6 L^3 (T_s - T_A) \qquad \text{Eqn. 1}$$

Where:

L = Characteristic length of the surface (m)
T_s = Temperature of the surface (^oC)
T_A = Temperature of the air (^oC)

Considering the dimensions of the opened area on the floor, $Gr*Pr$ equals 4.2×10^7, just below the 10^8 threshold for turbulent flow, suggesting that the flow is laminar. However, because the open area considered is surrounded by a much larger area of the floor where turbulent conditions exist, the assumption was made that the condition is really turbulent in the open area as well. Next, the convection coefficient *h* can be calculated from:

$$h = 1.31 * (T_s - T_A)^{0.33} \qquad \text{Eqn. 2}$$

Where:

h = Convection coefficient
T_s = Temperature of the floor surface (^oC)
T_A = Temperature of the air (^oC)

The convection coefficient can now be calculated using the measured average surface temperature and the air temperature for each supply water and air temperature combination.

In order for the model to calculate the radiative heat transfer from the top surface of the floor slab, the mean radiant temperature of the surfaces that the floor slab will radiate to and receive radiation from must be determined. We will refer to this temperature as the external radiation temperature since it is external to the concrete floor section under investigation. These radiant surfaces include components of the greenhouse structure and glazing, as well as some portion of the sky and the overhead heating pipes that will be heated to maintain the air temperature set point. The sky portion is considered small since a double-layer polyethylene film with an infrared barrier was used in this greenhouse. In order to determine a first approximation of the external radiation temperature, the concept of mean radiant temperature is employed. In this case, the mean radiant temperature is the area weighted average surface and sky temperature of all objects exchanging radiation with the floor slab. Furthermore, if we assume that the radiation exchange between the floor and objects above can be considered similar to that of two infinite parallel plates, we can describe this radiative heat transfer by the following simplified equation (Duffie and Beckman, 1991):

$$Q/A = [\sigma * (T_1^4 - T_2^4)] / [1/\varepsilon_2 + 1/\varepsilon_1 - 1] \qquad \text{Eqn. 3}$$

Where:

Q = Heat transfer by radiation (W)
A = Area (m^2)
σ = Stefan-Boltzman constant = 5.6697E^{-8} W/m^2K^4
T_1 = Temperature of surface 1 (K) (i.e., the floor surface temperature)
T_2 = Temperature of surface 2 (K) (i.e., the external radiation temperature)
ε_1 = Emissivity of surface 1
ε_2 = Emissivity of surface 2

In our case, surface 1 is the greenhouse floor and surface 2 is the mean radiant temperature of all objects (including the sky) above the floor. The measured net radiation values in the greenhouse can be entered in Equation 3 as Q/A. T_1 is represented by the average surface temperature of the floor, and ε_1 is a well documented property of concrete, with values ranging from 0.88 to 0.92 for typical concrete, and 0.92 to 0.97 for rough concrete. Since our floor's surface was finished very smooth, a value of 0.9 was used. For ε_2, we used an area-weighted average of the galvanized steel, aluminum, and polyethylene plastic film found in the greenhouse. The emissivity of aluminum varies considerably depending on condition, however an average value for oxidized aluminum of 0.2 was used. Values for galvanized steel also vary and an average value of 0.25 was used. An emissivity of the particular polyethylene film used in the greenhouse was not available but a value of 0.9 was assumed based on a reference for another type of polyethylene film. Using these values we solved Equation 3 for T_2 and found a first approximation for the mean radiant temperature of the objects with which the floor exchanges radiation. This value was then used as input in the model for the external radiation temperature.

The water temperature in each pipe at the location in the floor represented by the model is needed as input. By knowing the water temperature entering the loop, the water temperature exiting the loop, and the total length of the loop, a temperature loss per unit length of pipe could be determined. Since the distance through the loop to each pipe location represented by the model was known, the temperature at these points for each pipe could be calculated.

Results

With the appropriate inputs used for each of the eight water and air temperature combinations mentioned earlier, the model was run and the output compared to the measured floor surface temperature data. For all cases the model under-predicted the average surface temperature of the floor by an average of 3.20^{o}C (5.76^{o}F). The largest difference between the model's predicted average surface temperature and the average surface temperature measured in the greenhouse was 3.50^{o}C (6.30^{o}F). The smallest difference was 2.73^{o}C (4.91^{o}F). The standard deviation among the eight water and air temperature combinations was 0.27^{o}C (0.49^{o}F).

Figure 4 shows measured floor surface data (GH data) along with the predicted surface data (Model1) for the combination of a supply water temperature of 32°C (90°F) and a controlled air temperature of 16°C (61°F). The x-axis shows the position of the temperature measurement relative to the first (left-most) thermocouple.

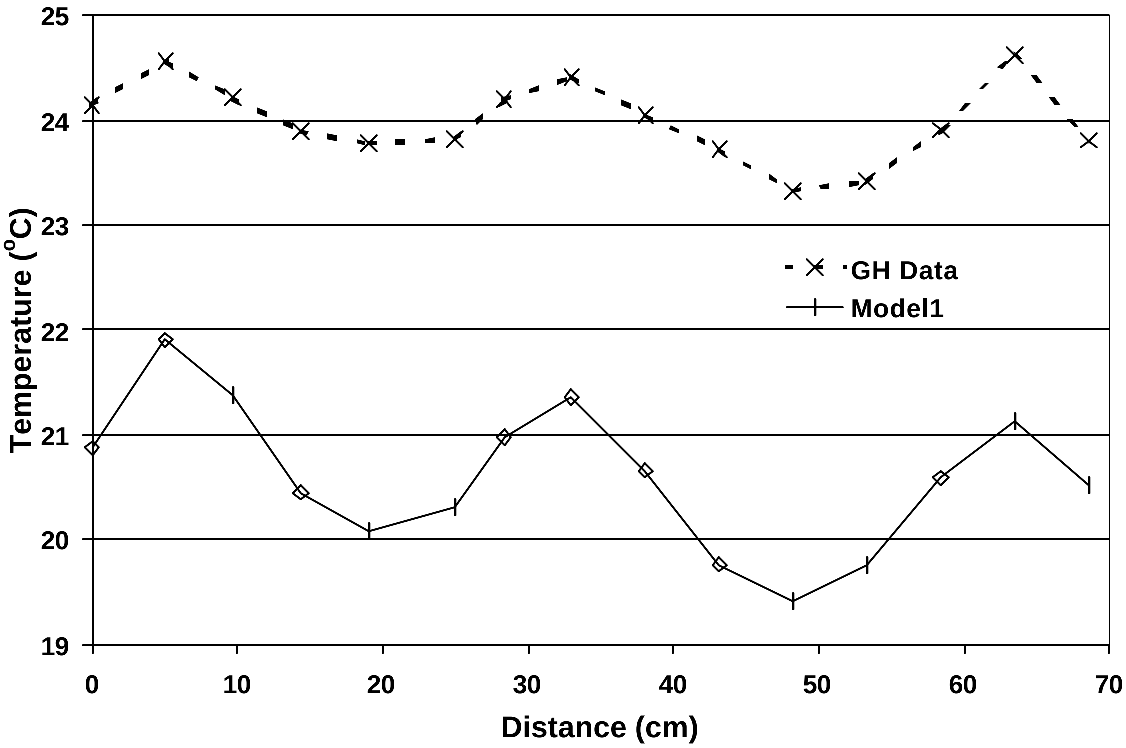

Figure 4. Floor surface temperatures, measured in the greenhouse and predicted by the model.

In an effort to improve the accuracy of the model predictions, different parameters were evaluated for their effect on model predictions. Reducing the convective heat transfer coefficient did not reduce the error enough, even when assumed to be negligible. Increasing the assumed conductive heat transfer coefficient of the concrete had poor results in improving the fit of the model's predictions and measured data, and little justification since the value used has been well established and varies only slightly among concrete types. By assuming an increase in the external radiation temperature that was used as a model input, the model's output matched the measured surface temperatures much better. Figure 5 shows two outputs of the model along with measured surface temperatures for the same case as shown in Figure 4. In this graph, Model1 is the output using the first assumed external radiation temperature as calculated from net radiometer data and Model2 is the output using an adjusted (and higher) external radiation temperature. As the net radiometer data was taken over the plant canopy it does not exactly represent the radiative environment over the bare section being modeled. In order for the model's predicted average surface temperature to equal the average surface temperature measured in the greenhouse for all eight combinations of supply water temperature and controlled air temperature, the external radiation temperature was increased by an average of 8.6°C (15.5°F) with a standard deviation of 0.85°C (1.54°F).

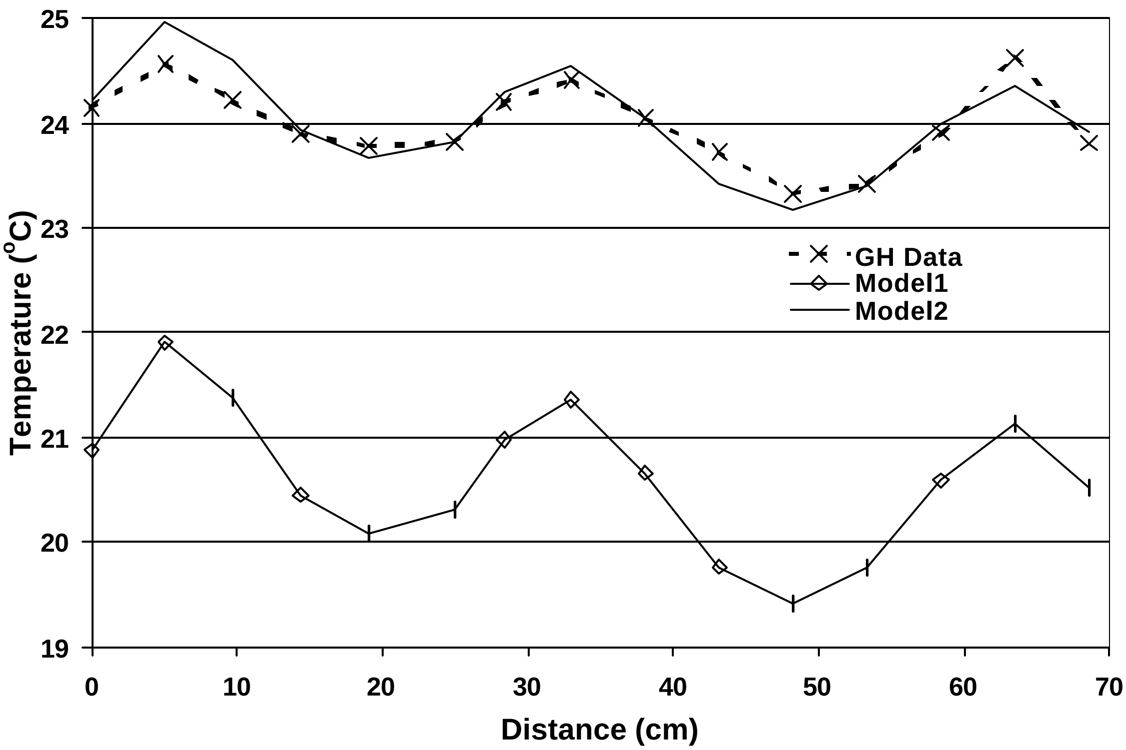

Figure 5. Model's output of floor surface temperature with both a calculated and calibrated external radiation temperature along with the greenhouse data.

Discussion and Conclusions

- Model1's output under-predicted the average floor surface temperature measured in the greenhouse by an average of 3.20°C (5.76°F), for the eight cases considered, with a standard deviation of 0.28°C (0.49°F).
- Adjusting the convection coefficient at the top boundary of the model or modifying the thermal conductivity of the concrete could not significantly improve the under prediction of Model1.
- By raising the external radiation temperature boundary condition used as input by an average of 8.6°C (15.5°F), Model2's predicted average surface temperature matched the measured average surface temperatures for all eight combinations of pipe water temperature and greenhouse air temperature.
- Both models reasonably match the horizontal variations in temperature with the measured data.
- In order to confidently verify the model's output a better method for determining the external radiation environment is necessary.
- More complete models need to be developed that include the soil below, the crop above, and all the thermal relationships that exist between them and the greenhouse.

The fact that Model1 consistently under-predicts the surface temperature of the floor as measured by thermocouples, clearly indicates there are one or more problems with this model. As using a higher external radiation temperature resulted in a good fit to the measured surface temperature data, and changing other aspects of the model did not improve the result, a better method of ascertaining the correct radiation transfer is needed. Additional measurements and other methods of determining this will be investigated and implemented during the next heating season.

The assumption that there is no energy flow to the soil underneath the concrete slab, although useful in our simplified model, is not correct. It is reasonable to ask how much energy is lost to the soil below the slab, and if, for example, changing the pipe elevation or adding insulation would affect this energy loss enough to be cost effective. An expanded model should be able to answer these and other related questions. The next generation of our model will include a soil component and the output of the model in this region will be calibrated and verified using temperature sensors already installed below the floor slab.

The most useful model would allow the user to input a desired supply water temperature and ambient greenhouse air temperature, and provide the resulting temperatures and heat fluxes for any area of interest. As the model exists now, a convection coefficient is required as input to determine the convective heat loss at the surface of the concrete. Since this coefficient changes depending on the floor surface temperature and the greenhouse air temperature, its value must be calculated for each case. In addition, the surface temperature must be known for this calculation. Since this is an output of the model it will not be known prior to running the model, and so another way of solving the convective heat loss is required. Incorporating a user defined function into the model that represents Equation 2, so that the value of the coefficient is updated after each model iteration is one remedy. Another is to incorporate a component for the air volume above the concrete slab into the model (similar to the soil component for the soil below the slab), and let the model calculate the heat fluxes above the slab including associated temperature gradients.

The current simplified version of the model does not incorporate a crop. The final model must incorporate pots positioned on the floor with a crop canopy above. As a result, changes in design parameters or control strategies can be evaluated for their impact on the crop. Ultimately, after the issues stated above have been resolved, the model needs to be verified for non-steady state conditions as well. When completed, such a model can be used to compare different control strategies including their impact on the crop and overall energy use of a floor heating system.

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