Numerical Modeling of Greenhouse Floor Heating

E. Reiss, D. R. Mears, T. O. Manning, G. J. Wulster, A. J. Both

Abstract. *A numerical simulation model of a greenhouse floor heating system was developed and validated using data collected in a research greenhouse located at Cook College, Rutgers University, New Brunswick, New Jersey. The model was then modified and used to evaluate two different heat pipe diameters and spacings that are typical in the greenhouse industry today: 13 mm (0.5 in.) diameter pipe placed on 22.9 cm (9 in.) centers, and 19 mm (0.75 in.) diameter pipe placed on 30.5 cm (12 in.) centers. Two heat pipe elevations within the solid concrete floor system were also simulated, and the effects of the pipe's vertical position, diameter, and spacing on surface heat flux, surface temperature, and surface temperature uniformity were evaluated. The simulation results showed that the smaller diameter pipe placed closer together and at a lower elevation provided the best temperature uniformity without compromising other performance criteria. The model was then further modified to simulate flats with growing media placed on the floor surface. Model simulations were conducted for six different supply water temperatures ranging from 32.2°C (90°F) to 60°C (140°F), while maintaining a target ambient greenhouse air temperature of 15.6°C (60°F). The simulation outputs showed that using the smaller diameter pipe placed closer together resulted in a higher surface heat flux, a higher growing media temperature, and greater temperature uniformity within the growing media, for each supply water temperature simulated.*

Keywords. *CFD, Concrete floor, Pipe diameter, Pipe spacing, Supply water temperature, Uniformity.*

For commercial greenhouse operations to be economically viable, growers must be able to produce products with a higher per-unit value compared to outdoor production, since higher initial investment and operating costs are incurred. Greenhouse environmental control systems (including hardware and software) can improve product quality and increase productivity. Heated ebb-and-flood floors are an example of a system that has become increasingly popular with growers because it can increase both crop production and quality, while reducing operating and labor costs.

Crop Production

The benefits of heated ebb-and-flood floors include: (1) high space efficiency, (2) efficient heat delivery directly to the growing media and root zone (in some cases allowing for lower aerial temperatures), (3) highly uniform heat distribution, (4) heat storage for possible use during power outages or boiler failures, (5) reduction in waterborne plant diseases because the plant foliage stays dry, (6) uniform irrigation up to field capacity, and (7) containment of all irrigation water. Common concerns about recirculating pathogens may be exaggerated, since Uva et al. (1998) reported that only 2% of 50 surveyed greenhouse operations reported disease problems associated with ebb-and-flood irrigation.

Several studies have reported on the benefits of root zone heating to crops grown on heated floors. Pardossi et al. (1984) increased root zone temperatures of two tomato varieties by three methods: nutrient solution heating in a hydroponic system, surface soil heating with hot water pipes, and deep soil heating with hot water pipes. All three methods of root zone heating produced higher and earlier yields over the control treatment. Janes and McAvoy (1983) found that increasing the root zone temperature could reverse the harmful effects of cool air temperatures on a poinsettia crop. Hurewitz et al. (1984) found that: (1) warming the root zone of tomato seedlings resulted in an increase in dry mass, (2) the net photosynthetic rate increased linearly with root zone temperatures up to 30°C, and (3) phosphorous uptake increased with an increase in root zone temperature.

Design

Early experiments on floor heating designs, including wet floors, dry floors, and sand floors, were reported by Giniger (1980), James (1980), and Roberts and Mears (1980). These designs were tested with different pipe spacing as well as with and without flats of plants growing on the floor. U-values (heat transfer coefficients) for different pipe spacings, floor types, and surface conditions (with and without flats, dry and wet flats, etc.) were determined. However, no U-values were reported for floors with heating pipes embedded in solid

Submitted for review in April 2006 as manuscript number SE 6449; approved for publication by the Structures & Environment Division of ASABE in November 2006. Presented at the 2005 ASAE Annual Meeting as Paper No. 054136, presented at the 2004 ASAE Annual Meeting as Paper No. 044040, and presented at the 2003 ASAE Annual Meeting as Paper No. 034039.

The authors are **Eugene Reiss, ASABE Member Engineer,** Manager, New Jersey EcoComplex Research Greenhouse, Rutgers University, Bordentown, New Jersey; **David R. Mears, ASABE Member Engineer,** Professor, Department of Plant Biology and Pathology, **Thomas O. Manning, ASABE Member Engineer,** Project Engineer, Bioresource Engineering, **George J. Wulster,** Extension Specialist and Professor, Department of Plant Biology and Pathology, and **Arend-Jan Both, ASABE Member Engineer,** Assistant Extension Specialist, Department of Plant Biology and Pathology, Rutgers University, New Brunswick, New Jersey. **Corresponding author:** A. J. Both, Department of Plant Biology and Pathology, 20 Ag Extension Way, Rutgers University, New Brunswick, NJ 08901; phone: 732-932-9534; fax: 732-932-7931; e-mail: both@aesop.rutgers.edu.

  ISSN 0001−2351

concrete, as is typical of today's heated ebb-and-flood floor systems.

Control System

Control is considered more challenging for floor heating systems than for forced-air or radiant heating because of the large thermal mass of the floor. This large thermal mass causes the floor to respond relatively slowly (over a period of several hours) to changes in heat input. A common feedback control strategy for floor heating is to control the supply temperature of the water in the floor heating loops based on the temperature of the floor itself or of the growing media in the pots or flats on the floor. Another strategy is to adjust the temperature of the water in the floor loop based on the deviation from the greenhouse air temperature setpoint. Because of the quicker response time of additional heat delivery systems, such as overhead and perimeter heating pipes that are commonly installed in combination with floor heating systems, potential problems with such feedback control are often masked.

Another strategy that can be used is to maintain a constant water temperature in the floor loops, regardless of inside or outside environmental conditions. The water temperature setpoint for this strategy should be determined to provide optimum average root zone temperatures without overheating the greenhouse aerial environment. Alternately, two water temperatures could be programmed into the control system, one somewhat higher than the other. The higher temperature would be used at night, when the heat load is expected to be greater, and the lower setting during the day. The changes in temperature might be programmed to occur some hours before the heat load is expected to change to account for the lag in response time. For this strategy to be effective, the time lag of the floor heating system must be known.

Takakura et al. (1994) proposed feedforward control, in which the control system acquires information about a future disturbance that has not yet affected the system and makes changes to the system before the disturbance occurs. For a greenhouse floor heating system, this would require, for example, the control system to acquire predictions of changing outside weather conditions and adjust the water temperature in the floor to accommodate these changes before they effect the greenhouse environment. Near-term weather predictions, such as 24 h temperature projections, are useful for this purpose, assuming the control software can be updated.

Simulation

Parker et al. (1981) developed a simulation model using finite difference analysis to predict transient heat and moisture transfer in a greenhouse soil heated by buried warm water pipes. Computer simulations were performed for three model cases: without buried pipes (case 1), buried pipes with 25°C (77°F) water (case 2), and buried pipes with 35°C (95°F) water (case 3). Each case was evaluated using the same weather data. Results showed that the mean root zone surface temperatures for cases 2 and 3 were 1.97°C and 4.64°C higher, respectively, compared to case 1. Results also showed only slightly higher air temperatures for cases 2 and 3 compared to case 1. The authors also reported heat savings of 18% and 35%, respectively, for cases 2 and 3 compared to case 1.

Kurpaska and Slipek (2000) developed a simulation model to investigate design parameters for two different greenhouse floor heating systems: heating pipes buried in the soil below the crop, and pipes laying on the surface of the soil (vegetation heating). The specific design parameters 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 uniformity of the temperature gradient around the crop's roots. Results showed that vegetation heating required on average 3°C (5.4°F) higher input water temperature to result in the same substrate temperature compared with the buried pipe system. Heat losses to the soil were greater when the buried pipe system was simulated compared to the vegetation heating system, but this difference was not quantified.

Accurate and flexible computer simulation models that have been verified with representative experiments 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 investigating all possible parameter combinations of potential interest. Computational fluid dynamics (CFD) is increasingly being used as an engineering design tool to model the interaction between the internal climates of greenhouses with outside weather conditions (Reichrath and Davies, 2002). CFD has been used to study the effects of side vent opening size and location on airflow patterns and temperature distribution in naturally ventilated greenhouses (Lee and Short, 2000). Kacira et al. (2004) analyzed the effect of wind speed, side ventilators, and span numbers on ventilation rates using the CFD approach, showing that when both side and roof ventilators were used, maximum greenhouse ventilation rates were achieved. Lee et al. (2002) used CFD models to study the effect of roof vent opening of fully open-roof style multi-span greenhouses, and validated the output with particle image velocimetry (PIV) data. Montero et al. (2005) investigated nighttime heat fluxes in unheated greenhouses, using a steady-state two-dimensional CFD model. Their model was then used to evaluate passive methods for reducing energy losses.

To our knowledge, no computer simulation models have been developed for the typical floor heating systems found in modern greenhouses. Therefore, the development of an accurate and verified computer model to investigate and quantify the performance of greenhouse floor heating systems was warranted. With such a model, 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. This article describes the development and validation of a model (using numerical methods) of a floor heating system that was installed in a research greenhouse. The model was then modified and used to investigate the effect of changing design parameters in floor heating systems on: (1) floor surface and growing media temperature, (2) floor surface and growing media temperature uniformity, and (3) heat flux upward (from the floor surface) and downward (to the soil below).

Materials and Methods

Collection of Model Validation Data

Data to develop and validate the model were collected in a 17.7 m (58 ft; east-west) by 18.3 m (60 ft; north-south) open-roof greenhouse. The greenhouse (model MX-II, Van Wingerden Greenhouse Co., Horse Shoe, N.C.) was located at Horticultural Research Farm 3, Cook College, Rutgers University, New Brunswick, New Jersey, and oriented with its ridges facing approximately north-south (Both et al., 2001). A typical floor heating system was installed in the greenhouse and was integrated with an ebb-and-flood floor irrigation system. Figure 1 shows a generalized cross-section (not to scale) of the installation. The system consisted of a 10.2 cm (4 in.) concrete floor slab with 19 mm (0.75 in.) (nominal inside diameter) polypropylene pipes embedded in the lower third of the floor. The greenhouse floor was divided into two identical heating zones, each with its own circulator pump and mixing valve so that each area could be individually controlled. Each area had five pipe loops, with each loop approximately 110 m (360 ft) long, looping back and forth from the north wall to the south wall three times before being reconnected to the return header located along the north wall. The system utilized a reverse return header system (Reiss, 2006) resulting in the same head loss and thus the same flow rate through and temperature drop across each loop. The spacing of the heating pipes was 30.5 cm (12 in.) on center. Water was heated by a gas-fired hot-water boiler and circulated throughout the floor zones, while a three-way mixing valve controlled the temperature of the water entering the pipe loops.

When the amount of heat being supplied to the greenhouse floor zones was insufficient to maintain the target air temperature setpoint, additional heat was supplied to an above-floor heat delivery system, consisting of aluminum StarFin heat pipes (TrueLeaf Technologies, Petaluma, Cal.). Two loops, each 67 m (220 ft) long, provided two runs of pipe, approximately 30 cm (12 in.) apart, spaced vertically around the perimeter of the greenhouse at an elevation just below gutter height at 3 m (10 ft). Five additional loops, each 36.6 m (120 ft) long, were positioned under the three central gutters and under each of the side vents along the east and west walls of the greenhouse (Reiss, 2006).

The greenhouse was instrumented with inside and outside sensors to document general environmental conditions including temperature, relative humidity, wind speed (outside only), and radiation. In addition, specific parameters such as temperatures at particular locations on the surface of the floor and in the growing media, net radiation above the floor or crop, and flow rates in the different heating zones were also collected. The sensor output was recorded with data loggers (model 21X, Campbell Scientific, Inc., Logan, Utah). The sample rate was 10 s, and data were stored as 1 min averages. These measurements were then used to calculate system parameters, including the total heat flux from the warm water circulating in the floor loops to the greenhouse environment. The measurements could also be used directly as inputs to the simulation model (e.g., the free stream air temperature) or to verify its output (e.g., the surface temperature of the floor or the root zone temperature at specific locations).

All sensors used, their calibration procedures, and their specific locations during data collection were described in detail by Reiss (2006). Poinsettia crops were grown in the greenhouse during data collection spanning the 2003-2004 and the 2004-2005 heating seasons.

Simulation Software

The geometry and meshing of all simulation models were developed using Gambit (Fluent, Inc., Lebanon, N.H.), a preprocessor for Fluent's CFD software. All zones within the model domain were meshed with a mesh size of 0.51 mm (0.02 in.). This grid size was established by conducting a grid analysis in which the model was constructed and solved with smaller and smaller mesh sizes until the change in the model results from one mesh size to the next was small (less than 2%). A quad-map meshing scheme was used, providing a regular structure (map) of quadrilateral mesh elements. The mesh was then imported into Fluent 6.2.16 (Fluent, Inc., Lebanon, N.H.). Here the "energy" model was employed, in which the discrete, non-linear governing equations for conduction, convection, and radiation are solved where appropriate using the finite volume method. No other models were required, as all three modes of heat transfer could be simulated successfully with this one model. In order to minimize computational resources, the segregated solver was used. This method solved the governing equations sequentially, after they were linearized for each control volume.

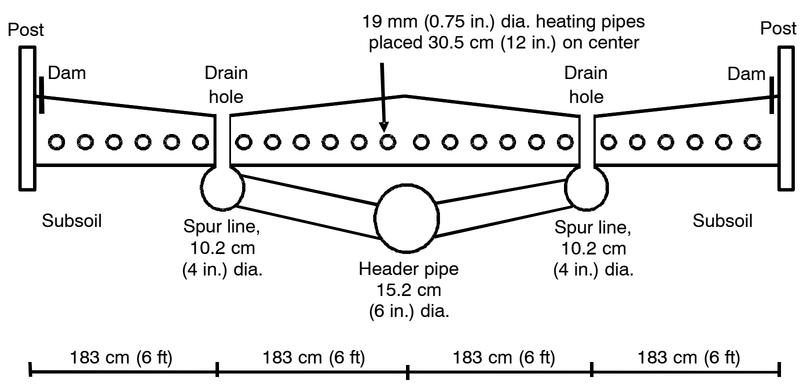

Figure 1. Cross-section (not to scale) of a typical floor heating installation integrated with an ebb-and-flood irrigation system. The recommended slope of the floor surface is 1.3 cm (0.5 in.) in 183 cm (6 ft), allowing for quick drainage after each irrigation cycle.

Simulation Models

Initial Model Based on the Heating System Installed in the Research Greenhouse

It was assumed that a small floor section could be modeled to characterize the entire system, since the design of the floor heating loops repeated every 1.83 m (6 ft). In addition, significant horizontal temperature gradients only occurred in the direction perpendicular to the length of the heating pipes, justifying a two-dimensional model. The developed model represented a vertical cross-section of the greenhouse floor perpendicular to the heating pipes, measuring 1.5 m (60 in.) wide, and included five pipes starting with a return pipe, followed by a supply pipe and three neighboring pipes carrying water between the supply and return pipes (fig. 2). The model covered a region of the floor with negligible heat flux through the side boundaries because of the very small temperature gradients at these boundaries. In the model, the thickness of the concrete floor was assumed constant (10.2 cm or 4 in.).

In order to validate this simulation model, 15 thermocouples were attached to the floor surface at 5.1 cm (2 in.) intervals, starting two inches to the left of the center of pipe S-1 and extending two inches to the right of pipe S-3 (fig. 2). Four different supply water temperatures were evaluated: 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 closely as possible to three target air temperatures: 15.6°C (60°F), 18.3°C (65°F), and 21.1°C (70°F).

Boundary Conditions

The boundary condition at the bottom of the concrete slab was assumed adiabatic. This assumption was justified because the heat flux to the soil below the concrete floor has little impact on the temperature distribution or heat flux above the pipes. Subsequent analyses with a soil zone included below the concrete floor slab confirmed this assumption. In this case, the model was run with both an adiabatic condition between the concrete bottom and the soil zone, and a coupled condition, where conduction from the concrete floor to the soil below was modeled. In both cases, the heat flux through the top boundary of the model (top of the concrete slab) and the temperatures at this top boundary were essentially identical for each simulation.

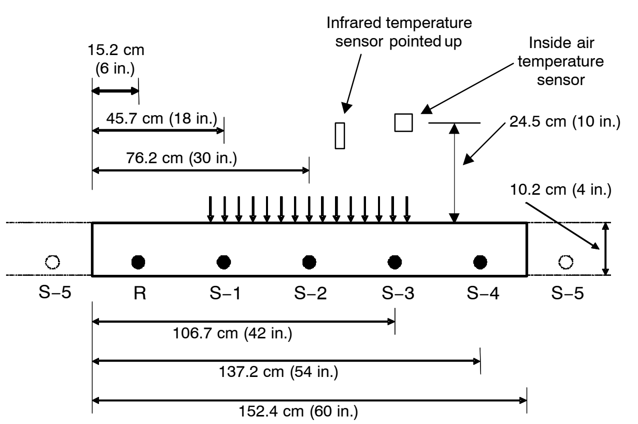

Figure 2. Cross-section of the floor section used for the simulations showing the 15 thermocouples centered over heating pipes S-1 through S-3 (R = return, S = supply), as indicated by the arrows at the floor surface. Also shown are the locations of the infrared temperature sensor and inside air temperature sensor.

Similar to the boundary conditions at the bottom of the concrete slab, an adiabatic condition was defined at both side boundaries. The assumption that no heat flows through the sides of the concrete zone was justified considering the fact that the side boundaries of the concrete slab were located at an equal distance between two heating pipes, and the temperature difference between these two pipes was small. In addition, the temperatures of the 15 surface locations being simulated were a reasonable distance away from the simulated floor section's side boundaries. This assumption was verified in subsequent analyses by expanding the width of the simulated slab and adding additional heat pipes to the model.

At the top surface of the concrete slab, a thermal boundary was chosen where both convective and radiative heat losses occurred, and appropriate coefficients were defined (Reiss, 2006).

Input Parameters

All input parameters for the model were derived from data collected during the early morning hours from midnight to 05:00 h. Air and pipe water temperatures were kept constant for at least 24 h before the data were collected in order to promote steady-state conditions inside the greenhouse. Only data collected on days when the outside conditions during this time period were constant or slowly changing were used, and the data collected and calculated during this 5 h period were averaged to one data point for each parameter.

The inside air temperature (fig. 2) was used as the free stream air temperature in the model. This allowed for the convection heat loss to be calculated by the model. The water temperature in each heating pipe was needed as input. By measuring the water temperatures entering and exiting a loop, and the total length of a loop, the water temperature at each pipe location could be determined.

For the simulations without a crop on the floor, the concrete surface was considered as a heated flat plate facing upward. Simplified equations for convective heat loss from horizontal plates in air have been developed (ASHRAE, 2005). Because the model surface was part of a much larger greenhouse floor surface, the heat flow from the surface of the floor was considered turbulent, allowing for the calculation of the appropriate convection coefficient (h).

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 combined surfaces that the floor slab radiates to and receives radiation from had to be determined. This temperature is commonly referred to, in Fluent, as the external radiation temperature. These radiant surfaces include all components of the greenhouse structure and glazing, including the overhead heating pipes that are used to maintain the air temperature setpoint. In addition, some portion of the sky is included as part of the combined radiant surfaces, since the glazing is partially transparent to thermal radiation. The mean external radiation temperature was determined from data collected with an infrared temperature sensor located just above the floor surface and pointed upward (fig. 2).

Material Properties

Table 1 lists various material properties used for the simulations. All properties are for standard temperature and pressure and, except for the thermal conductivity of concrete, taken from the literature.

Table 1. Material properties used in the simulation model.

Material	Density, kg m^{-3} (lb ft^{-3})	Specific Heat, J kg^{-1} K^{-1} (Btu lb^{-1} °F^{-1})	Thermal Conductivity, W m^{-1} K^{-1} (Btu h^{-1} ft^{-1} °F^{-1})
Air	1.1614 (0.0725)	1,007 (0.214)	0.0263 (0.0152)
Concrete	2,465 (153.89)	880 (0.210)	2.4 (1.4)
Polypropylene	901(56.26)	1,800 (0.430)	0.13 (0.0751)
Water	992 (61.93)	4,178 (0.998)	0.631 (0.3646)

Model Calibration

The model's predicted surface temperatures were compared to the surface temperatures that were measured in the greenhouse for each of the 12 cases considered. For the first simulation run, a typical thermal conductivity value of 1.4 W m^{-1} K^{-1} (0.81 Btu h^{-1} ft^{-1} °F^{-1}) for concrete was used for each case (Incropera and DeWitt, 1996). With this value, the model underpredicted the surface temperature of the concrete by 2.1°C (3.7°F) on average. In an effort to improve the accuracy of the model predictions, different parameters were evaluated for their effect on the model's temperature predictions. Since the thermal conductivity of concrete can vary depending on density, moisture content, and material composition, the model was calibrated by adjusting concrete's thermal conductivity value until the resulting difference between the measured and predicted temperatures was found acceptable. An adjusted thermal conductivity of 2.4 W m^{-1} K^{-1} (1.4 Btu h^{-1} ft^{-1} °F^{-1}) was used for concrete in all successive simulation runs. It is understandable that this concrete floor has a relatively high thermal conductivity, as the ebb-and-flood watering system keeps it saturated with moisture. Having calibrated and verified the model, it was then used to investigate several alternative design and management concepts.

Evaluation of Pipe Size, Pipe Spacing, and Pipe Location

Two pipe elevations, i.e., the bottom of the pipe 13 mm (0.5 in.) above the bottom of the 10.1 cm (4 in.) thick concrete slab, and the pipe centered in the slab, were compared for the two common pipes sizes used in the industry: 13 mm (0.5 in.) and 19 mm (0.75 in., nominal inside diameter). Two different soil thermal conductivity values were used to represent relatively wet or dry soils: 0.6 W m^{-1} K^{-1} (0.35 Btu h^{-1} ft^{-1} °F^{-1}), and 1.3 W m^{-1} K^{-1} (0.75 Btu h^{-1} ft^{-1} °F^{-1}). Two inlet pipe water temperatures, 48.9°C and 32.2°C (120°F and 90°F), and two air temperatures, 21.1°C and 15.6°C (70°F and 60°F), were used for each of the pipe configurations, yielding 32 simulations. Cross-linked polyethylene (PEX) heating pipe with a thermal conductivity of 0.38 W m^{-1} K^{-1} (0.22 Btu h^{-1} ft^{-1} °F^{-1}) was assumed for all simulations. During these simulations, supply and return pipes were placed next to each other in alternating order, as is common in commercial greenhouse applications. For each pipe diameter simulated, the corresponding model evaluated a floor slab section containing three return pipes and two supply pipes, resulting in a slab width of 1.1 m (45 in.) for the 13 mm (0.5 in.) pipes and 1.5 m (60 in.) for the 19 mm (0.75 in.) pipes.

In order to model heat flux to the soil underneath the floor slab, a wall boundary was included in the Fluent software to simulate the soil below the bottom of the concrete slab. The two soil conductivities simulated were assigned to this wall boundary, along with a 1.5 m thickness. Below this wall boundary, a "deep soil zone" was included, where a constant temperature of 12.2°C (54°F) was assigned, which represented the mean annual deep soil temperature for New Jersey. Assuming a commercial greenhouse with a length of 58 m (190 ft), the 19 mm (0.75 in.) heating pipe was installed in continuous loops running back and forth the entire greenhouse length; the maximum recommended loop length for this pipe diameter is 122 m (400 ft). For the 13 mm (0.5 in.) pipe diameter, the pipes were assumed to be fed from both end walls and running only half the length of the greenhouse; the maximum recommended loop length for this pipe diameter is 76 m (250 ft). In either case, the simulations were performed for a location halfway down the supply pipe and halfway down the return pipe (assuming the supply and return pipe form a single pipe loop, as is generally the case). The temperature difference across each pipe loop (from inlet to outlet) was kept constant (irrespective of the greenhouse air temperature): 5.9°C (10.6°F) for a supply water temperature of 48.9°C (120°F), or 1.8°C (3.2°F) for a supply water temperature of 32.2°C (90°F).

In order to determine the average floor surface temperature, locations at the top boundary (i.e., the top of the concrete floor) in each model were defined. For the 1.5 m (60 in.) wide model, these locations were spaced every 4.9 cm (2 in.), while for the 1.1 m (45 in.) model, the interval between locations was 3.7 cm (1.5 in.). With these respective spacings, some of the locations could be defined to fall directly over the center of each pipe, and each model had the same number of locations defined between pipes. This way, the fact that the model represented three return pipes and only two supply pipes did not effect the output, since only the floor section over two return and two supply pipes was considered in the evaluation.

Evaluation of a Layer of Growing Media on Top of the Floor

The simplified situation of plug flats located on top of a heated floor was evaluated. A 5.1 cm (2 in.) continuous layer simulating the growing media in the flats and positioned directly on top of the floor was added to the simulation model, allowing the model to remain two-dimensional. For this set of simulations, two pipe diameter/spacings were modeled: 13 mm (0.5 in.) diameter pipe placed on 22.9 cm (9 in.) centers, and 19 mm (0.75 in.) diameter pipe placed on 30.5 cm (12 in.) centers. For both pipe diameter/spacings, the pipe was positioned with the bottom of the pipe 13 mm (0.5 in.) above the bottom of the concrete floor slab. Six supply water temperatures of 32.2°C (90°F), 37.8°C (100°F). 43.3°C (110°F), 48.9°C (120°F), 54.4°C (130°F), and 60°C (140°F) were considered for the simulations with only one air temperature: 15.6°C (60°F). Since the highest two supply water temperatures were not used during the validation measurements, the temperature differences across a heating loop exposed to these temperatures were extrapolated from data based on the measured temperature difference for the four lower supply water temperatures (Reiss, 2006).

For the 13 mm (0.5 in.) diameter pipe placed on 22.9 cm (9 in.) centers, ten pipes were included in the model domain with an equal number of alternating supply and return pipes, resulting in a simulated slab width of 2.3 m (90 in.). For the 19 mm (0.75 in.) diameter pipe placed on 30.5 cm (12 in.) centers, eight pipes were included in the model domain with an equal number of alternating supply and return pipes, resulting in a simulated slab width of 2.4 m (96 in.). This increase in the number of heating pipes included in the simulations was done so that sufficient simulation data representing the center of the slab could be evaluated while ignoring data generated near the side boundaries of the slab, where boundary effect errors existed. In the growing media, 25 measurement points were distributed evenly every 3.8 cm (1.5 in.) over and between five heating pipes (three return and two supply) for the case with the 13 mm (0.5 in.) diameter pipe placed on 22.9 cm (9 in.) centers. For the case with the 19 mm (0.75 in.) diameter pipe placed on 30.5 cm (12 in.) centers, 25 measurement points were distributed using the same spacing, but over and between four heating pipes (two supply and two return). The 25 measuring points were evaluated for three elevations measured from the bottom of the media: 0.3 mm (0.125 in.), 25.4 mm (1 in.), and 50 mm (1.9 in.).

With the addition of a layer of growing media to the model, material properties for this zone had to be provided as input to the model. Using a water release curve for a typical greenhouse growing media (Mears et al., 1975), a moisture content (wet basis) of 75% was chosen for the simulation runs. Based on the moisture content-thermal conductivity relationship determined by Ali (1973), the corresponding thermal conductivity for the media at this moisture content was calculated to be 0.53 W m^{-1} K^{-1} (0.31 Btu h^{-1} ft^{-1} $°F^{-1}$). For simulating the heat flux to the soil below the floor, a soil thermal conductivity value of 0.6 W m^{-1} K^{-1} (0.35 Btu h^{-1} ft^{-1} $°F^{-1}$) was used.

RESULTS

INITIAL MODEL BASED ON THE HEATING SYSTEM INSTALLED IN THE RESEARCH GREENHOUSE

While the average absolute error of surface temperatures for all 12 simulations was small (0.44°C, table 2), the surface heat flux was not predicted as well. This could be the result of an error in the model's heat flux calculation or an error in the way the heat flux in the greenhouse was measured or calculated. Although the model consistently underpredicted the surface heat flux, the model's output can still be used to make relative comparisons between different design parameters, such as pipe size, spacing, and elevation in the slab. It can also be used to compare floor performance when different supply water and air temperatures are used as setpoints in the greenhouse.

Table 2. Measured and predicted data for the 12 model simulations used to validate the model.

Supply Water Temp. (°C)	Greenhouse Air Temp. (°C)	Convection Coefficient (W m^{-1} K^{-1})	External Radiation Temp. (°C)	Average Floor Temperature: Measured, °C (SD)	Predicted, °C (SD)	Measured Minus Predicted	Surface Heat Flux: Measured (W m^{-2})	Predicted (W m^{-2})	% Error in Predicted Heat Flux
32.5	21.3	2.1	17.1	25.7 (0.35)	25.3 (0.38)	0.4	55.7	48.3	13.2
32.5	18.6	2.3	11.0	23.7 (0.45)	22.8 (0.51)	0.9	78.0	65.4	16.1
32.5	15.8	2.5	9.1	22.6 (0.49)	21.7 (0.56)	0.9	85.8	72.8	15.1
38.1	21.3	2.4	15.5	27.4 (0.57)	27.3 (0.56)	0.1	78.8	71.5	9.3
38.0	18.5	2.5	13.2	26.1 (0.61)	26.0 (0.62)	0.1	89.3	79.6	10.9
38.0	15.8	2.7	10.5	24.7 (0.66)	24.6 (0.69)	0.2	99.5	89.2	10.3
43.6	21.4	2.6	15.2	29.2 (0.77)	29.7 (0.73)	−0.4	98.0	91.8	6.3
43.6	18.9	2.8	14.6	28.5 (0.78)	28.9 (0.76)	−0.4	104.8	96.8	7.6
43.7	16.4	2.9	11.1	27.2 (0.83)	27.4 (0.84)	−0.2	118.3	107.9	8.8
49.3	21.2	2.8	13.4	31.1(0.93)	31.2(0.95)	−0.1	129.0	115.0	10.8
49.2	18.6	2.9	11.3	29.9 (0.98)	31.2 (0.93)	−1.3	135.2	115.9	14.3
49.2	16.0	3.0	9.2	28.7 (1.04)	29.1(1.04)	−0.4	141.8	131.8	7.1
					Average absolute error:	0.44		Average % error:	10.8

Table 3. Input and output data for simulations using a soil thermal conductivity value of 0.6 W m^{-1} K^{-1} (0.35 Btu h^{-1} ft^{-1} $°F^{-1}$).

Pipe Size (mm)	Pipe Position	Water Temp.: Supply (°C)	Return (°C)	Air Temp. (°C)	External Rad. Temp. (°C)	Convection Coefficient (W m^{-2} K^{-1})	Floor Surface Temp., °C (SD)	Surface Heat Flux (W m^{-2})	Soil Heat Flux (W m^{-2})
19	Low	32.0	31.2	21.1	13.4	1.9	24.3 (0.50)	61.5	5.7
19	Low	32.0	31.2	15.6	9.2	2.5	22.2 (0.62)	80.2	5.1
19	Low	47.8	44.8	21.1	13.4	2.9	31.6 (1.02)	123.7	9.3
19	Low	47.8	44.8	15.6	9.2	3.2	29.4 (1.14)	143.6	8.7
19	Middle	32.0	31.2	21.1	13.4	2.1	25.0 (0.79)	66.6	5.7
19	Middle	32.0	31.2	15.6	9.2	2.6	23.1 (0.99)	86.8	5.1
19	Middle	47.8	44.8	21.1	13.4	3.0	32.9 (1.59)	134.7	9.3
19	Middle	47.8	44.8	15.6	9.2	3.3	30.9 (1.80)	156.4	8.7
13	Low	32.0	31.2	21.1	13.4	2.1	24.9 (0.22)	66.9	6.1
13	Low	32.0	31.2	15.6	9.2	2.6	23.1 (0.28)	87.1	5.6
13	Low	47.8	44.8	21.1	13.4	3.0	32.8 (0.50)	135.1	10.1
13	Low	47.8	44.8	15.6	9.2	3.3	30.8 (0.55)	156.7	9.6
13	Middle	32.0	31.2	21.1	13.4	2.2	25.7 (0.42)	72.8	6.1
13	Middle	32.0	31.2	15.6	9.2	2.7	24.1 (0.52)	94.9	5.6
13	Middle	47.8	44.8	21.1	13.4	3.1	34.4 (0.89)	148.1	10.0
13	Middle	47.8	44.8	15.6	9.2	3.4	32.6 (0.99)	171.9	9.5

Table 4. Input and output data for simulations using a soil thermal conductivity value of 1.3 W m^{-1} K^{-1} (0.75 Btu h^{-1} ft^{-1} °F^{-1}).

Pipe Size (mm)	Pipe Position	Water Temp. Supply (°C)	Water Temp. Return (°C)	Air Temp. (°C)	External Rad. Temp. (°C)	Convection Coefficient (W m^{-2} K^{-1})	Floor Surface Temp., °C (SD)	Surface Heat Flux (W m^{-2})	Soil Heat Flux (W m^{-2})
19	Low	32.0	31.2	21.1	13.4	1.9	24.0 (0.53)	59.5	12.0
19	Low	32.0	31.2	15.6	9.2	2.5	22.0 (0.65)	78.4	10.9
19	Low	47.8	44.8	21.1	13.4	2.9	31.2 (1.06)	120.3	19.7
19	Low	47.8	44.8	15.6	9.2	3.2	29.0 (1.18)	140.4	18.4
19	Middle	32.0	31.2	21.1	13.4	2.1	24.7 (0.83)	64.6	12.0
19	Middle	32.0	31.2	15.6	9.2	2.6	22.9 (1.03)	85.0	10.8
19	Middle	47.8	44.8	21.1	13.4	3.0	32.5 (1.66)	131.2	19.5
19	Middle	47.8	44.8	15.6	9.2	3.3	30.6 (1.87)	153.1	18.3
13	Low	32.0	31.2	21.1	13.4	2.1	24.7 (0.23)	65.1	12.9
13	Low	32.0	31.2	15.6	9.2	2.6	22.9 (0.27)	85.4	11.9
13	Low	47.8	44.8	21.1	13.4	3.0	32.5 (0.52)	131.9	21.3
13	Low	47.8	44.8	15.6	9.2	3.3	30.5 (0.56)	153.7	20.3
13	Middle	32.0	31.2	21.1	13.4	2.2	25.5 (0.44)	71.0	12.8
13	Middle	32.0	31.2	15.6	9.2	2.7	23.9 (0.54)	93.2	11.8
13	Middle	47.8	44.8	21.1	13.4	3.1	34.0 (0.92)	144.9	21.1
13	Middle	47.8	44.8	15.6	9.2	3.4	32.2 (1.02)	168.8	20.1

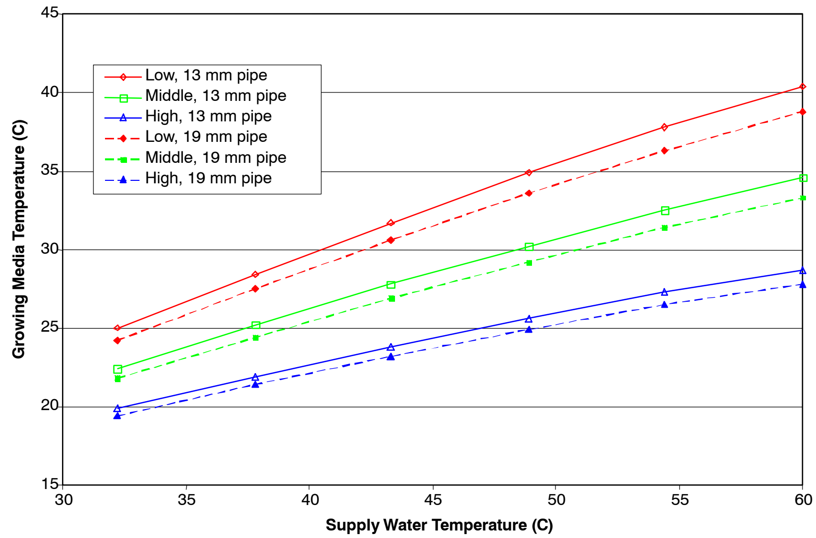

Figure 3. Simulated average growing media temperatures for two heating pipe diameters (and corresponding spacing distance) at three locations in the growing media [low = 0.3 mm (0.125 in.), middle = 25.4 mm (1 in.), and high = 50 mm (1.9 in.) measured from the bottom of the growing media] for various supply water temperatures using an air temperature of 15.6°C (60°F).

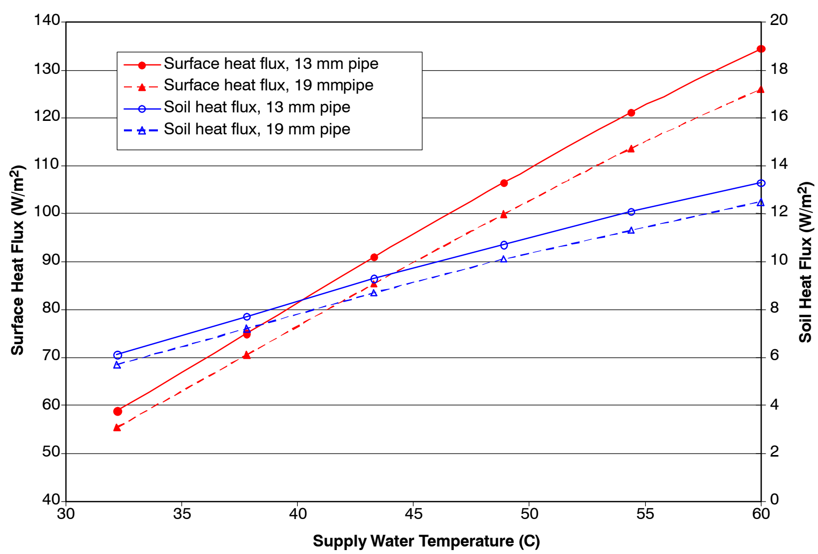

Figure 4. Simulated average surface and soil heat fluxes for two heating pipe diameters (and corresponding spacing distance) for various supply water temperatures using an air temperature of 15.6°C (60°F). For both pipe diameters, the heating pipes were positioned with their bottoms 13 mm (0.5 in.) above the bottom of the concrete floor slab.

Evaluation of Pipe Size, Pipe Spacing, and Pipe Location

Soil Thermal Conductivity

The two different soil conductivity values simulated resulted in very similar average surface temperature and surface heat fluxes (tables 3 and 4). The average surface temperature difference for all 16 designs was 0.3°C (0.54°F), with a standard deviation of 0.07°C (0.13°F). The average decrease in surface heat flux was 2.3%, with a standard deviation of 0.4% when comparing a soil conductivity of 1.3 W m^{-1} K^{-1} (0.75 Btu h^{-1} ft^{-1} $°F^{-1}$) with a value of 0.6 W m^{-1} K^{-1} (0.35 Btu h^{-1} ft^{-1} $°F^{-1}$). The flux to the soil below the floor with a soil conductivity of 1.3 W m^{-1} K^{-1} (0.75 Btu h^{-1} ft^{-1} $°F^{-1}$) was on average 2.1 times greater than comparable simulations with a soil conductivity of 0.6 W m^{-1} K^{-1} (0.35 Btu h^{-1} ft^{-1} $°F^{-1}$). This indicates that the condition of the soil under a floor-heated greenhouse has little impact on the delivery of heat to the greenhouse, but additional heat is required for the downward loss.

Pipe Position

The average surface temperature was higher for the middle pipe position compared with the lower position in the slab: on average 1.1°C for the 19 mm (0.75 in.) pipe and 1.3°C for the 13 mm (0.5 in.) pipe. When evaluating the surface flux for comparable simulations, the average increase in surface heat flux comparing the lower pipe position to the middle position was 9%. Increasing the water temperature, increasing the water/air temperature difference, decreasing the pipe size/spacing, and/or increasing the soil thermal conductivity all resulted in a larger increase in the surface heat flux when changing the pipe location from the lower to the middle position. There was very little effect on the soil heat flux when changing the pipe position from the lower to the middle position. Raising the pipe from the lower position to the middle position resulted in less uniform surface temperatures.

Table 5. Standard deviations for each set of 25 temperature data points at three elevations in the growing media for 13 mm (0.5 in.) diameter pipe placed on 22.9 cm (9 in.) centers and 19 mm (0.75 in.) diameter pipe placed on 30.5 cm (12 in.) centers (in parentheses). Media locations: low = 0.3 mm (0.125 in.), middle = 25.4 mm (1 in.), and high = 50 mm (1.9 in.) measured from the bottom of the growing media. An air temperature of 15.6°C (60°F) was maintained.

Supply Water Temp. (°C)	Temperature Standard Deviation		
	Low (°C)	Middle (°C)	High (°C)
32.2	0.18 (0.41)	0.11 (0.27)	0.08 (0.19)
37.8	0.24 (0.53)	0.15 (0.35)	0.10 (0.24)
43.3	0.30 (0.65)	0.19 (0.43)	0.13 (0.30)
48.9	0.37 (0.78)	0.24 (0.52)	0.16 (0.36)
54.4	0.47 (0.93)	0.31 (0.63)	0.21 (0.43)
60.0	0.60 (1.14)	0.40 (0.76)	0.28 (0.52)

Pipe Diameter/Spacing

The smaller diameter pipe on closer spacing resulted in higher average surface temperatures for all simulations. The value of the soil conductivity had virtually no impact on surface temperature or heat flux upwards. As the difference in water to air temperature increased for the four water/air temperature combinations simulated, the difference in average surface temperature between the two pipe sizes/spacings increased. Although the heat flux to the soil increased with the smaller pipe size/spacing, the percentage of total heat input to the floor that was lost to the soil below did not increase, and in fact decreased slightly.

Evaluation of a Layer of Growing Media on Top of the Floor

Figure 3 shows that for all three elevations, the smaller diameter pipe placed closer together resulted in higher media temperatures, and the difference in media temperature between the two pipe configurations increased from the top of the media to the bottom, and as the inlet pipe water tempera–

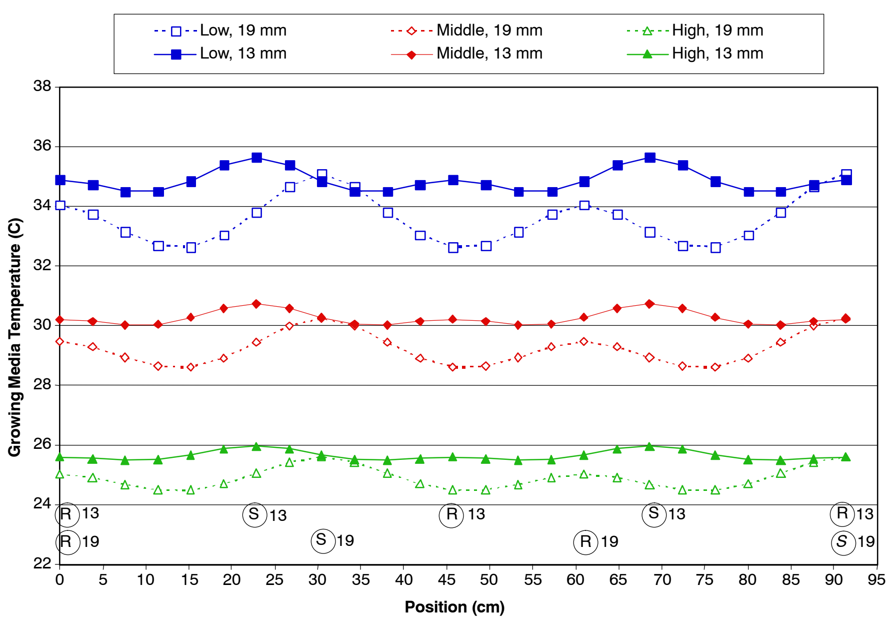

Figure 5. Growing media temperature for both heating pipe configurations at three elevations, using a 48.9°C (120°F) supply water temperature and maintaining a 15.6°C (60°F) air temperature. Media locations: low = 0.3 mm (0.125 in.), middle = 25.4 mm (1 in.), and high = 50 mm (1.9 in.) measured from the bottom of the growing media. The locations of the return and supply pipes are approximated by the letters R and S in the bottom of the graph; 19 indicates the 19 mm (0.75 in.) pipe, and 13 indicates the 13 mm (0.5 in.) pipe diameter.

ture increased. Figure 4 shows that the smaller diameter pipe placed closer together provided a higher heat flux to the media surface above as well as to the soil below the floor for the same pipe inlet water temperature. The difference in performance between the two pipe configurations increases slightly with increasing inlet pipe water temperature.

To provide a measure of temperature uniformity, the standard deviation was calculated for each set of 25 data points. Table 5 reports these values for the 13 mm (0.5 in.) pipe on 22.9 cm (9 in.) centers and the 19 mm (0.75 in.) pipe on 30.5 cm (12 in.). When comparing the two pipe configurations, on average, the standard deviation for the larger diameter pipe placed farther apart is 2.2 times greater compared to the smaller diameter pipe placed closer together, indicating a less uniform temperature distribution. Figure 5 shows trends of the growing media temperature at three different elevations for both heating pipes configurations when maintaining a 48.9°C (120°F) supply water temperature and a 15.6°C (60°F) air temperature.

Discussion and Conclusions

Initial Model Based on the Heating System Installed in the Research Greenhouse

The model predicted temperatures on the concrete surface fairly well for a wide range of pipe water and air temperature combinations. The thermal conductivity for concrete needed for the model to calibrate correctly suggests a potential error in the model. However, a high moisture content of the concrete as a result of frequent irrigation cycles could be a justification for the high concrete thermal conductivity value used as input in the model. The underprediction of the surface heat flux adds to the plausibility of a model error. Direct measurement of the thermal conductivity of the actual concrete used under the tested moisture conditions could be very helpful. Although the measurements used to develop and validate the model were collected very carefully and all sensors were calibrated, it is possible that data collection was a significant cause for the error in some of the model predictions.

Evaluation of Pipe Size, Pipe Spacing, and Pipe Location

The thermal conductivity of the soil had little effect on the surface temperature, surface heat flux, or the uniformity of surface temperature. It did, however, have a direct impact on the heat flux to the soil below, indicating the importance of quantifying the soil conductivity under a particular floor heating system so that the potential economic benefits of installing insulation under the floor can be fully understood.

Raising the pipe position in the simulations resulted in higher surface temperatures and surface heat fluxes, while the soil flux decreased only slightly. In addition, the temperature uniformity at the surface decreased. Thus, as temperature uniformity is important for crop quality, a lower pipe position should be used.

The simulations showed that with the 13 mm (0.5 in.) pipe placed on 22.9 cm (9 in.) centers, there is an increase in both surface temperature and surface heat flux for all cases, compared to the 19 mm (0.75 in.) pipe on 30.5 cm (12 in.) centers, regardless of pipe position or soil thermal conductivity. In addition, although there is also greater heat flux to the soil below, the percentage of the total heat input to the floor that is transferred to the soil did not increase with closer pipe spacing.

Since one of the greenhouse heating design companies reported only a slight increase in cost to install 13 mm (0.5 in.) pipe placed on 22.9 cm (9 in.) centers compared to 19 mm (0.75 in.) pipe on 30.5 cm (12 in.) centers, it appears the smaller pipe diameter installed at a closer spacing is the preferred option. However, there may be situations where the reduced maximum loop length would require or justify the use of the larger pipe diameter at the wider spacing, particularly when surface temperature uniformity is a less important design criterion. As a practical matter, the spacing of the pipe has less impact on surface temperature uniformity or surface heat flux at lower desired soil temperatures.

Evaluation of a Layer of Growing Media on Top of the Floor

The output data from this set of simulations show that the 13 mm (0.5 in.) diameter pipe placed on 22.9 cm (9 in.) centers provided a higher average media temperature and a higher surface heat flux for any given inlet pipe water temperature when compared to the 19 mm (0.75 in.) diameter pipe placed on 30.5 cm (12 in.) centers. At the same time, for any given inlet pipe water temperature, the smaller diameter pipe placed closer together provided a considerably (approximately half the standard deviation) more uniform temperature distribution throughout the media.

Additional simulations should be run using other free-stream air temperatures as input. Families of curves could then be generated that would provide useful information for determining appropriate air and inlet pipe temperatures to produce proper media temperatures for a particular crop. The resulting surface heat fluxes for various inlet pipe water and air temperature combinations could then be determined.

Considering that there appears to be no economic disadvantage to installing 13 mm (0.5 in.) diameter pipe placed on 22.9 cm (9 in.) centers compared to the 19 mm (0.75 in.) diameter pipe placed on 30.5 cm (12 in.) centers, and that these simulations show a considerable increase in media temperature uniformity when the smaller diameter pipe is modeled compared to the larger diameter pipe, it follows that the smaller diameter pipe placed closer together is most likely the best choice of pipe diameter and spacing for plant production using flats.

References

Ali, G. 1973. Thermal properties of composting material. MS thesis. New Brunswick, N.J.: Rutgers University, Department of Biological and Agricultural Engineering.

ASHRAE. 2005. *Handbook of Fundamentals.* Atlanta, Ga.: ASHRAE.

Both, A. J., E. Reiss, D. R. Mears, and W. J. Roberts. 2001. Open-roof greenhouse design with heated ebb and flood floor. ASAE Paper No. 014058. St. Joseph, Mich.: ASAE.

Giniger, M. 1980. Embedded plastic pipe in a sand floor. Special Studies Project. New Brunswick, N.J.: Rutgers University, Department of Biological and Agricultural Engineering.

Hurewitz, J., M. Maletta, and H. W. Janes. 1984. The effects of root zone heating at normal and cool air temperatures on growth and photosynthetic rates of tomatoes. *Acta Horticulturae* 148: 871-876.

Incropera, F. P., and D. P. DeWitt. 1996. *Introduction to Heat Transfer.* New York, N.Y.: John Wiley and Sons.

James, M. F. 1980. Thermal performance of embedded pipe porous concrete floor heating systems for greenhouse use. MS thesis. New Brunswick, N.J.: Rutgers University, Department of Biological and Agricultural Engineering.

Janes, H. W., and R. McAvoy. 1983. Deleterious effects of cool air temperature reversed by root-zone warming in poinsettia. *HortScience* 18(3): 363-364.

Kacira, M., S. Sase, and L. Okushima. 2004. Effects of side vents and span numbers on wind-induced natural ventilation of a gothic multi-span greenhouse. *Japan Agric. Res. Quarterly* 38(4): 227-233.

Kurpaska, S., and Z. Slipek. 2000. Optimization of greenhouse substrate heating. *J. Agric. Eng. Res.* 76(2): 129-139.

Lee, I., and T. H. Short. 2000. Two-dimensional numerical simulation of natural ventilation in a multi-span greenhouse. *Trans. ASAE* 43(3): 745-753.

Lee, I., S. Sase, L. Okushima, A. Ikeguchi, and W. Park. 2002. The accuracy of computational simulation for naturally ventilated multi-span greenhouse. ASAE Paper No. 024012. St. Joseph, Mich.: ASAE.

Mears, D. R., W. J. Roberts, G. A. Taylor. 1975. Controlling moisture levels in trough culture tomato and cucumber production. *Trans. ASAE* 18(1): 145-148, 151.

Montero J. I., P. Muñoz, A. Antón, and N. Iglesias. 2005. Computational fluid dynamics modeling of night-time energy fluxes in unheated greenhouses. *Acta Horticulturae* 691(1): 403-409.

Pardossi, A., R. Tesi, and M. Bertolacci. 1984. Root zone warming in tomato plants in soil and NFT. *Acta Horticulturae* 148: 865-867.

Parker, J. J., M. Y. Hamdy, R. B. Curry, and W. L. Roller. 1981. Simulation of buried warm water pipes beneath a greenhouse. *Trans. ASAE* 24(4): 1022-1029.

Reichrath, S., and T. W. Davies. 2002. Using CFD to model the internal climate of greenhouses: Past, present, and future. *Agronomie* 22(1): 3-19.

Reiss, E. 2006. Modeling greenhouse floor heating using computational fluid dynamics. MS thesis. New Brunswick, N.J.: Rutgers University, Department of Plant Biology and Pathology.

Roberts, W. J., and D. R. Mears. 1980. Floor heating of greenhouses. ASAE Paper No. 804027. St. Joseph, Mich.: ASAE.

Takakura, T., T. O. Manning, G. A. Giacomelli, and W. J. Roberts. 1994. Feedforward control for a floor heat greenhouse. *Trans. ASAE* 37(3): 939-945.

Uva, W. L., T. C. Weiler, and R. A. Milligan. 1998. A survey on the planning and adoption of zero runoff subirrigation systems in greenhouses. *HortScience* 33(2):193-196.