Greenhouse Floor Heating, Preliminary Results from the 2002-2003 Heating Season

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Abstract

Floor heating in greenhouses has become increasingly popular over the past several decades due to the considerable benefits it provides. Extensive work was done on earlier versions of warm floor designs to determine their heat transfer coefficients and thermal masses. Typical floor heating designs of today differ from those early systems, and have not been researched as thoroughly. With the goal of quantifying the performance of these modern designs, a recently constructed open-roof greenhouse was outfitted with a typical heated ebb and flood floor system, and instrumented to measure the heat input to the floor as well as other energy flows. A mean heat transfer coefficient from the floor heating pipes to the growing area was determined to be 5.97 W/m^2-K (1.05 Btu/hr-ft^2-°F) and three control strategies were implemented and evaluated. Effective evaluation of the strategies was found to be difficult due to very different outdoor environmental conditions that were present for each control strategy. In future work, the thermal mass of the system will be determined and a model will be developed for the floor system and verified by data collected. With such a model, different control strategies can be effectively and quantitatively compared.

Introduction

Floor heating in greenhouses has become more and more popular over the past two decades because of the considerable benefits warm floors have on greenhouse crops and on the grower's bottom line. Early in its evolution, floor heating could be either a wet system with a gravel and water pond under a porous concrete slab, or a dry system where pipes would be run in the concrete slab itself or in a layer of sand or other aggregate material. The wet system is especially well suited for solar energy collection and industrial waste heat utilization (Roberts and Mears, 1979). Now with the benefits of bottom watering becoming well understood and the synergy of both bottom heat and bottom watering becoming clear, many greenhouse growers are utilizing heated ebb and flood floors in their plant productions systems. These newer generation ebb and flood floors typically utilize solid concrete slabs approximately 10 cm (4 in.) thick, with 1.9 – 2.5 cm (¾– 1 in.) plastic heating pipes positioned in the lower third of the slab. The pipe loops are laid out on 25 – 30 cm (10 – 12 in.) centers and warm water is pumped through the pipes heating the concrete slab, growing media, and eventually the greenhouse air.

With the growing adoption of warm floors for plant production systems, it is important to understand how these floors perform so that optimal control strategies can be utilized. Quantification of the heat transfer characteristics of the system's components, i.e., the heat transfer coefficient (U-value), and thermal mass of the floor and growing medium, is essential to the understanding and quantification of the floor's performance, and should be determined before control strategies can be developed and tested.

Extensive experiments were conducted on the early floor heating designs, i.e., wet floors, dry floors, and sand floors (James, 1980; Roberts and Mears, 1980). These floors were tested with different pipe spacings as well as with and without plants growing on them. Data were obtained from relatively small research greenhouses as well as large commercial ranges utilizing solar energy, industrial waste heat, and heat from conventional boiler systems. Floor material and construction, pipe spacing, and type of crop on the floor all have significant effects on the U-value and thermal mass of the floor system. This work yielded U-values for different pipe spacing, floor types and surface conditions (with flats, without flats, dry flats, wet flats, etc.) that were tested, but no data has been reported, as far as the authors are aware, that describes the U-value and thermal mass for plastic heating pipe embedded in solid concrete floors that are so typical of modern heated ebb and flood floor systems.

Control strategies for floor heating systems can be more challenging than other types of greenhouse heat delivery systems because of the slow response time of the floor. This slow response time is due to the large thermal mass of the concrete and, to a lesser extent, the growing media used for the plants. Because of this large thermal mass, the energy or heat being transferred from the floor and growing media to the greenhouse air is not necessarily the same quantity as the heat being transferred to the floor from the warm water in the pipes at any point in time. In other words, there is a significant lag between when heat is supplied to the floor and when that heat reaches the pots on the floor or the greenhouse air. In the same way, heat can continue to be delivered to the pots and greenhouse air hours after heat is no longer being added to the floor.

Because of this long lag time between the input to, and the output of the floor, typical feedback control algorithms that are so common in heating control strategies, may not be good choices. They will only cause an action once a deviation from the set point occurs, and the crop will not see the result of that action until some time much later than is the case with conventional air heating systems. One feedback 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 the growing media in the pots on the floor. Another strategy adjusts the temperature of the water in the floor loop based on the greenhouse air temperature deviation from the set point. Because of the relatively quick response time of the additional heat delivery systems (i.e., overhead heating pipes that are commonly installed in combination with floor heating systems), the problems with feedback control may largely be masked. For example, good control of the greenhouse air temperature may be achieved, but full utilization of the floor may not have occurred.

Another strategy that is commonly used is to hold the water temperature in the floor loop constant, regardless of inside or outside environmental conditions. The water temperature set with this strategy should be adjusted to provide optimum average soil temperatures without overheating of the aerial environment. Alternately, two water temperatures could be programmed into the control system, one somewhat higher than the other. The higher one would be used at night when the heat load is expected to be greater than during the daytime, and the other used during the day. The changes in temperature might be programmed some hours before the heat load is expected to change to account for the large response time lag of the floor. For this strategy to be effective the time lag of the floor heating system must be known. Some of the problems of feedback control may be overcome by these approaches but there will still be inefficiencies.

Other control strategies have been proposed such as feedforward control (Takakura et al., 1994) where the control system acquires information about future disturbances that have not yet affected the system, and makes changes to the system before the disturbances are felt. In a greenhouse floor heating system this would require, for example, the control system to acquire predictions in changing outside weather conditions, and adjust the water temperature in the floor to accommodate these changes before they had an effect on the greenhouse environment. Again, knowledge of the time lag between introduction of extra heat to the floor heating system and its delivery to the soil and air above is essential to successfully implement such a control strategy.

While many floor heating system control strategies can yield good results, the authors believe that there is potential to improve on these strategies so greater economic benefit can be realized from these systems. To this end, a recently constructed open-roof greenhouse (Both et al., 2001) was outfitted with a heated ebb and flood floor system, and research was conducted on various control strategies. The goal was to find ways to quantify the performance and determine the most efficient and beneficial strategies. In addition, a U-value was determined for this type of warm floor with potted crops. The following is a discussion of the preliminary results of these studies.

Methods

The 17.7 by 18.3 meter (58 ft. by 60 ft.) greenhouse floor was divided into two separate heating zones, each with a three-way mixing valve to provide control for the water temperature in the floor loops. Thermocouples were positioned in dry wells in the heating pipes in each heating zone to monitor the water temperature at important locations in the floor-heating loop. One was positioned between the boiler and the mixing valve, just before the mixing valve, to measure the temperature of the water supplied to the mixing valve. Another was positioned just after the mixing valve, which measured the mixed temperature of the water entering the floor loops in the concrete floor, and a third was positioned to measure the temperature of the water exiting the floor loops. This water either returns to the floor loops through the mixing valve, returns to the boiler, or some of each, depending on the position of the mixing valve. A flow sensor measured the quantity of water that returns to the boiler to be reheated from the floor loops. From measurements obtained by these thermocouples and flow sensors, the amount of heat being added to the floor can be determined given that:

$$Q_{tf} = mc_p(T_{fb}-T_{tb}) \qquad \text{Eqn. 1}$$

Where:

Q_{tf} = total heat supplied to the floor in W (Btu/hr)
m = mass flow rate of water returning to the boiler to be reheated in l/min (gpm)
c_p = specific heat of water in J/kg-K (Btu/lb$_m$-$^\circ$F)
T_{fb} = Temperature of water supplied to the mixing valve in $^\circ$C ($^\circ$F)
T_{tb} = Temperature of water returning to the boiler in $^\circ$C ($^\circ$F)

When the environmental conditions inside and outside the greenhouse, as well as the heat input to the floor, are reasonably constant for several hours, it is reasonable to assume that the heat being added to the floor is equal to the heat leaving the floor. The heat leaving the floor can be described by:

$$Q_{lf} = U_f\, A_f\, (T_f - T_a) \qquad \text{Eqn. 2}$$

Where:

Q_{lf} = Heat leaving the floor in W (Btu/hr)
U_f = Heat transfer rate of the floor in W/m^2-K (Btu/hr-ft^2-$^\circ$F)
A_f = Area of the floor in m^2 (ft^2)
T_f = Average temperature of the water in the floor pipe in $^\circ$C ($^\circ$F)
T_a = Temperature of the greenhouse air in $^\circ$C ($^\circ$F)

Then, $mc_p(T_{fb}-T_{tb}) = U_f A_f (T_f - T_a)$, and with U_f being the only unknown in the above equation, a U-value for the floor can be determined. It should be noted that U_f is the mean heat transfer coefficient from the water in the heating pipes, through the floor and crop, to the greenhouse air based on a unit floor area, and that this heat transfer is a result of conduction, convection and radiation. Similar instrumentation was installed in the supplemental overhead heating pipes, so that the heat contribution by this system could be determined as well.

Other environmental parameters were also monitored including outside air temperature, indoor and outdoor solar radiation, and wind speed, so a heat loss coefficient (U-value) for the greenhouse structure could be determined and an energy balance could be calculated. All environmental and heating parameters were logged using a data logger (Campbell Scientific, Inc., Logan, UT; Model 21X) resulting in one-minute averages.

During the first heating season (2002 - 2003) three control strategies were used. First, the temperature of the water supplied by the mixing valve to the floor was controlled by a temperature sensor placed at the bottom of a pot on the floor. A poinsettia crop was being grown at that time. An environment controller (Argus Control Systems, Ltd., White Rock, British Columbia), utilizing a typical PI (proportional-integral) feedback control algorithm used this temperature to maintain a predetermined pot temperature set point. The larger the deviation between the set point and the pot temperature, and the longer the deviation from the set point lasted, the more the mixing valve opened and the warmer the water was entering the floor pipe loops. A maximum supply water temperature of 60 °C (140 °F) was implemented in the control program so the water temperature would not exceed the recommended temperature for the plastic pipe. No minimum temperature was prescribed.

During the second strategy, the same controller and algorithm was used, but the greenhouse air temperature was used as the set point temperature instead of the pot temperature. Further, a maximum water temperature of 38 °C (100 °F) and a minimum temperature of 29.5 °C (85 °F) were used. The control system could then modulate the temperature within those limits. The minimum pipe inlet temperature was increased to 38 °C (100 °F) from 15:00 to 17:30 hr to prepare the floor for the nighttime heating load.

During the last strategy a constant water temperature was supplied to the floor pipe loops regardless of any environmental conditions. The temperature selected was 38 °C (100 °F).

While we were interested in testing the performance of these strategies, we were also interested in gaining confidence in the reliability of our sensors and data collection system. In addition, we wanted to be sure that the parameters we were measuring provided us with the information needed to accurately quantify the performance of the floor as well as evaluate its efficiency and effectiveness. The objective of the control strategies was to deliver as much of the total heat requirement of the greenhouse as possible from the floor system, without exceeding desirable pot temperatures or adding heat to the greenhouse when it was not needed.

Results

Figure 1 shows data for a typical day where the first control strategy was used to control the pot temperature. The pot temperature set point was 24 °C (75°F).

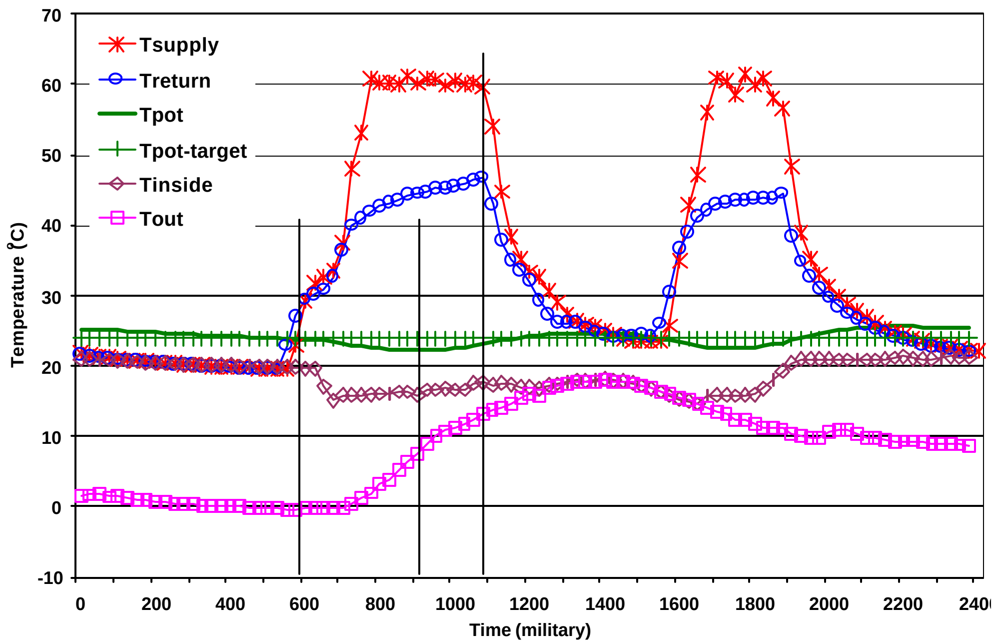

Figure 1. Control of pot temperature by floor pipe water temperature.

It should be noted that during the implementation of this strategy, DIF was being used to control crop elongation, and therefore the day/night set points for the greenhouse air temperature were 15.5/21 °C (60/70 °F). Because air temperature greatly influences pot temperature (Figure 2), this DIF control caused the greatest heat requirement of the pots to occur during the day when the heat requirement of the greenhouse was the lowest.

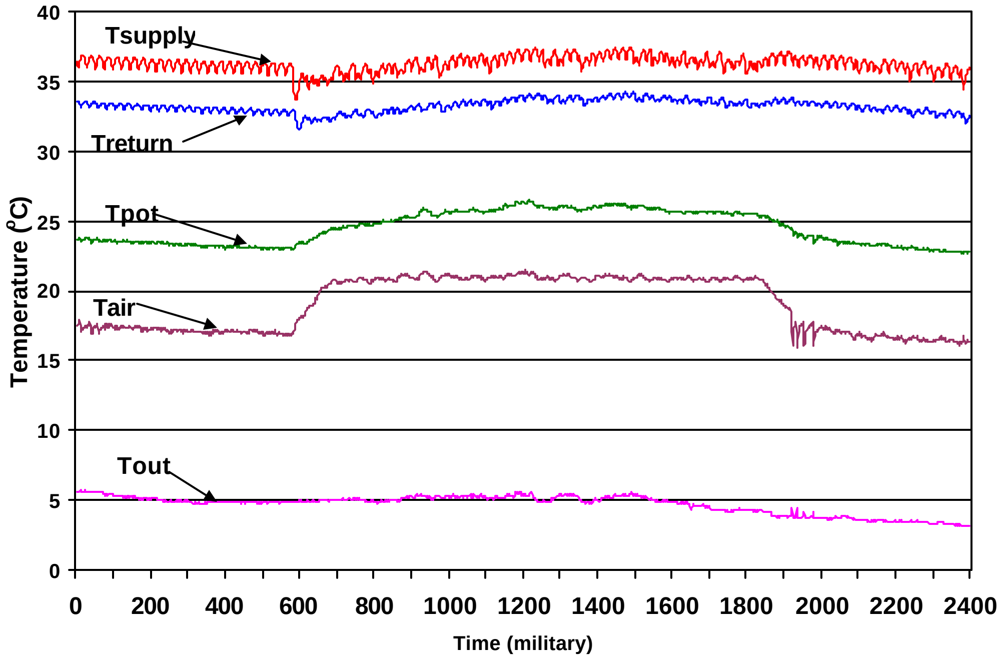

Figure 2. Effect of greenhouse air temperature on pot temperature.

This strategy therefore cannot fairly be compared to the other two strategies where the day/night set points were 21/15.5 °C (70/60 °F) or 24/18 °C (75/65 °F). It (Figure 1) is instructive, however, in showing that feedback control only acts when a deviation from the set point is detected, and because of the large thermal mass of the floor, it takes about three and a quarter hours after an increase in pipe temperature (05:45 hr, first vertical line) before the falling temperature of the pot starts to flatten out and then increases in response to the heat input (09:00 hr, second vertical line). As the difference between pot temperature and pot set point temperature start to decrease, the mixing valve starts to close (10:45 hr). More than five hours after the mixing valve first opened, the pot finally reaches the desired set point temperature. At that point the mixing valve closes completely, but the floor continues to deliver heat to the pots (and greenhouse environment) causing an overshoot of the pot temperature. Effectively, because of the long delay in pot temperature response to a change in pipe temperature, this strategy behaves like on/off control, where the mixing valve opens to allow the maximum supply temperature to the floor as long as the pot temperature is below the set-point temperature, and then closes completely when the pot temperature reaches the set point.

Figure 3 shows a typical 24-hour period using the second control strategy, attempting to control air temperature with the floor heating system. In this case the DIF strategy for air temperature was not used. Also shown in this figure is the data for water flow to the boiler which was used in Eqn. 1 to compute the rate of heat supply to the floor. In the early morning of this day, the heat demand to the greenhouse was fairly high and the mixing valve supplies the maximum water temperature to the floor. As the greenhouse environment started to receive solar radiation at around 09:00 hr, the heat demand was reduced to where only the minimum temperature water was delivered to the floor by the mixing valve. By providing this minimum temperature the floor did not have the opportunity to get too cold but also did not provide more heat than was required by the greenhouse. That, at least, was the goal of this strategy. At 15:00 hr the water temperature was forced to 38 °C (100 °F) for 2.5 hrs. In doing so heat was provided to the floor so when the nighttime heating load occurred, the floor would be warmed up and ready to provide the required heat.

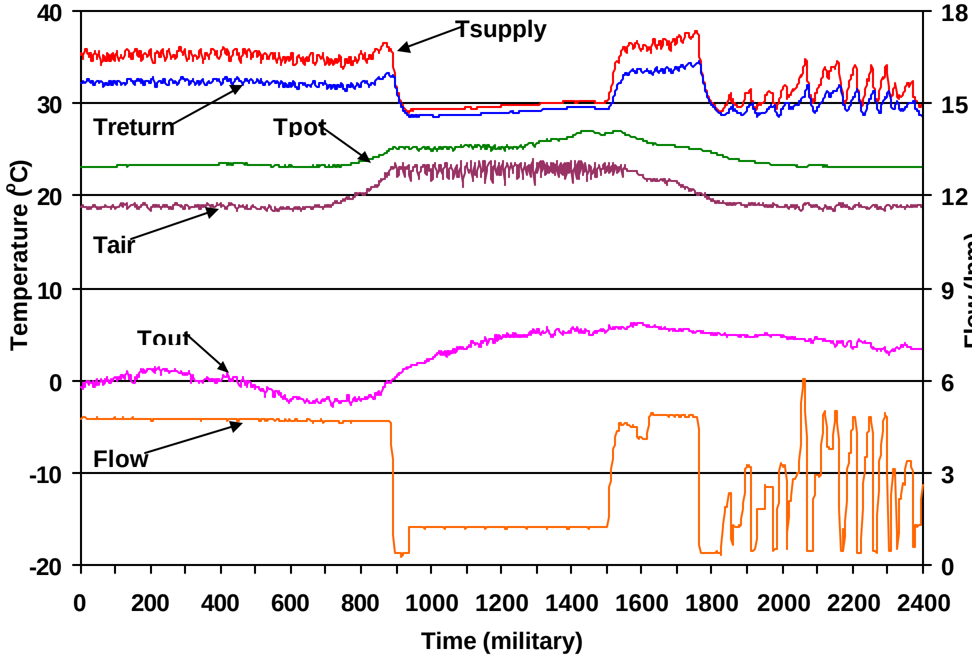

Figure 3. Second strategy, controling air temperature by pipe water temperature.

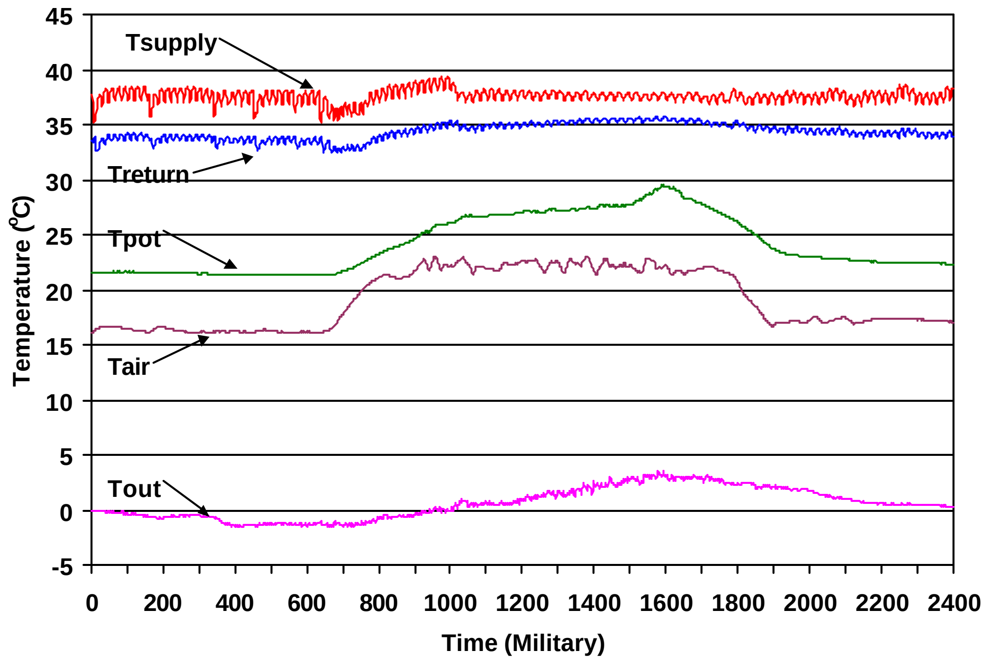

Figure 4. Third strategy, constant inlet pipe temperature of 38 ˚C (100 ˚F).

Figure 4 shows the results of the implementation of the third control strategy. As stated earlier a constant temperature of 38 °C (100 °F) was delivered to the floor by the mixing valve. If the greenhouse required more heat than could be supplied by the floor, more heat was supplied by the overhead heating system (as was the case with the other strategies), and if excess heat was present, venting would occur (again, as was the case with the other strategies). It should be noted that if warmer daytime temperatures do not adversely affect the crop, the greenhouse air temperature could be allowed to rise close to the floor temperature. This way, little or no heat will be transferred from the floor to the greenhouse environment preventing venting of heat supplied by the boiler to the floor. It is important to note that the greater the allowable increase in greenhouse air temperature in the daytime relative to the night minimum, the greater the proportion of the greenhouse heating need that can be supplied by the floor without wasting heat.

During the early morning of February 17, 2003 (Figure 5) the boiler shut down (no crop was present) while the outside temperature was approximately –9.4 °C (15 °F). The boiler failure was not rectified until 16:00 hr on the 18th, but the inside air temperature never dropped below 7.2 °C (45 °F) throughout 29 hours after the boiler failed. This minimum air temperature occurred at 7:30 hr on the 18th with an outside temperature of 3.9 °C (25 °F). At that time, the floor was providing approximately 86.7 W/m^2 (27.5 Btu/hr-ft^2), only slightly less than the 101 W/m^2 (32 Btu/hr-ft^2) the floor typically provides. In addition, throughout this period the pot temperature remained roughly 2.8 °C (5 °F) above the air temperature. This unplanned experiment demonstrated the important feature of floor heating systems in providing an increased amount of time available for repairing heating system failures. Also, analysis of the rate of change of temperatures in this scenario provided additional information on the thermal properties of the floor heating system.

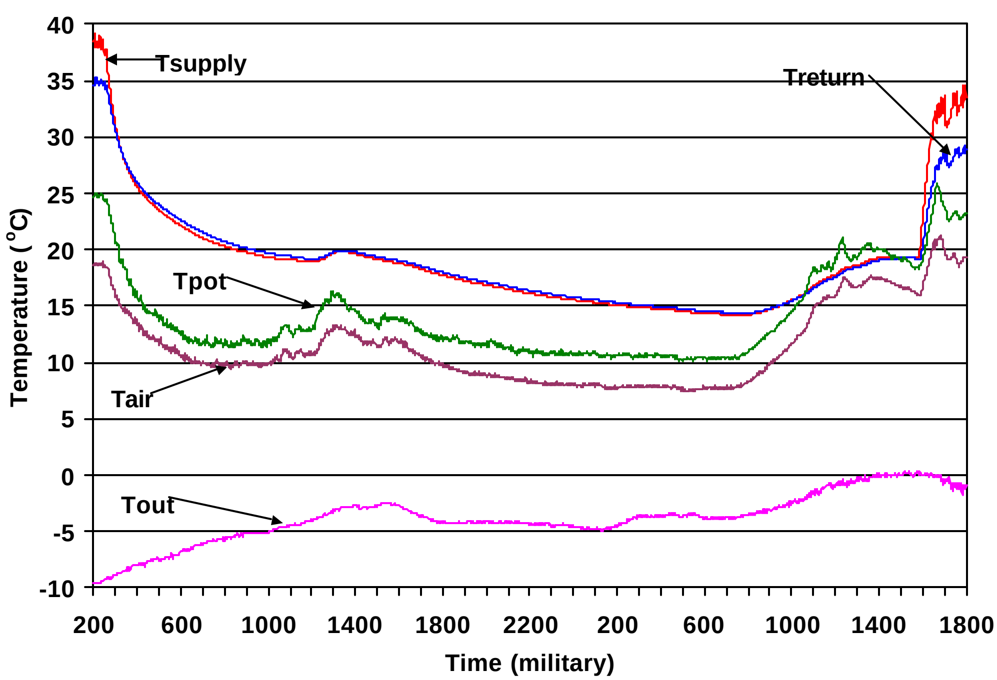

Figure 5. Data showing result of boiler failure on Feb 17, 2003.

As stated earlier, if the heat input to the floor as well as the environmental conditions inside the greenhouse are fairly constant, a mean U-value for the floor can be determined. This situation occurred during a significant number of nights, and the U-value calculated was very similar for each of these nights. In addition, there was a 24-hour period on February 16th (Figure 6) where conditions were excellent for determining the mean U-value. Although the U-value fluctuated a fair amount, the average of this 24-hour period yielded a mean U-value of 5.97 W/m^2-K (1.05 Btu/hr-ft^2-°F). The fluctuation of the U-value seen in Figure 6 is due to the on/off cycling of the boiler, and the approximate three-minute travel time for the water to make its way through each 109 m (360 ft) of floor loop length. Because of this travel time, a volume of water coming from the boiler, and a similar volume returning to the boiler, whose temperatures are being measured at the same point in time, are not the same volumes. This causes a variable temperature difference to be calculated resulting in a fluctuating instantaneous U-value.

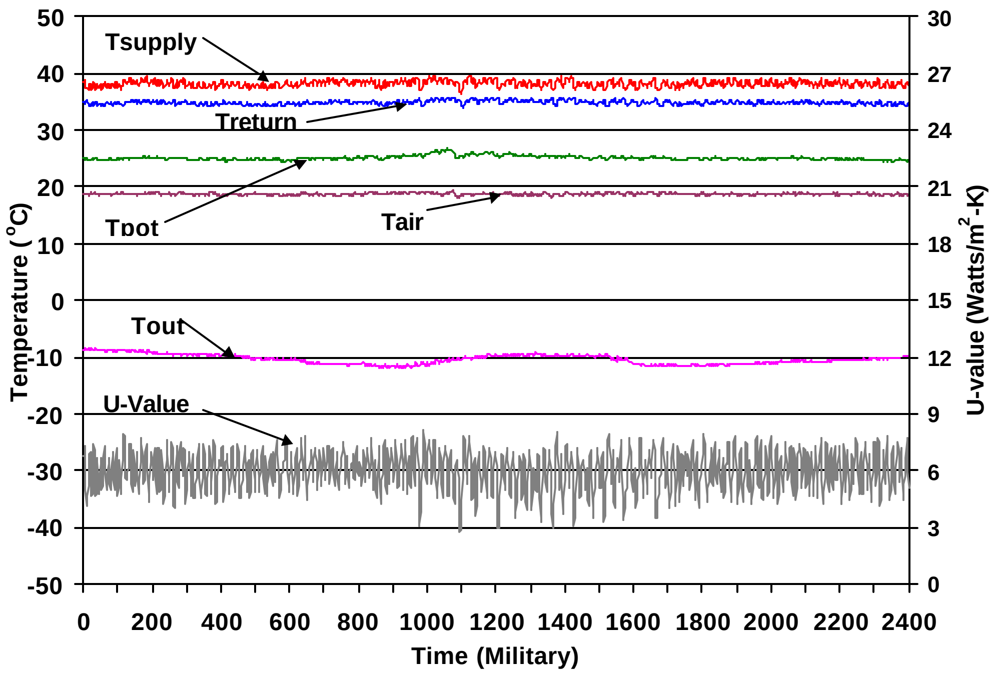

Figure 6. Data showing constant conditions during which the floor U-value was determined.

In an effort to compare the strategies and try to quantify their performance, the contribution by the floor to the entire greenhouse heat requirement was calculated for about 27 days worth of data for both the second and third control strategies. These daily percentages are graphed versus average daily outdoor temperatures, and can be seen in Figures 7 and 8 for control strategies 2 and 3, respectively. As expected, each graph shows that as the average daily outdoor temperature increased, the percent contribution of the floor increased. However, as shown in the graph of the third strategy (Figure 8), for any daily average temperature, the percent contribution of the floor is higher than for the second strategy (Figure 7). This suggests that the third strategy will provide a higher overall contribution by the floor to the heating requirement than the second strategy. As stated earlier, providing as much of the total heat requirement of the greenhouse as possible without waste or overheating the pot, is the most desirable criteria for an appropriate floor heating control strategy. In interpreting this data it is important to note that the two strategies were implemented under different outside environmental conditions. The second strategy was implemented much closer to the winter equinox and therefore the heat requirement of the greenhouse was greater compared to when the third strategy was implemented. Data shown in Figure 7 were collected from the end of December (2002), through the end of January (2003), while the data shown in Figure 8 were collected from the middle of February to the middle of March (2003).

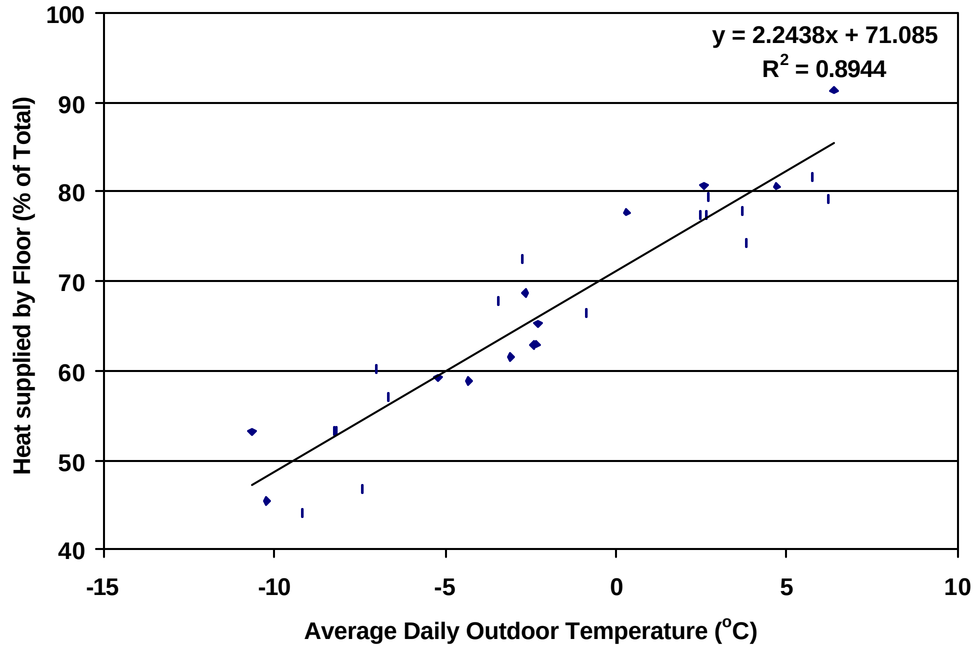

Figure 7. Percent of heat supplied by the floor using second control strategy.

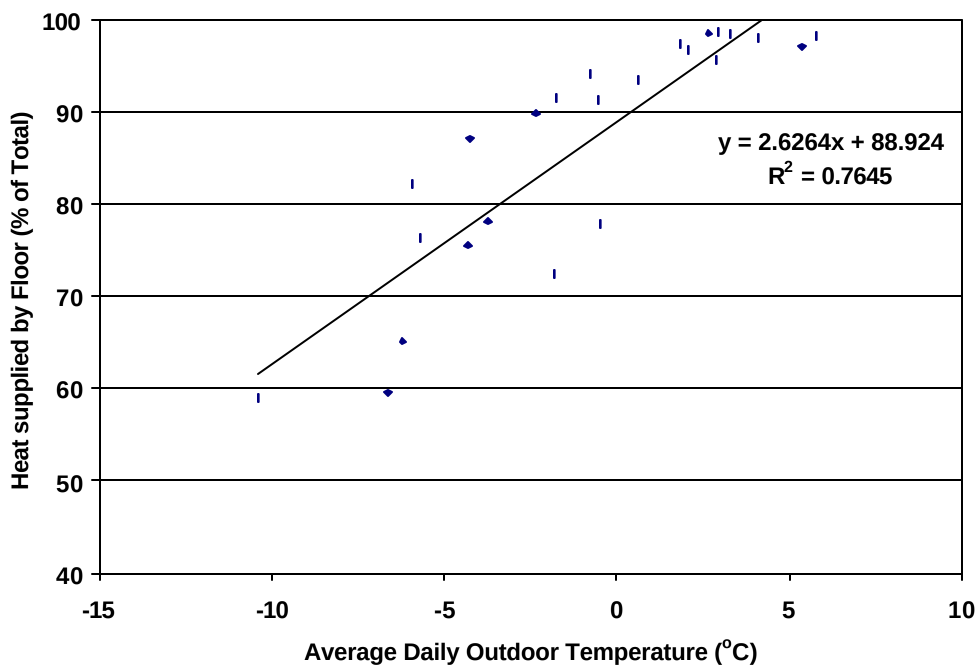

Figure 8. Percent of heat supplied by the floor using third control strategy.

Figures 9 and 10 (second and third control strategies, respectively) show the excess or deficit amounts of heat that was provided by the entire greenhouse heat delivery system on a daily basis, including solar radiation, as a function of the solar gain measured inside the greenhouse. The data considered for these figures is from the same dates as evaluated for Figures 7 and 8. The total heat requirement for the day was calculated, and subtracted from the total energy input to the greenhouse to determine the deficit/excess. The total heat requirement was calculated by integrating the following equation over the entire day:

$$Q_l = U_h A_h (T_a - T_o), \quad \text{Eqn. 3}$$

where:

Q_l = Heat loss from the greenhouse in W/m^2 ($Btu/hr\text{-}ft^2$)
U_h = U-value of the greenhouse in $W/m^2\text{-}K$ ($Btu/hr\text{-}ft^2\text{-}^\circ F$)
A_h = Surface area of the greenhouse in m^2 (ft^2)
T_a = Greenhouse air temperature in $^\circ C$ ($^\circ F$)
T_o = Outside air temperature in $^\circ C$ ($^\circ F$)

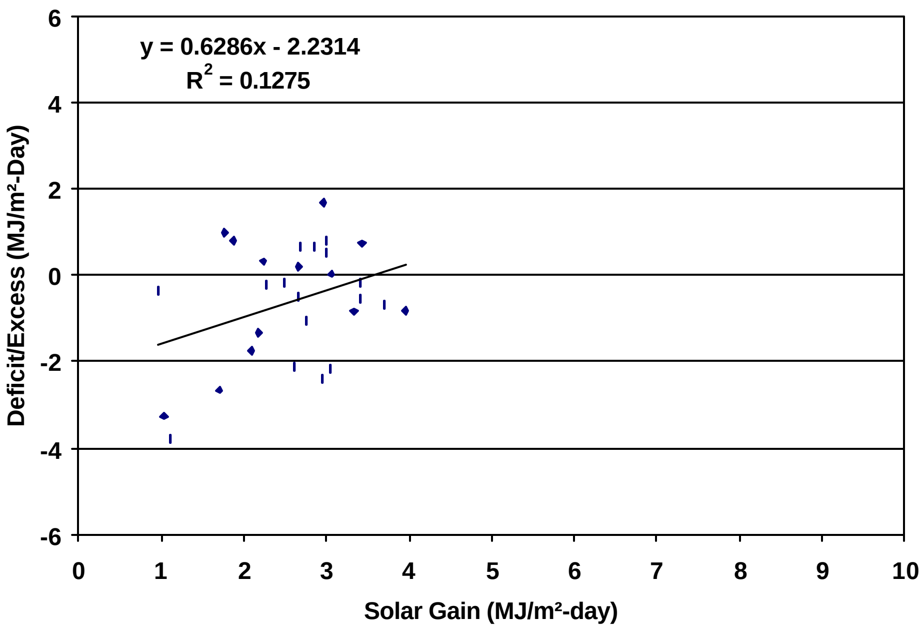

Figure 9. Daily deficit/excess of the heat provided to the greenhouse versus daily integral of inside solar radiation (second strategy).

This energy balance gives an indication of the amount of heat being wasted, or vented out of the greenhouse, as a result of the floor delivering heat when it was not needed. An average U-value for the greenhouse structure of 3.97 $W/m^2\text{-}K$ (0.7 $Btu/hr\text{-}ft^2\text{-}^\circ F$) was used for these calculations. At any given time, the U-value will vary slightly depending on the amount of cloud cover and wind speed (Figure 11). The data points in Figure 11 are all average values averaged from approximately two hours after dusk to one hour before dawn. In Figure 11 the degree of cloud cover is indicated by the net radiation values. Less radiative heat loss indicates more cloud cover. The negative values indicate radiation leaving the greenhouse to the sky and deep space, and cloud cover inhibits this radiation loss. Therefore there is some inherent variability in the U-value determined by this energy balance. It is clear that there are more data points showing higher excess in Figure 10 than in Figure 9 indicating that more of the heat

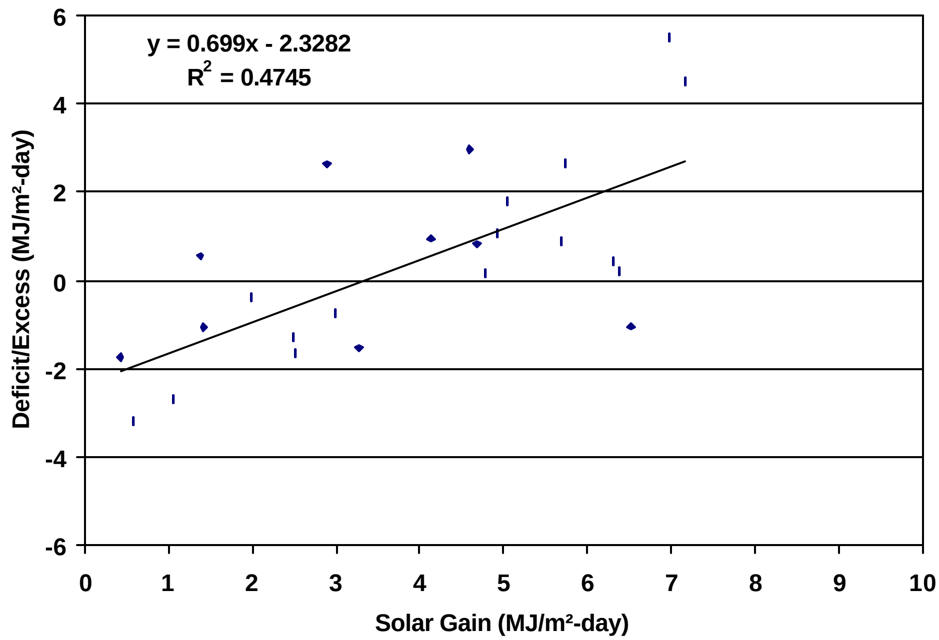

Figure 10. Daily deficit/excess of the heat provided to the greenhouse versus daily integral of inside solar radiation (third strategy).

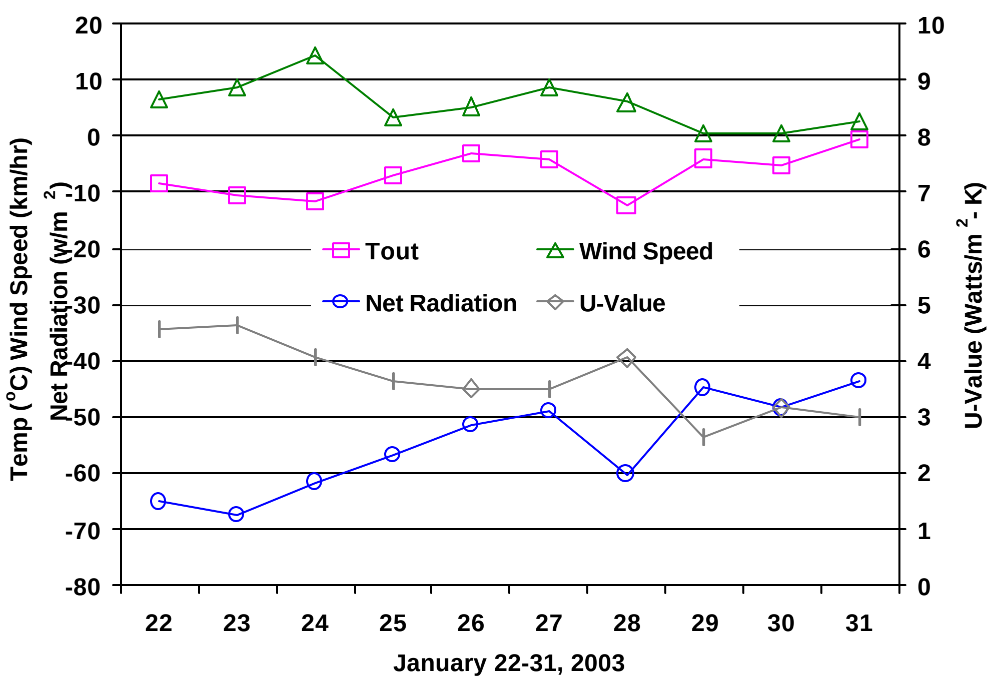

Figure 11. Effect of wind speed and radiation loss on the greenhouse U-value.

provided by the floor had to be vented from the greenhouse using the third strategy. Again it must be pointed out that the strategies were implemented during different outdoor conditions (temperature and solar radiation) and that it would be unwise to come to any final conclusions about the relative efficiency of these strategies from this data. It would not be surprising, however, to find that a strategy such as this, which has a constant water temperature supplied to the floor, might be providing more heat than required on warm sunny days. As noted earlier, by increasing the daytime cooling set point, and letting the greenhouse air temperature rise during the day, the difference between the floor surface temperature and the greenhouse air temperature will become smaller, and little heat transfer will occur from the floor to the greenhouse, thereby reducing the potential for wasted heat.

Future Work

Because of the difficulty in keeping all conditions constant for all strategies, it was hard to make accurate comparisons and evaluations of the different strategies that were implemented. By knowing the heat transfer characteristics of the floor and growing media, simulations of different strategies using the same weather data can be performed and more accurate comparisons can be made. Toward that end, the thermal mass of the floor and growing media will be determined. It is also hoped that a model can be constructed in FLUENT (Fluent, Lebanon, NH) that represents the performance of the floor, and that this model can be verified by temperature data collected in various locations in the floor slab and growing media. These data points should also facilitate the determination of a time constant for the floor as well as the relationship between the water temperature in the pipe loops and the temperature of different locations of the floor and growing media. With accurate floor temperature data, a U-value for the surface of the concrete floor can also be determined. With this model, and the ability to simulate many control strategies, it is hoped that recommendations can be made on how best to control these types of heated floors.

Conclusions

On nights when inside and outside environmental conditions along with floor inlet pipe temperatures were constant, a mean heat transfer coefficient from the floor heating pipes to the greenhouse air was determined to be 5.97 W/m^2-K (1.05 Btu/hr-ft^2-˚F).

An unplanned boiler failure showed that even after 29 hours without heat, and outside temperatures averaging –5 ˚C (23 ˚F), the inside air temperature did not drop below 7.2 ˚C (45 ˚F). At that time the floor was providing 86.7 W/m^2 (27.5 Btu/hr-ft^2), only 14% less than it typically provides. This also shows another important feature of floor heating systems: they can provide valuable time to correct heating system failures.

Maintaining a fixed pot temperature using the floor heating system and a typical PI feedback control strategy was found to be unsatisfactory and quite inefficient, particularly in combination with a DIF air temperature strategy. The feedback control strategy caused considerable overshooting of the temperature set point resulting in inefficient control.

A comparison of the second (controlling greenhouse air temperature) and third (constant supply water temperature) control strategies suggested that the third strategy allowed the floor to deliver a higher percentage of the total heating requirement of the greenhouse compared to the second strategy. In addition, during implementation of the third strategy, more heat was vented from the greenhouse than during the second strategy. However, because the outside temperature and solar radiation conditions were so different when the two strategies were being evaluated, it could not be concluded that these findings were solely a result of the control strategies.

Because of the difficulties in evaluating different control strategies during changing outdoor conditions, the need to develop an accurate model of the floor's thermal performance became evident. More instrumentation must be installed so the temperature gradients in the floor as well as growing media can be accurately determined. This will allow the model to be calibrated and verified.

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