2013

EVALUATION OF ROOT ZONE HEATING IN A COMMERCIAL GREENHOUSE

Han Wang
University of Windsor

Recommended Citation

Wang, Han, "EVALUATION OF ROOT ZONE HEATING IN A COMMERCIAL GREENHOUSE" (2013). *Electronic Theses and Dissertations*. 4917.
https://scholar.uwindsor.ca/etd/4917

EVALUATION OF ROOT ZONE HEATING IN A COMMERCIAL GREENHOUSE

by

Han Wang

A Thesis
Submitted to the Faculty of Graduates Studies
through Mechanical, Automotive and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
2013

EVALUATION OF ROOT ZONE HEATING IN A COMMERCIAL GREENHOUSE

by

Han Wang

APPROVED BY:

A. Fartaj

Department of Mechanical, Automotive & Materials Engineering

T. Bolisetti

Department of Civil & Environmental Engineering

R. Barron, Co-Advisor

Department of Mechanical, Automotive & Materials Engineering

R. Balachandar, Co-Advisor

Department of Mechanical, Automotive & Materials Engineering

May 17th, 2013

DECLARATION OF PREVIOUS PUBLICATION

I, Han Wang, hereby declare that I am the sole author of this thesis under the co-supervision of Dr. Barron and Dr. Balachandar. This thesis includes original research that has been previously published/submitted for publication in peer reviewed conference proceedings, as follows.

Thesis Chapter	Publication title/full citation	Publication status
Chapters 2, 3, 4	Wang, H., Balachandar, R. and Barron, R.M. *Evaluation of root zone heating system on tomato production in a commercial greenhouse.* 24th Canadian Congress of Applied Mechanics, Saskatoon, SK, Canada, June 2013.	Accepted

I certify that I have properly acknowledged the contribution of other researchers to my thesis and have obtained written permission from each of the co-authors to include the above materials in my thesis. I am aware of the University of Windsor Senate Policy on Authorship and I certify that the material contained in this thesis describes work completed during my registration as a graduate student at the University of Windsor.

I declare that to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, I certify that I have not included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

Tomatoes, cucumbers and peppers are common greenhouse crops in Canada. In order to extend the growing season and reduce energy costs, a plant root heating system has been considered in this thesis. Although there is evidence to support the argument that root zone temperature has a significant effect on energy conservation, seed germination and plant growth, information regarding the temperature distribution in the root zone and the causal relationship between root zone temperature, energy savings and fruit yield in a commercial greenhouse is still scarce. This thesis describes a greenhouse experiment utilizing heated water flow through a rectangular plastic duct system to control the root zone temperature. The research investigates the effect of root zone temperature on yield, and whether the system can maintain a desired root zone temperature under typical greenhouse operating conditions. The relationship between the desired root zone temperature, the ambient temperature of the greenhouse and the required temperature of the water flowing through the duct system is also examined.

DEDICATION

To my parents, Yixin Wang and Xiaochun Zhou

ACKNOWLEDGEMENTS

This research was funded through the NSERC Engage Program, the FedDev Applied Research and Commercialization (ARC) Extension Program. Stratus Hydroponics International Inc. provided information on the experimental bench-top heating system and Stratus Plastics International Inc. supplied the plastic ducts. AMCO Produce Inc. (Leamington, ON) provided greenhouse facilities for the research contained in this thesis, and a new experiment has been set up at JEM Farms (Leamington, ON).

I would like to express my thank you to my advisors, Dr. Barron and Dr. Balachandar, for their support, knowledge and input to my thesis work. Without their patience and understanding on the difficulties of this research, I would not have been able to successfully complete it.

I would especially like to thank Matthew St. Louis for his dedicated help. Without his support, I would not have been able to successfully accomplish the experiment.

I would also like to thank all my colleagues for their time and knowledge that they shared during my study.

I would like to extend my thank you to all faculty and staff members of the Department of Mechanical, Automotive and Materials Engineering, Faculty of Graduate Studies, and my friends for their help.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS, SYMBOLS, NOMENCLATURE

RZT	Root zone temperature
T_∞	Ambient root temperature
T_{in}	Water temperature in the duct
T_{RZ}	Root zone temperature
T_{PVC}	Plastic duct temperature
t_{RZ}	Thickness of the root zone slab
t_{PVC}	Thickness of the plastic duct
K_{RZ}	Thermal conductivity of the growth medium
K_{PVC}	Thermal conductivity of the plastic duct

CHAPTER1

INTRODUCTION

A greenhouse is a framed or an inflated structure covered with a transparent or translucent material, e.g. plastic or glass, in which crops can be grown under the conditions of at least a partially controlled environment and which is large enough to permit persons to work within it to carry out agricultural operations [1]. Nowadays, sophisticated techniques are available to modern commercial greenhouse operators to control environmental factors, such as ambient temperature and natural sunlight (see Figure 1). The plants are grown on a bench which is elevated off the floor. The growth medium, or root zone, is a slab of porous-like material which is placed on top of the bench and is employed for plant cultivation instead of soil. The growth medium has been engineered for optimum resaturation capacity and distribution of water throughout the full depth of the slab. Drip irrigation and CO_2 enrichment techniques which are able to enhance photosynthesis and growth are widely applied in greenhouse operations. Moreover, perimeter pipes or some other floor heating system affords the heat for the whole greenhouse, especially during the cold nights in winter. Decent ventilation also can be achieved by utilizing jet-tube fans. If the ambient temperature inside the greenhouse becomes too high, venting is an alternative method of climate regulation. Also, artificial light is in widespread use in greenhouses.

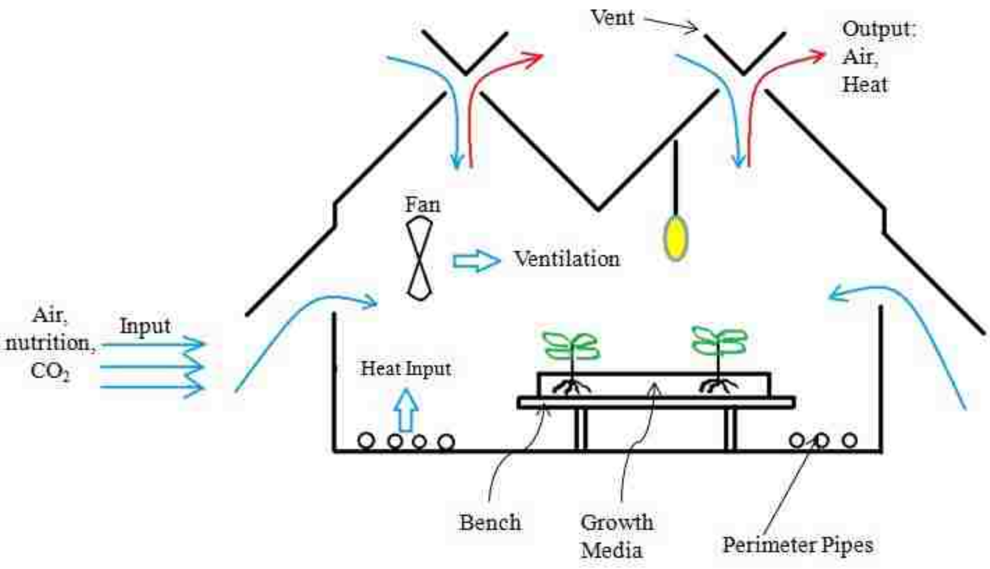


Figure 1: Greenhouse layout

During the period from March to December, Canadian greenhouse production is a major market force. However, there is a lack of supply of greenhouse products in winter months due to the high cost of providing artificial light and heat during the cold season [2]. For this reason, some of the major Canadian greenhouse owners have decided to invest considerable capital to set up operations in the warmer climates of the southern USA or Mexico.

Bench-top heating has been proposed as a technique to expand the growing season in cold climates, to reduce energy costs and to achieve an optimum growing environment for the plants. Bench-top heating is a greenhouse production method that provides heat directly to the growth medium, i.e., the root zone, to obtain an optimum root temperature, rather than warming up the ambient air temperature of the greenhouse. Several root zone temperature control systems have been developed. In this thesis, the performance of a new type of bench-top heating method, utilizing rectangular plastic ducts instead of traditional various parallel vessels or tubes, is investigated.

Tomatoes are a leading greenhouse crop in Canada. Root zone temperature has long been considered as an important factor in the growth of tomato plants [3]. Nevertheless, the knowledge regarding the effect of root zone temperature on tomato plants is incomplete and contradictory. In contrast with the massive amount of information on conventional bench-top heating methods, scientific analysis of this new type of bench-top heating method is scant. Hence, the main objective of this thesis is to obtain scientific evidence of the performance of this new type of bench-top heating system and quantify its effect on earliness and fruit yield of tomato plants in a commercial greenhouse environment.

The thesis consists of five chapters. In Chapter 2, a review of the literature and a discussion of contradictory views on the influence of root zone temperature on tomato plants are presented. The experimental setup and details of the equipment are described in Chapter 3. Experimental results and discussions are given in Chapter 4. Two simple mathematical models, one numerical using computational fluid dynamics (CFD), and one analytical, are proposed in Chapter 5. The conclusions and suggestions for future studies are drawn in the sixth chapter.

CHAPTER 2

REVIEW OF LITERATURE

2.1 General Introduction to the Literature

Many experiments have been conducted to reveal the relationship between the temperature of the aerial part of a plant and the ambient temperature of the greenhouse. For instance, Linacre [4] reported that there was a tendency for the difference between leaf and air temperatures to be negative in hot weather, and positive under cooler conditions. However, no literature is available to describe how the temperature of the root system could be measured or controlled, and how the ambient room temperature and the root zone temperature (RZT) are related.

It is well known that RZT has a vital influence on the growth and development of many plant species. However, the main reason why RZT research has been somewhat neglected may be due to the observation of Went [5]. He reported that the growth rate of tomatoes was found to depend on the temperature at the plant tops rather than at the plant roots. Richards et al. [6] also conducted a large number of experiments to determine the minimum, maximum and optimum root zone temperatures for many plant species. They concluded that RZT had an influence on plant height and dry weight, but that the effect of RZT on plant growth was limited.

In subsequent studies, researchers have attempted to clarify the importance of root zone temperature. Brouwer and Levi [7] performed an experiment on bean plants with radio-active tracers. They reported that root zone temperature impacted water uptake, leaf elongation and photosynthesis of the plants. Similar phenomena were observed by McAvoy and Janes [8] for chrysanthemums and by Moorby and Graves [9] for lettuce.

However, the information with respect to the effect of RZT on tomato plants is paradoxical. On one hand, experiments have been conducted which suggest that root zone temperature does have an effect on tomato plants. Cannell et al. [10] discovered that tomato plants achieved maximum growth at RZT of 20℃. On the other hand, contradictory experimental results of the root zone temperature effects on tomato plants have also been observed. For instance, Went [5] claimed that when other growth conditions were optimal, root zone temperature did not impact tomato plant growth.

Bench-top heating has been proposed as a technique to control root zone temperature, thereby expanding the growing season in cold climates, reducing energy costs and achieving an optimum growing environment for the plants. Nevertheless, reliable information on the performance of the bench-top heating method in a commercial greenhouse is limited.

The following sections, therefore, will deal with the published literature on three topics: 1) the significance of root zone temperature (RZT), 2) ambiguous results of the effects of RZT on tomato plants, and 3) the bench-top heating method.

2.2 The Significance of Root Zone Temperature (RZT)

2.2.1 Definition of root zone temperature

Root zone temperature is self-explanatory, referring to the temperature in the area of the roots [11]. The soil or growth medium is not only a substrate whose purpose is to support and stabilize plants and act as a reservoir for water and nutrients, but also a living entity [12]. Pianta [12] explained that three main aspects of soil or growth medium, namely biological, physical and chemical, were directly affected by root zone temperature in different ways. He also claimed that if root zone environments were maintained consistently in the comfort zone, plants became more photosynthetically efficient and stress free. For instance, with proper root zone temperature management, tropical plants can be cultivated at 7 ℃ ambient air temperature in combination with a root zone temperature of 21℃ [13].

2.2.2 The importance of root zone temperature

It has been reported that root zone temperature was an important factor in plant growth from germination and emergence through vegetative growth to floral initiation and reproductive growth [14]. Jaworski and Valli [15] found a close relationship between tomato seed germination and soil temperature. They concluded that low root zone temperature resulted in delayed germination and in reduced germination percentages. Moreover, the optimal temperature varies for the growth of different plant organs and for different developmental stages of the same plant organ [16]. Brouwer [17] conducted experiments on peas and discovered that 24 ℃ was a favourable root zone temperature for the earliest growth stage, while 17℃ was the root zone temperature at which optimum roots development occurred for the later stage. Brouwer [17] also claimed that a root zone temperature of 10℃ resulted in the highest dry weight yields. Eguchi et al. [18] studied the influence of RZT on potatoes and found that the optimum root zone temperature dropped from 27℃ to 21℃ over the time span of the grow season.

Optimum root zone temperatures are also species specific [16]. Many examples can be found in previous studies, for instance, for poinsettia, the optimum root zone temperature is around 25℃, while it is approximately 13℃ for roses [16]. David [19] conducted a series of experiments to determine the optimum temperature for cool and warm season crops (See Table 1).

Temperature for:	**Cool Season:** broccoli, cabbage, cauliflower	**Warm Season:** tomatoes, peppers, squash, melons
Germination	4℃ to 32℃; 27℃ optimum	10℃ to 38℃; 27℃ optimum
Growth	Daytime ❖ 18℃ to 27℃ preferred ❖ 4℃ minimum Nighttime ❖ > 0℃, tender transplants ❖ > mid-20s ℃, established plants	Daytime ❖ 30℃ optimum ❖ 16℃ minimum ❖ A week below 13℃ will stunt plant, reducing yields Nighttime ❖ > 0℃
Flowering	❖ Temperature extremes lead to bolting and buttoning.	Daytime ❖ 35℃ by 10 a.m., blossoms abort Nighttime ❖ < 13℃, non-viable pollen (use blossom set hormones)
Soil	❖ Use organic mulch to cool soil ❖ Since seeds germinate best in warm soils, use transplants for spring planting, and direct seeding for mid-summer plantings (fall harvest)	❖ Use black plastic mulch to warm soil, increasing yields and earliness of crop

Table 1: Temperature comparison of cool season and warm season crops [19]

An extensive growth analysis has shown that root zone temperature is more critical than leaf temperature [20]. The main reason why root zone temperature is important to plants is that RZT has an ability of adjusting the rate of physiological processes, such as water and minerals uptake, leaf growth and metabolite concentrations. More specifically, Falah et al. [21] observed the response of tomato root uptake to high temperature and concluded that the long term effects of high solution temperature led to reduced oxygen solubility and the increased enzymatic oxidization of phenolic compounds in root epidermal and cortex tissues, while the short term effects of high solution temperature resulted in the increase of water and nutrients uptake and affected membrane transport. Compared to high root zone temperature, Kramer [22] reported that low RZT inhibited water uptake and transpiration due to the increase of stomatal resistance, which agrees with the conclusion of Diczbalis and Menzel [23].

Phosphorus, as one of the three main nutrients required by plants, plays a crucial role in plant yield. Several studies have examined the relationship between RZT and phosphorus levels. Lingle et al. [24] discovered that lower root zone temperature with increased levels of phosphorus resulted in larger percent increase of weight in tomato growth, which was confirmed by Locascio et al. [25] and Cannell et al. [10]. Bruton et al. [26] and BassiriRad [27] went further, and concluded that the rate of root respiration and ion uptake was influenced by root zone temperature if other growth factors remained optimum.

2.3 The Controversy of the RZT Effects on Tomato Plants

As indicated earlier, a number of papers related to root zone temperature effects have been published. However, the information regarding the root zone temperature effect on tomato plants is paradoxical.

2.3.1 In favour of the effect of RZT on tomato plants

The relationship between tomato seed germination and root zone temperature has been studied by Jaworski and Valli [15], who concluded that low root zone temperature resulted in delayed germination and reduced germination percentages of tomato plants. Adebooye et al. [14] also reported that high root zone temperature speeded up tomato emergence. Moreover, root zone temperature has a remarkable effect on the plant growth of tomatoes. Moorby and Graves [9] reported that an increase in the root temperature of tomatoes from 25 - 30 ℃ always generated an increase in the growth rate, leaf area, total dry matter production and absorption of nitrogen, phosphorus and potassium. Abd el Rahman et al. [28] grew tomato plants for four weeks at a constant air temperature of 25℃ combined with different root zone temperatures of 16.8, 20, 25.3 and 29.9℃. They discovered that the highest rate of plant growth and transpiration occurred at the highest root temperature by measuring transpiration and a vast number of plant parameters. However, they also found that root growth was only slightly affected by root zone temperature. Jaworski and Valli [15] published a series of data to verify the effect of RZT on plant height and dry weight of shoots (Table 2). Furthermore, it was observed by Nkansah and Tadashi [29] that root zone temperature impacts tomato plants yield. Jones et al. [30] and Sandwell [31] reported that root zone temperature increased tomato yield, especially under low night air temperatures (9℃). Gosselin and Trudel [32] observed that maximum tomato yields were achieved with a combination of 18 ℃ night air temperature and 24 ℃ root zone temperature.

Root Temperature (℃)	13	18	24	29	35
Plant Height (inches)	1.7	3.5	3.5	6.0	5.1
Dry Weight (mg)	41	335	435	995	777

Table 2: Tomato plant height and dry weight affected by root zone temperature [15]

2.3.2 Against the effect of RZT on tomato plants

As mentioned in section 2.1, Went [5] claimed that when other growth conditions were optimal, root zone temperature did not impact tomato plants growth. In contrast to the results provided by Moorby and Graves [9] and Abd el Rahman et al. [28] mentioned above, Cooper [33] reported that the main effect of root zone temperature was only observed during the first two weeks after emergence. After that, the tomato growth curves for the different root zone temperatures were almost parallel. Fujishige and Sugiyama [34] grew young tomato, cucumber and sweet pepper plants at root zone temperatures between 10°C and 35°C for ten days. They found that the effect of root temperature was relatively small at lower ambient air temperatures. Compared to the observation of Jones et al. [30], Sandwell [31] and Gosselin and Trudel [32], Canham [35] found that yields were almost the same if the plants were cultivated at high air and low root temperatures, compared to the plants raised at low air and high root temperatures, and the latter ones requires less energy. Harssema [3] grew tomatoes at a constant root temperature in a greenhouse throughout the whole year. He discovered that the influence of root zone temperature on yield was relatively small.

2.4 Bench-top Heating System

2.4.1 Root zone temperature control systems

In a greenhouse, ambient temperature can be regulated by many means. However, altering root zone temperature is more difficult. Several root zone temperature control systems have been developed. Ingram et al. [36] designed an electronic root system with a thermistor feedback mechanism which allows operators to adjust the root zone temperature accurately. However, the defect of this system was the lack of its cooling ability. The bench-top heating method is another solution to this problem. This method delivers heat directly to the growth medium, to obtain an optimum root temperature, rather than warming up the ambient air temperature of the greenhouse. A conventional bench-top heating system consists of plastic tubes, a pump, a water heater and temperature sensors. Hot water is distributed through plastic tubes arrayed in continuous loops fixed to the benches, as illustrated in Figure 2.

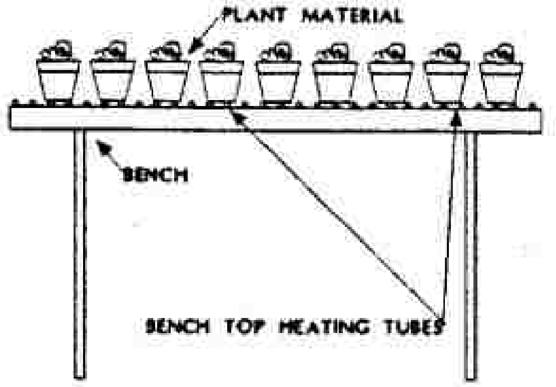


Figure 2: Conventional bench-top heating method [37]

2.4.2 Advantages of bench-top heating method

The benefits of the bench-top heating method have been well documented. The major advantage of bench-top heating is energy conservation, while achieving optimum plant growth at the same time. Jenkins et al. [38] conducted an experiment in a commercial greenhouse to compare two types of heating systems: bench-top heating system and perimeter heating system. They found that the bench-top system consumed at least 25% less energy compared to the perimeter heating system. Sachs [39] reported that greenhouse ambient temperature could be reduced by 10℃ if an optimum root zone temperature could be maintained. The reduction of ambient temperature leads to less temperature difference between the inside sidewalls of the greenhouse and outside, which reduces considerable energy consumption. Moreover, in order to achieve the optimum root temperature, it is more economical to heat the root zone directly due to less demands of fuel instead of heating the soil by heating the air [16]. However, one important observation is that a bench-top heating system is not able to provide all the heat required by the greenhouse and results in non-uniform temperature distribution in the canopy [39].

2.5 Objectives

Many experiments on the effect of root zone temperature on plant growth have been conducted. However, the information regarding the root zone temperature on tomato plants is inconsistent. Particularly, the influence of root zone temperature on tomato yield has not been clearly verified. Furthermore, data on bench-top heating is sparse, especially on the type utilizing a rectangular plastic duct to transport the heated water. The overall objectives of this research are to analyze the RZT effectiveness and develop simple mathematical models to describe the system behaviour. In order to achieve these objectives, this thesis will address the following:

1) Conduct an appropriate set of experiments to collect data on RZT in a full-scale greenhouse environment.
2) Devise a methodology to extract and analyze the key information from the vast amount of experimental data collected.
3) Use the information to assess the effectiveness of bench-top heating, specifically with respect to the relationship between RZT and tomato yield.
4) Develop a simplified mathematical model of the bench-top heating system.

CHAPTER 3

EXPERIMENTAL SETUP

3.1 Introduction

In the literature review, the relationship between the root zone temperature and tomato yield was presented, although there is some disagreement among researchers as to the magnitude of the effect. Additionally, the need for analysis of this new type of bench-top heating method was demonstrated. The information that would be most useful to growers should be obtained from experiments conducted in a commercial greenhouse. Many environmental factors (e.g., air temperature, irrigation, CO_2 and humidity) can be regulated in a commercial greenhouse. However, sun radiation cannot be fully controlled, and the above-mentioned factors vary day by day. Under these conditions, it is difficult to reproduce the results in general. Much more effort, therefore, must be devoted to data sampling of root zone temperature and the analysis of the results.

3.2 Experimental Layout

As mentioned before, a traditional bench-top heating system is comprised of a water heater, a pump, a flow meter, and piping system. EPDM tubes or PVC round pipes are usually placed in parallel on the top surface of the benches (see Figure 2). In contrast to conventional methods, a new type of bench-top heating method with a rectangular plastic duct replacing the pipes, as seen in Figure 3, was tested in this experiment. Since the rectangular plastic duct has a larger surface area in contact with the growth medium, it is expected to enhance the heat transfer between the flowing heated water in the duct and the growth medium.

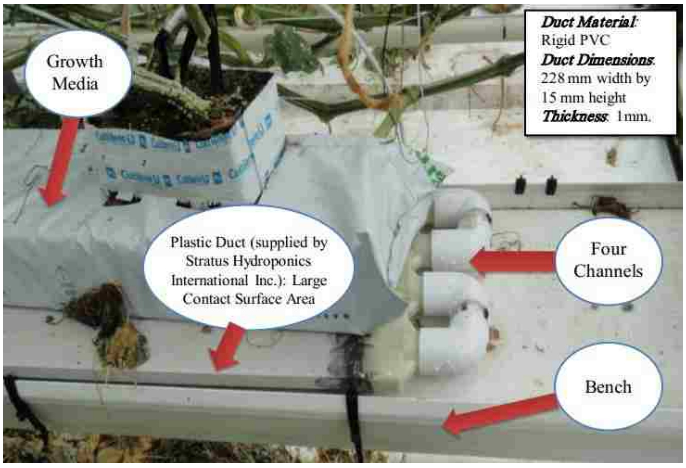


Figure 3: Rectangular plastic duct system

Three bench rows of young tomato plants were cultivated in a large commercial greenhouse in Southwestern Ontario, from February to October, 2012, each row measuring 76 m in length. As demonstrated in Figure 4, for the first two rows, i.e. the feed (F) and return (R) lines, hot water was pumped through plastic ducts arrayed in a continuous loop under the growth medium and fixed to the benches. The third row was set up as a control (C) line without utilizing any bench-top methods. The purpose of this row was to provide comparative data for analysis of the temperature measured in the two experimental lines. Root zone temperature, water temperature, ambient temperature and flow rate were continuously measured, while plants were regularly harvested.

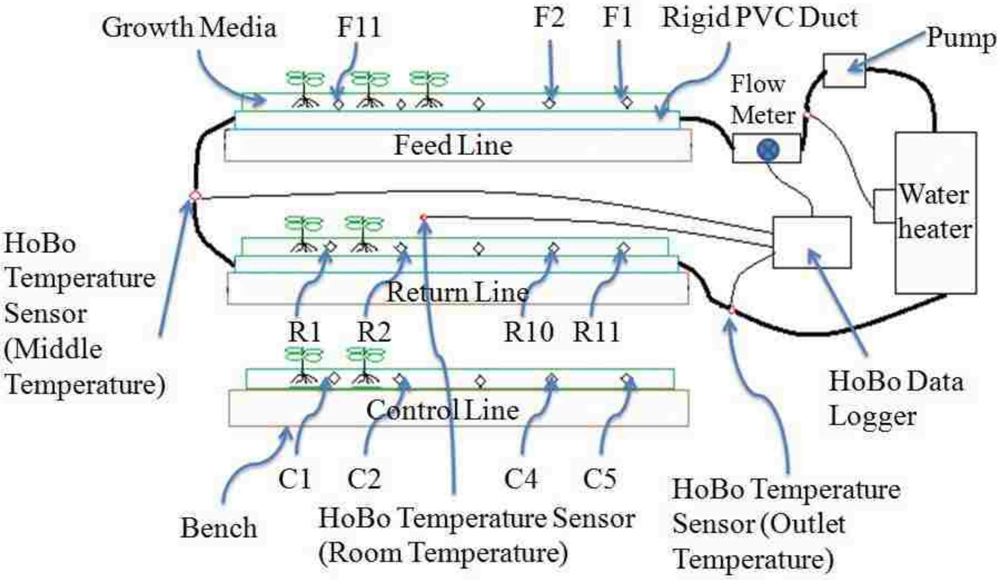


Figure 4: Experimental layout

3.3 Rectangular Rigid PVC Duct

The rectangular duct with four flow channels employed in the experiment is made of rigid PVC (see Figure 3). The dimensions of the duct cross-section were 228 mm width by 15 mm height, with walls having 1 mm thickness. Nylon fittings were used to connect several pieces of ducts together to fit the length of the row (76 m).

3.4 Experimental Equipment

3.4.1 iButton temperature sensors

Temperatures were measured by two types of sensors. Root zone temperatures were recorded using calibrated iButtons (Model DS 1922L [40]) which were fixed onto aluminum handles, as shown in Figure 5, a computer chip enclosed in a 16 mm thick stainless steel casing containing a temperature sensor, memory and battery [41]. The dimensions of the iButton sensor are illustrated in Figure 6. This device provides temperature measurements in the range from -40℃ to +85℃ with 0.5℃ resolution and a manufacturer's stated accuracy of ±1℃ [41]. Each iButton temperature sensor is lasered with a unique 64-bit registration number which ensures its traceability (see Figure 7) [41]. A total of twenty-seven iButton sensors were inserted into the mid-section of the growth medium to measure and record the root zone temperature (see Figure 4 and Figure 8). Eleven iButtons were used for each of the feed and return lines (F1 to F11 and R1 to R11, respectively), and five were inserted in the control line (C1 to C5). The sampling interval was set to take data every half-hour. A one-wire device was used to download the iButton data to a computer for analysis (see Figure 9).

Figure 5: An iButton sensor fixed on an aluminum plate

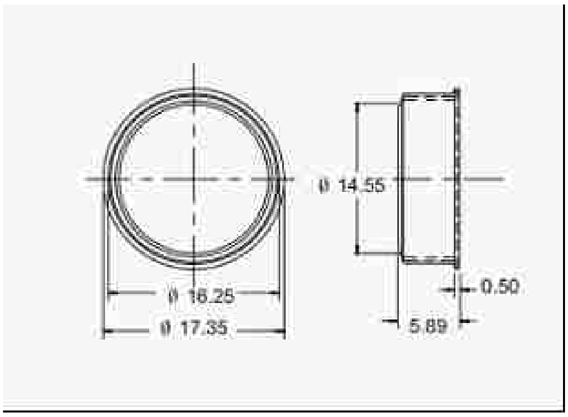


Figure 6: The dimensions (mm) of DS 1922L [41]

Figure 7: Unique 64-bit registration number [41]

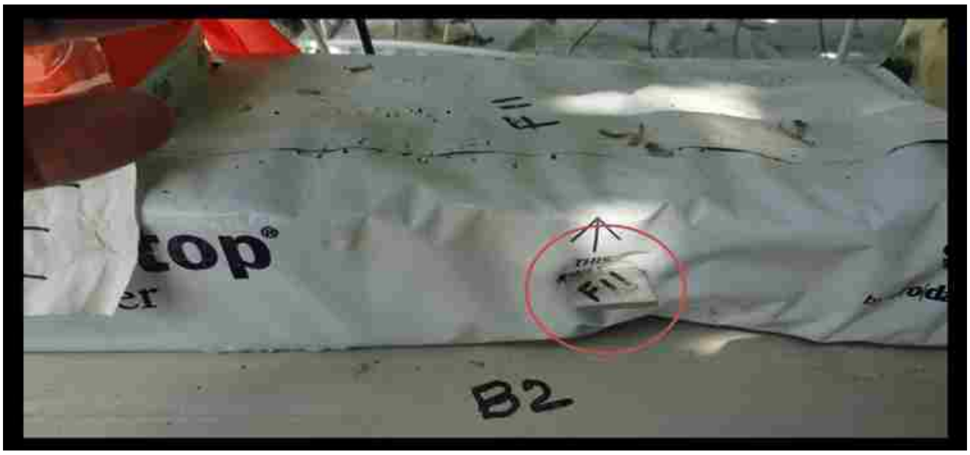


Figure 8: An iButton sensor inserted into the mid-section of the growth medium

Figure 9: One-wire device

3.4.2 Hobo system

Three Hobo temperature sensors (S-TMB-M0XX) and one pulsed adapter were hooked up to a Hobo data logger (see Figure 10) to measure the water temperature at the end of the feed line, the outlet temperature (at end of return line), the ambient room temperature and the flow rate, as illustrated in Figure 4. The Hobo temperature smart sensor shown in Figure 11 offers temperature measurements in the range from -40°C to 100°C at sensor tip [42]. Resolution is at less than 0.03°C and accuracy is at less than ±0.2°C, when the Hobo temperature sensor operates at temperatures from 0°C to 50°C [41]. The sampling rate of the data logger was also set at half an hour. For inlet temperature, a feedback control system was used, consisting of an electronic device which connected a temperature sensor with the water heater in order to maintain the inlet water temperature in a specified range from 21°C to 23°C. This range of temperature was chosen since 18-25°C is considered to be optimal for tomato plants.

Figure 10: Hobo data logger

Figure 11: Hobo temperature smart sensor

CHAPTER 4

RESULTS

4.1 Root Zone Temperature

4.1.1 Heat loss over the length of the duct system

As mentioned in the previous chapter, experiments were carried out utilizing the bench-top heating method with rectangular plastic duct in a commercial greenhouse to examine its performance and investigate the impact of root zone temperature on yield of tomato plants. However, quantification of root zone temperature effects is difficult in a greenhouse where changes in air temperature and the radiation load make accurate control of the growth medium temperature challenging [43]. Therefore, before proceeding to analyze the data to determine the effect of the hot water flowing through the duct under the growth medium, it was important to establish whether there was any significant heat loss over the length of the duct system.

Figure 12 illustrates the root zone temperature measurements along the control line at 10:30 AM on March 25 and 2:30 AM on March 26, as well as the ambient greenhouse temperature at these times. At 10:30 AM, when the ambient temperature was 20.2°C, the root zone temperature in most sections along the entire length of the control line was below the ambient temperature, varying from 19.2°C to 20.6°C. At 2:30 AM on the following day, the ambient temperature dropped to 16.3°C, the root zone temperatures along the row fluctuated from 16.2°C to 18.1°C. As a comparison, Figure 13 illustrates the root zone temperature measurements along the duct with bench-top heating treatment taken at the same time as in Figure 12. At 10:30 AM, when the ambient temperature was 20.2°C, the root zone maintained temperatures from 20.1°C to 21.2°C along the entire length of duct, i.e., from sensors F1 to R11. By 2:30 AM the ambient temperature had dropped to 16.3°C, while the root zone temperature varied between 18.2°C and 20.7°C.

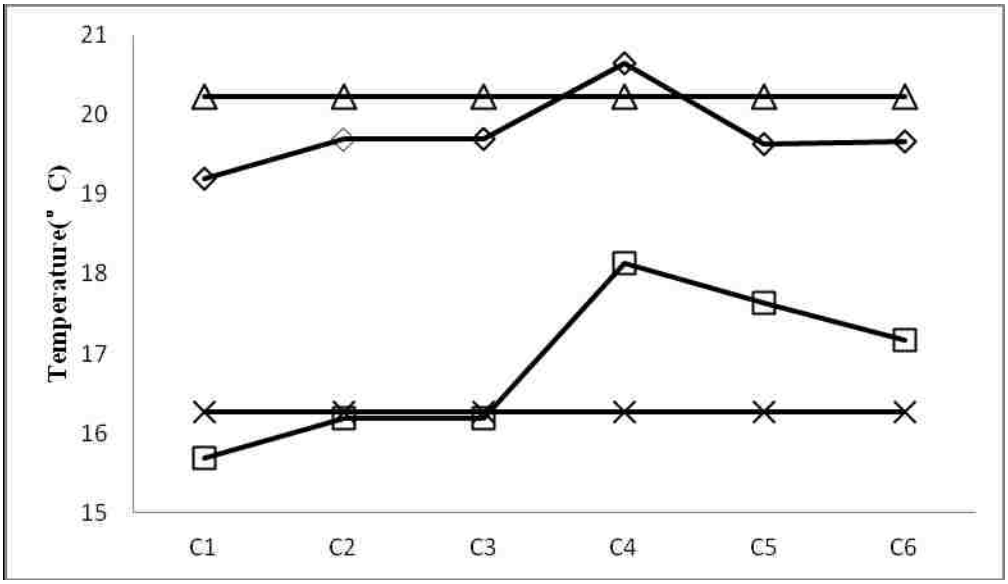


Figure 12: Temperature distribution along the control line
(ambient: 10:30 AM - Δ, 2:30 AM - x; root zone: 10:30 AM - ◊, 2:30 AM - □)

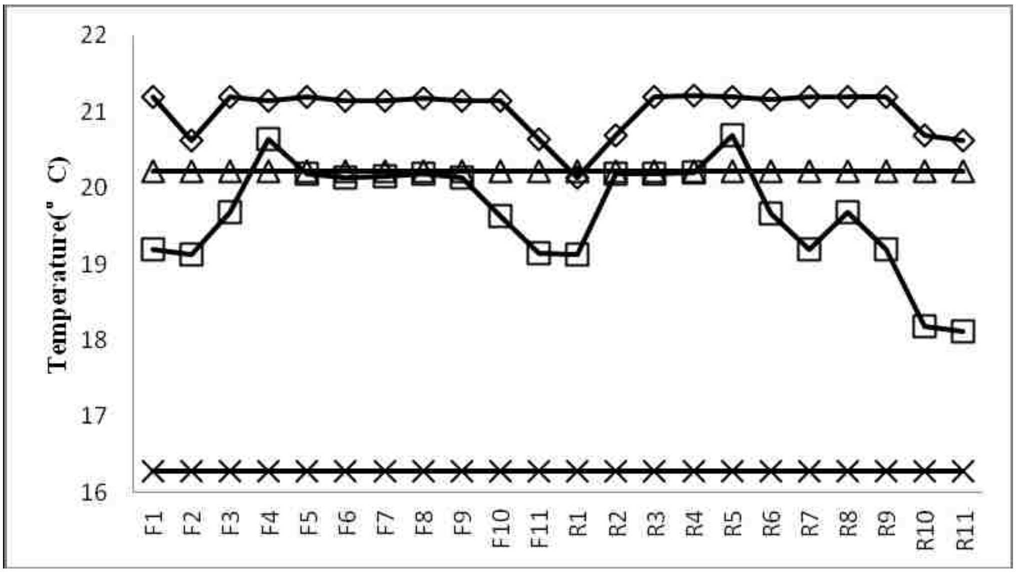


Figure 13: Temperature distribution along the feed (F) and return (R) lines
(ambient: 10:30 AM - Δ, 2:30 AM - x; root zone: 10:30 AM - ◊, 2:30 AM - □)

These two figures illustrate two important features of the bench-top heating system. Firstly, the maximum temperature difference from one end of the line (F1) to the other (R11) is only about 2.5°C, establishing that there is little heat loss along the length of the duct. Secondly, the system is able to maintain the root zone temperature in the optimal range even when the ambient temperature falls below the minimum desirable temperature. This could have significant implications for energy conservation and reduction of operating costs.

March 27 was a typical day. Further evidence which is representative of the temperature distribution along the two different lines on other days through different time periods are shown in Appendix A.

4.1.2 Root zone temperatures in a 24-hr period

4.1.2.1 Root zone temperatures comparison at two locations

Having established that the root zone temperature remains at an acceptable level irrespective of the location along the line, data from the center of the feed (F6) and control (C3) lines were selected for further analysis. Figure 14 illustrates the variation of the root zone temperature and the ambient room temperature over a single day (March 22) at the locations F6 and C3. It is clear from the results that there is always a time lag between the changes in the ambient temperature and root zone temperature. This observation agrees with the conclusion of Abd el Rahman et al. [28] who reported that with fluctuating day and night temperatures, even in relatively small containers, the root temperature lags behind air temperature considerably. Moreover, the spike in the ambient temperature occurring in the early afternoon is not felt so dramatically in the root zone, which is true even without the bench-top heating. However, the non-heated line (C3) experiences a small dip in temperature to about 17.5°C from midnight until 8:00 AM, while the heated line (F6) maintains a temperature above 19.6°C over the entire 24-hr cycle. This is one of the important advantages of root zone heating, since the greenhouse operator can allow the ambient temperature to drop while still maintaining the desired temperature in the root zone.

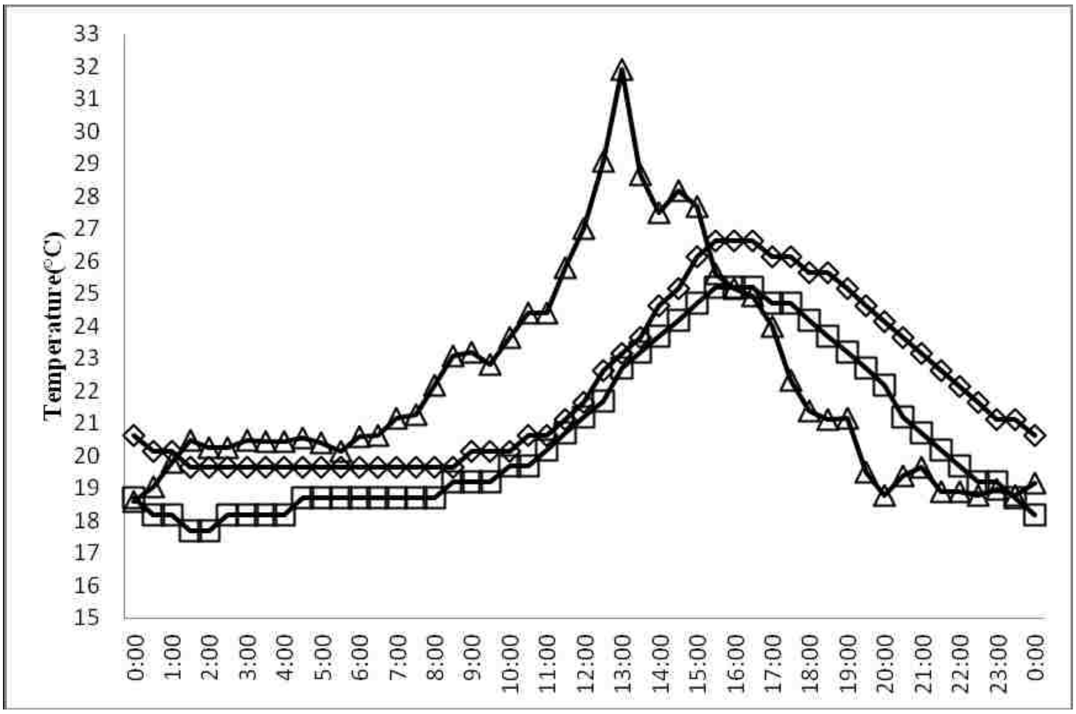


Figure 14: Daily (Mar. 22) temperature at sensors F6 and C3
(ambient: Δ; root zone: F6-◊, C3-□)

This feature is even more prominent in the data collected on April 22, as shown in Figure 15. (One should note that 2012 was somewhat unusual in that many days in April were colder than in March.) On April 22, the ambient temperature varied from 11.3°C to 17.1°C while the root zone temperature in the control line (C3) dipped to a minimum of 15.2°C at 4:00 AM and remained below 18°C until 9:00 AM. On the other hand, the heated line (F6) maintained root zone temperatures between 18.1°C and 22.1°C throughout the 24-hr period. Additional information about daily temperatures at sensors F6 and C3 on different days is presented in Appendix B.

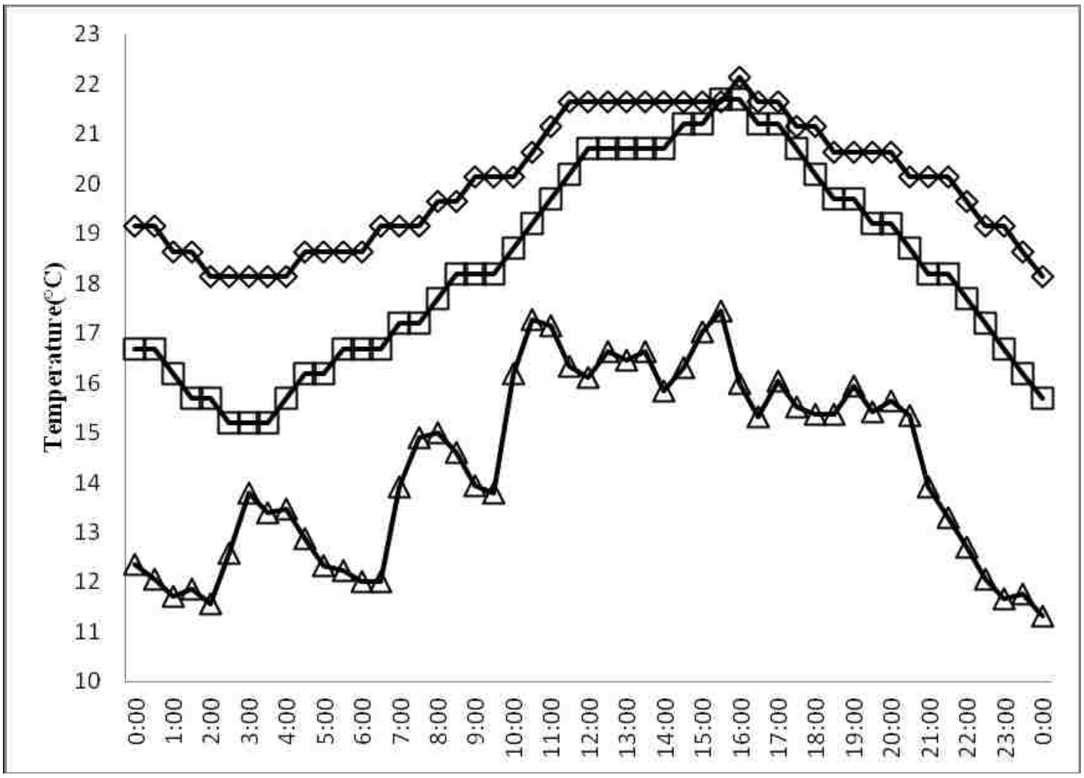


Figure 15: Daily (Apr. 22) temperature at sensors F6 and C3
(ambient: Δ; root zone: F6-◊, C3-□)

4.1.2.2 Root zone temperatures comparison over two lines

After comparing the root zone temperatures at the center of the two lines, data from the entire feed and control lines were chosen for inspecting the system performance. Temperatures at six points (a, b, c, d, e and f) on April 21 (see Figure 16) which has the lowest ambient room temperature during the whole month were selected to plot Figure 17 (a - f). Five points (a, b, c, d and e) are the turning points on the curve of ambient temperature. Point f represents the highest room temperature on April 21.

It is easy to ascertain that the root zone temperature of the experimental lines is consistently higher than the root zone temperature of the control line over the whole day. Especially, when the ambient temperature was lowest (approximately 10.7°C at 2:00 AM), the bench-top heating method maintained the root zone temperature of the experimental line at around 18°C, while the root zone temperature in the control line varied from 14.1°C to 17.1°C. This observation confirms our expectation that the bench-top heating system can hold the root zone temperature in the desired range of 18 - 25°C, which is considered to be optimal for tomato plants.

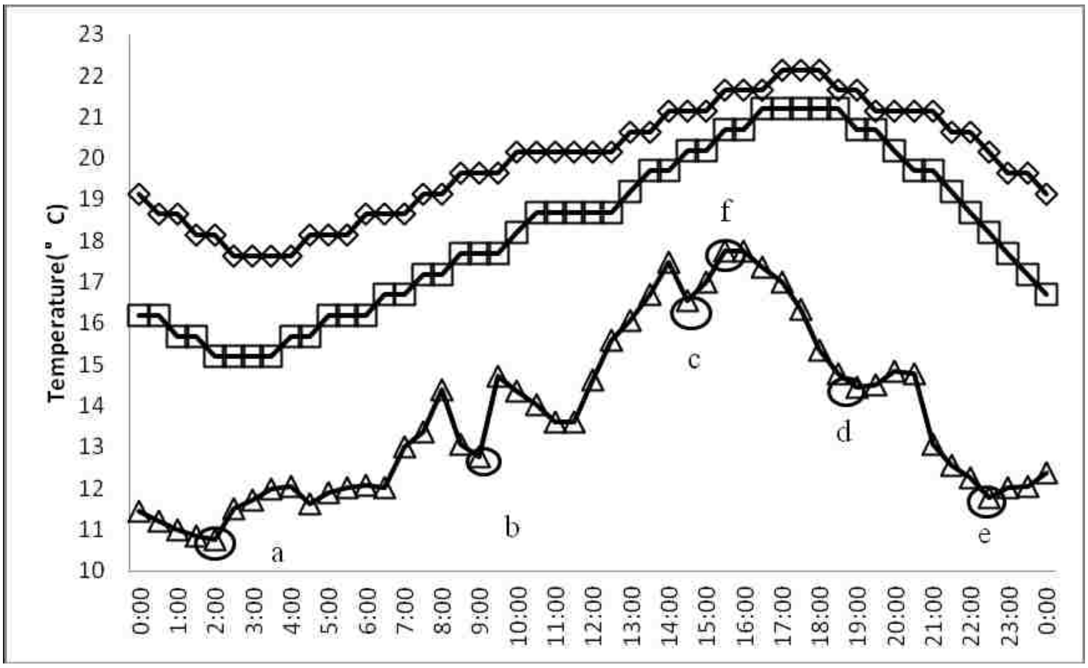
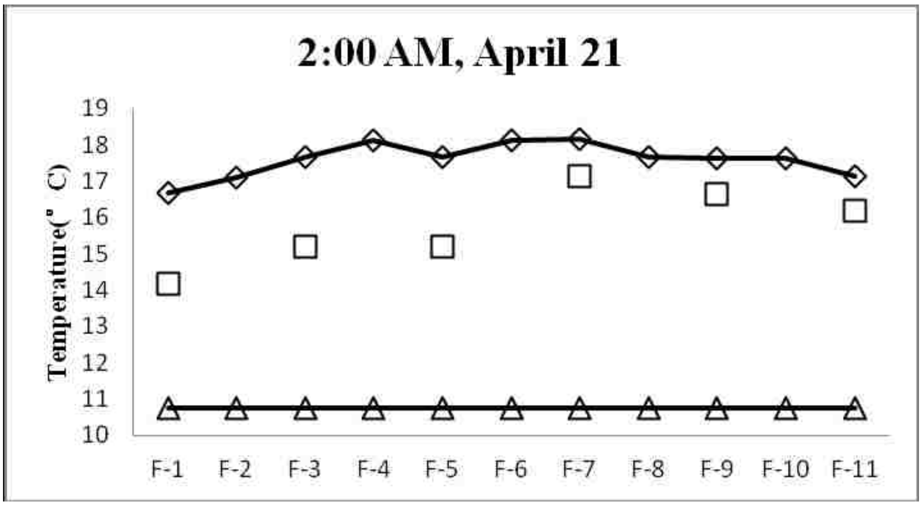
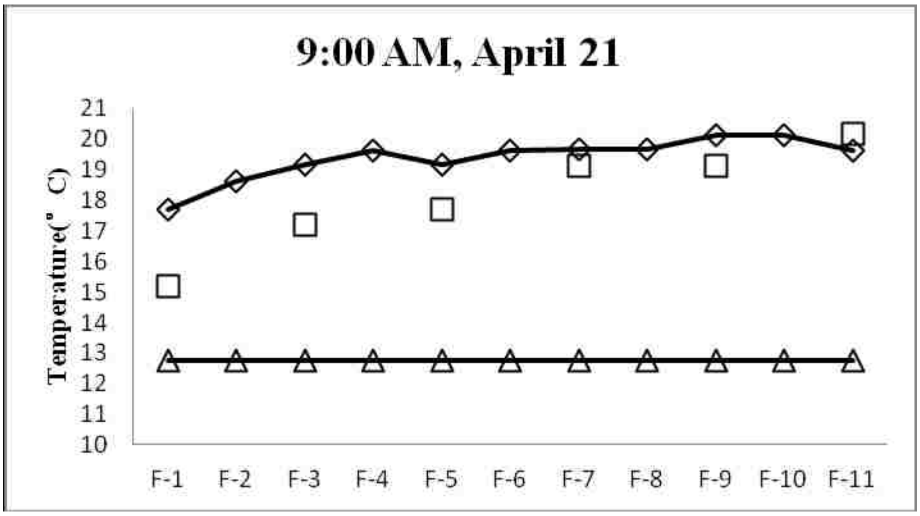


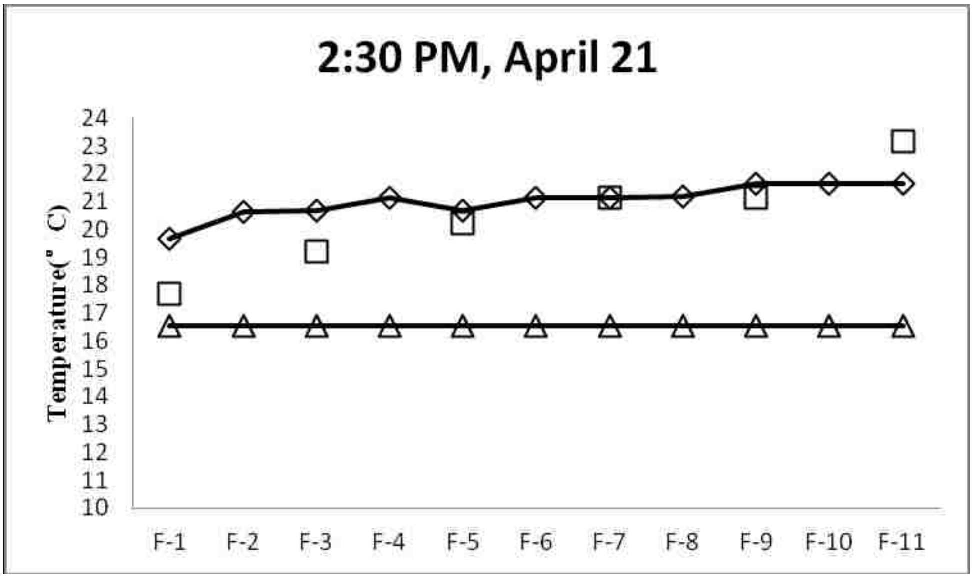
Figure 16: Daily (Apr. 21) temperature at sensors F6 and C3
(ambient: Δ; root zone: F6-◊, C3-□)



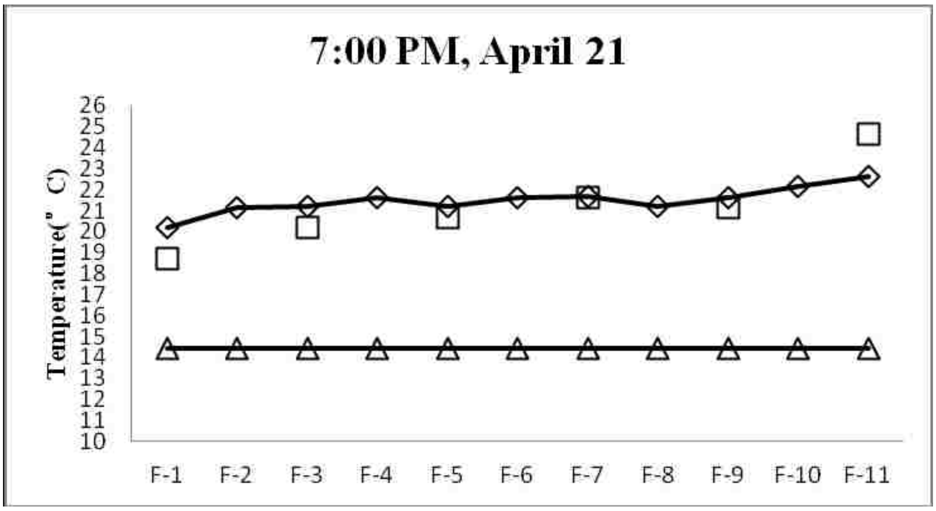
(a)


9:00 AM, April 21
Temperature(° C)
21
20
19
18
17
16
15
14
13
12
11
10
F-1
F-2
F-3
F-4
F-5
F-6
F-7
F-8
F-9
F-10
F-11

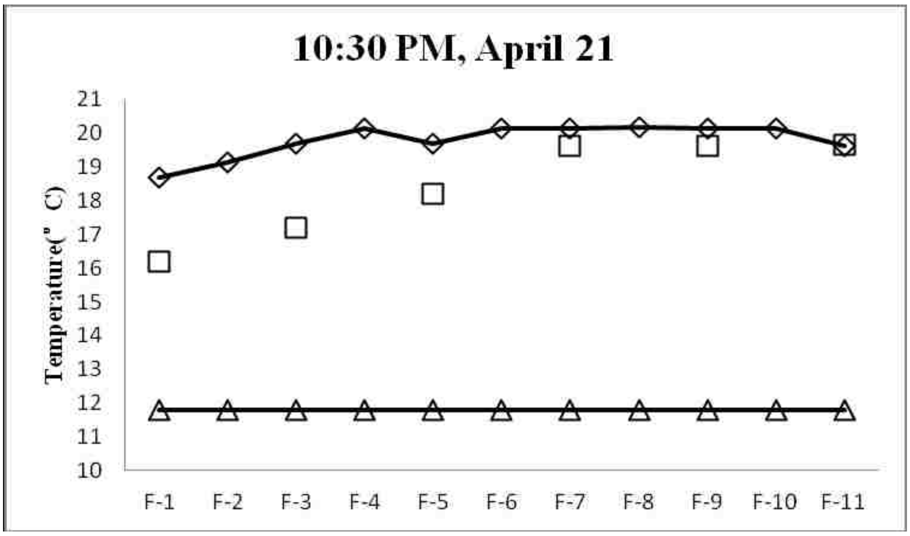
(b)


2:30 PM, April 21
Temperature(° C)
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
F-1
F-2
F-3
F-4
F-5
F-6
F-7
F-8
F-9
F-10
F-11

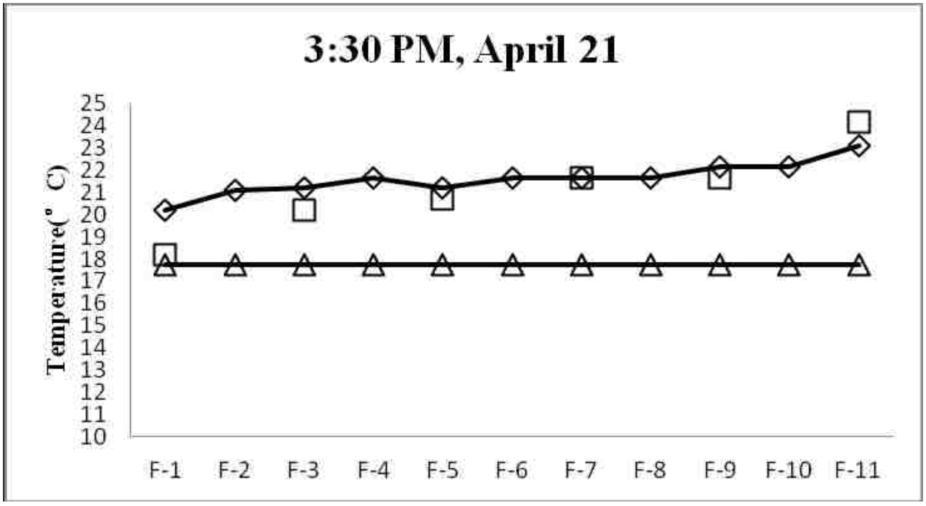
(c)


7:00 PM, April 21
Temperature(° C)
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
F-1
F-2
F-3
F-4
F-5
F-6
F-7
F-8
F-9
F-10
F-11

(d)



(e)



(f)

Figure 17: Temperature comparison at point a, b, c, d, e and f
(ambient: Δ; root zone: feed line-◊, control line-□)

In order to confirm this observation, data on March 27 was chosen to plot Figures 18 and 19. Figure 18 illustrates the variation of the root zone temperature and the ambient room temperature on March 27 at the locations F6 and C3. Same as in Figure 16, data at six points (A, B, C, D, E and F) were chosen to plot Figure 19 (A -F) to exam the root zone temperature distribution over the entire length.

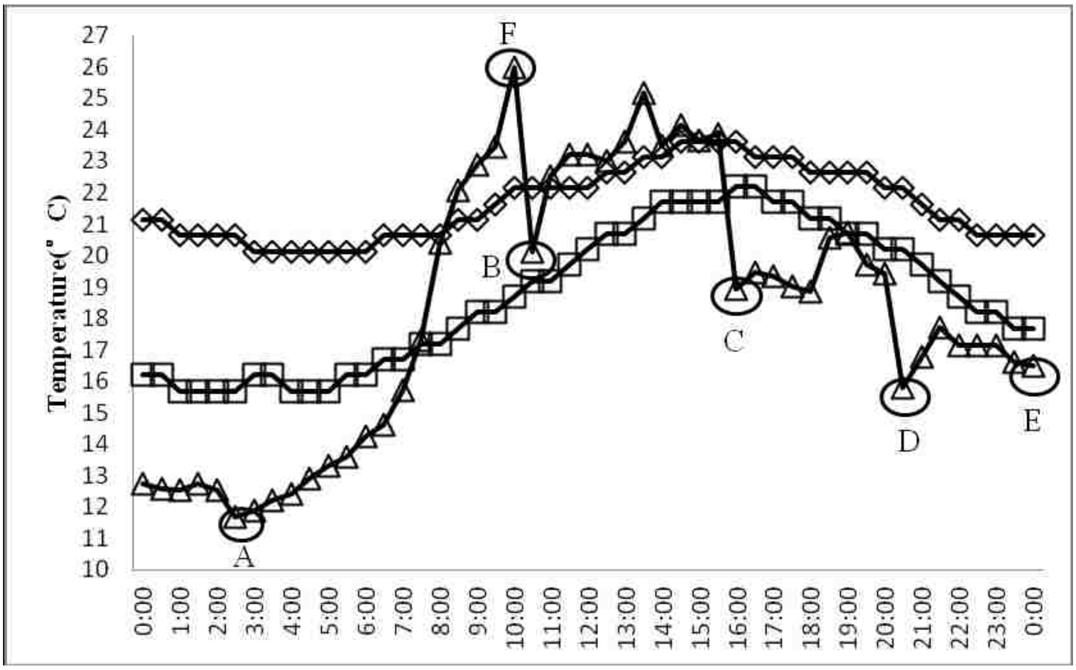
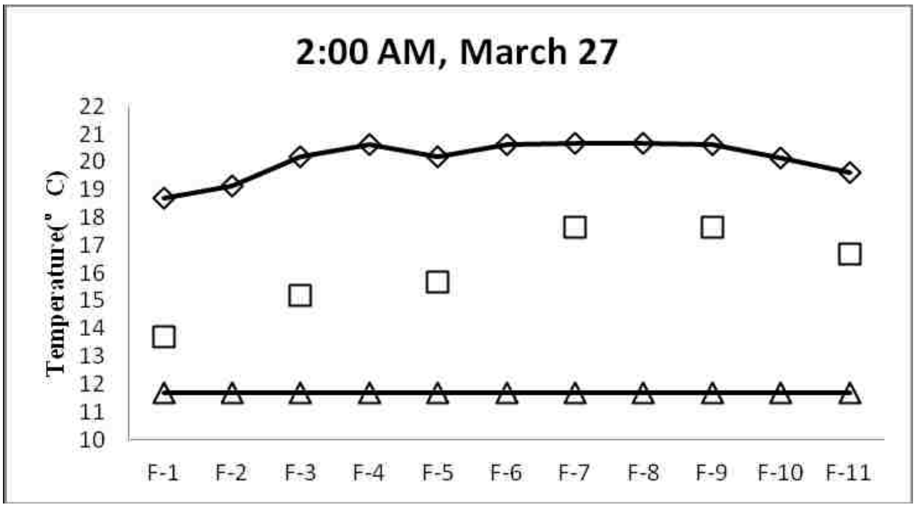
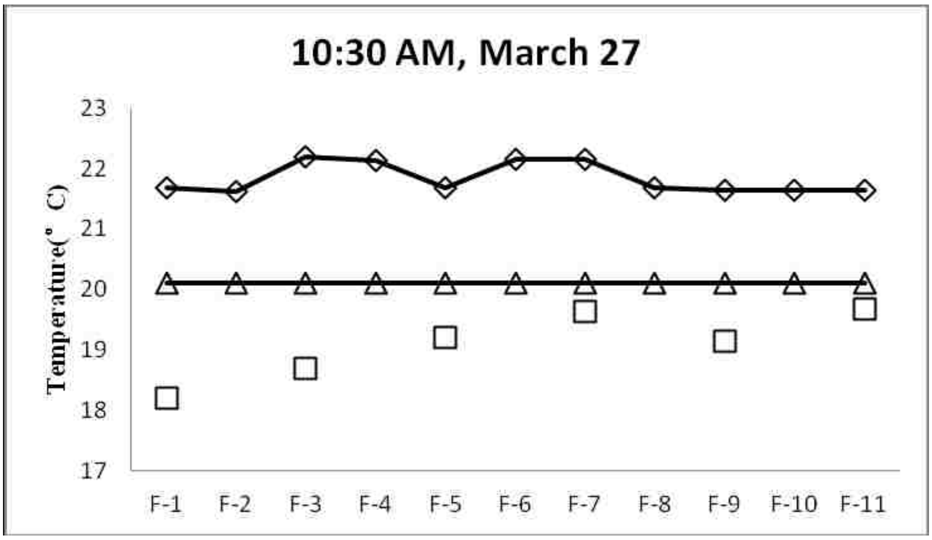


Figure 18: Daily (March 27) temperature at sensors F6 and C3
(ambient: Δ; root zone: F6-◊, C3-□)

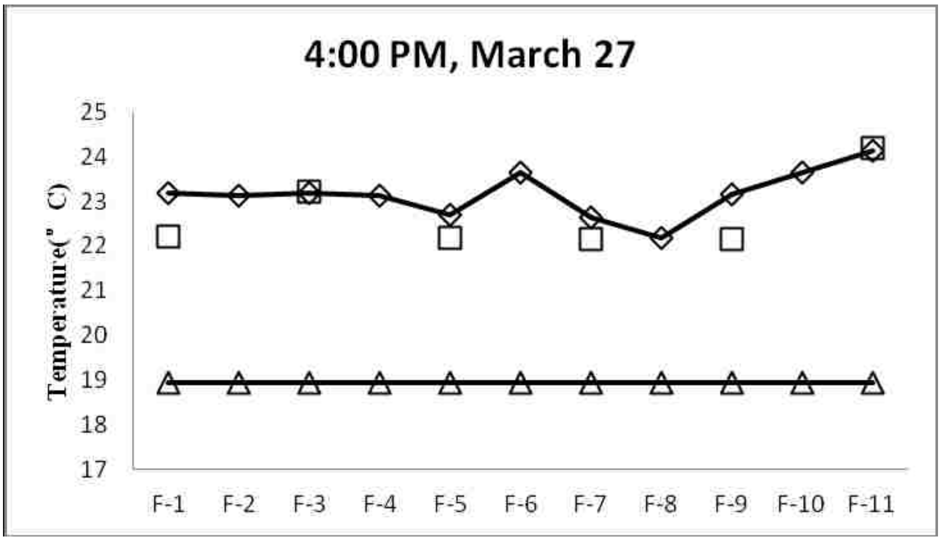
Again, it is easy to notice that root zone temperature of the experimental lines is consistently higher than the root zone temperature of the control line on March 27, which is consistent with the observation on April 21. Particularly, at 10:30 AM, when the root zone temperature of the control line was approximately 1°C lower than the ambient temperature, the root zone temperature of the experimental line was 2°C higher than the ambient temperature.



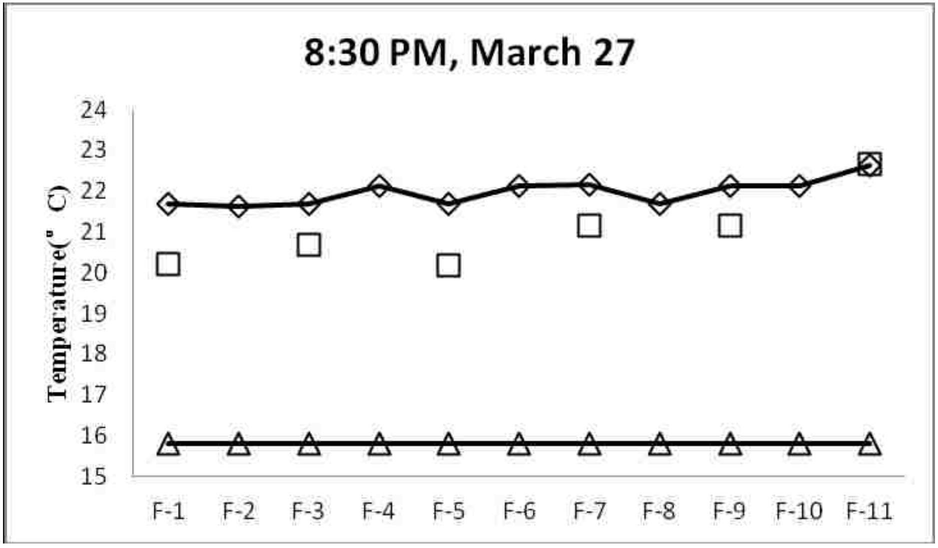
(A)


10:30 AM, March 27
Temperature(° C)
23
22
21
20
19
18
17
F-1
F-2
F-3
F-4
F-5
F-6
F-7
F-8
F-9
F-10
F-11

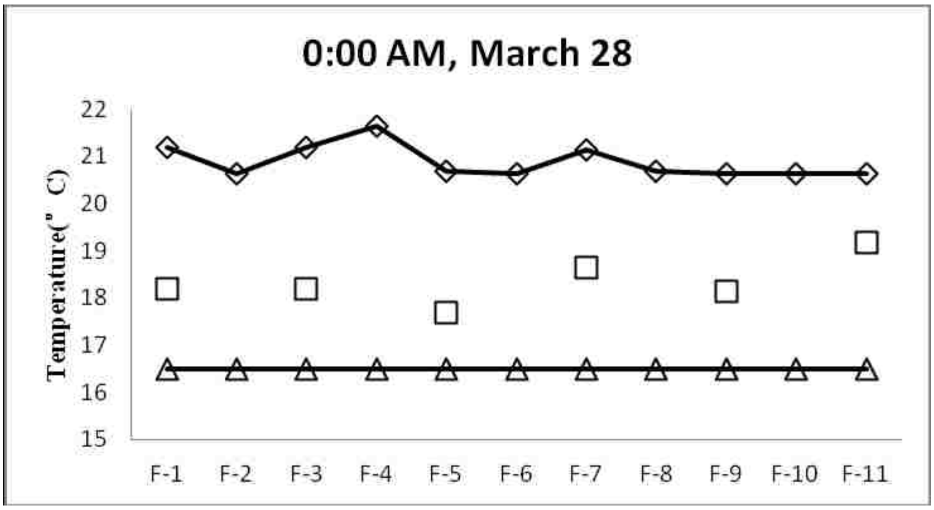
(B)


4:00 PM, March 27
Temperature(° C)
25
24
23
22
21
20
19
18
17
F-1
F-2
F-3
F-4
F-5
F-6
F-7
F-8
F-9
F-10
F-11

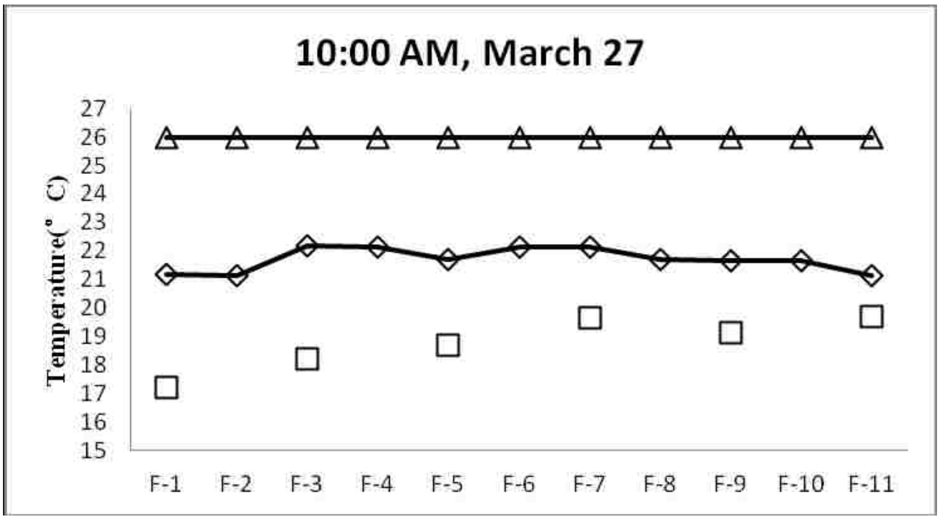
(C)


8:30 PM, March 27
Temperature(° C)
24
23
22
21
20
19
18
17
16
15
F-1
F-2
F-3
F-4
F-5
F-6
F-7
F-8
F-9
F-10
F-11

(D)



(E)



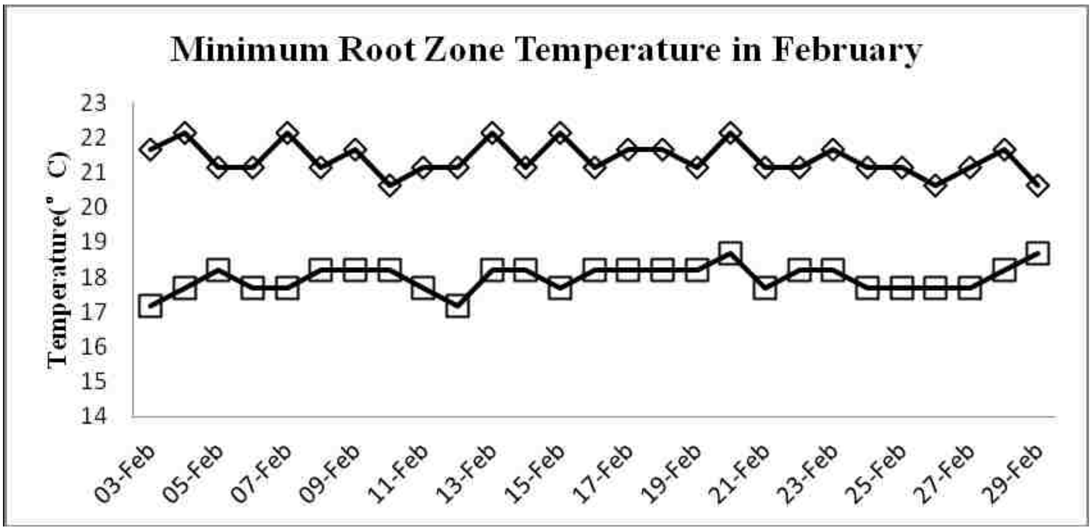
(F)

Figure 19: Temperature comparison at point A, B, C, D, E and F
(ambient: Δ; root zone: feed line-◊, control line-□)

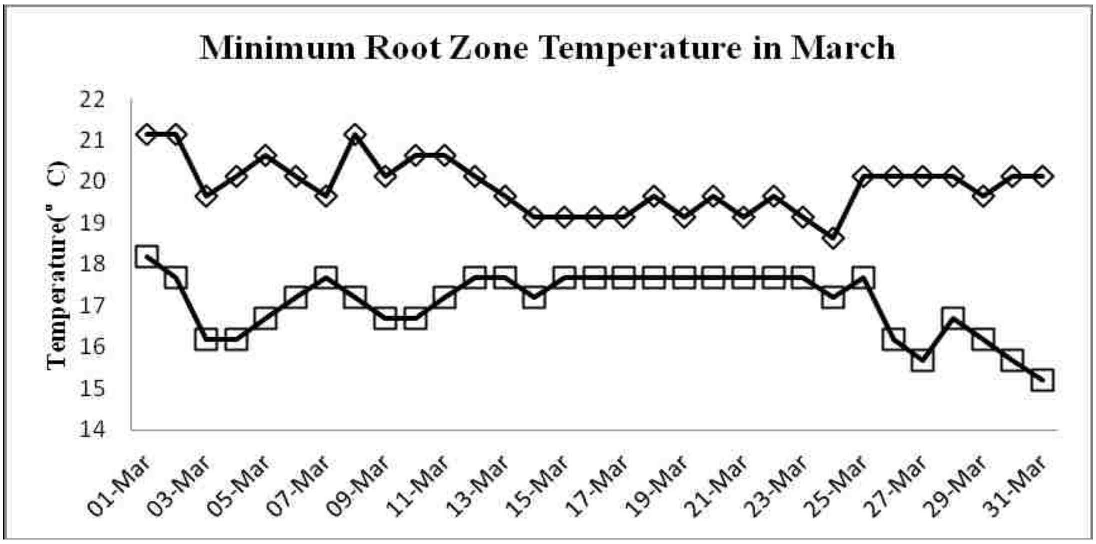
4.1.3 Comparison of extreme temperatures

Having compared the RZT differences between the heated line and the control line over one single day, it is useful to examine the performance of the new type of bench-top heating system over one month. Maximum and minimum RZT for each day over three months (February to April) from the center of the feed (F6) and control (C3) lines were selected.

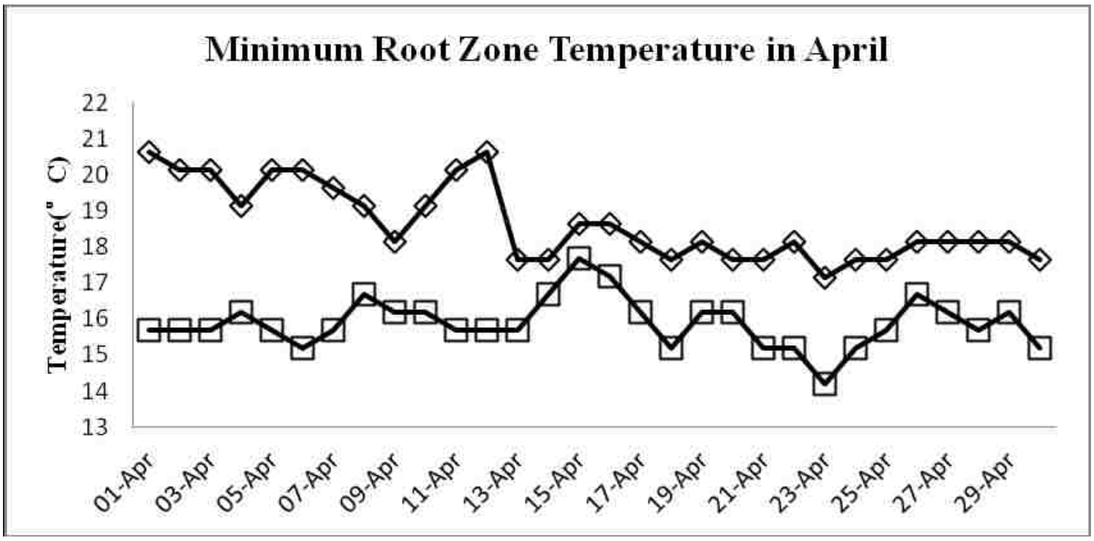
Figure 20 (a - c) presents the minimum RZT over every day from February, March and April, respectively. Figure 21 (A - C) illustrates the maximum root zone temperatures for each day in February, March and April, respectively. It is easy to observe that the minimum RZT of the heated line was consistently higher than the RZT of the control line every month. On March 31, when the minimum RZT of the control line dipped to 15.1°C, the RZT in the experimental line maintained at 20.1°C. In addition, it is important to point out that the minimum RZT of the heated line was maintained to be in the range from 18 to 22 °C over the entire three months. Furthermore, even though the maximum temperature change trend of the heated line followed the curve of the control line, the maximum RZT of the heated line was still higher than the maximum RZT of the control line. These observations provide strong evidence that utilizing this type of bench-top heating method gives the greenhouse operator the ability to decrease the ambient temperature without causing harm to plant production.



(a)

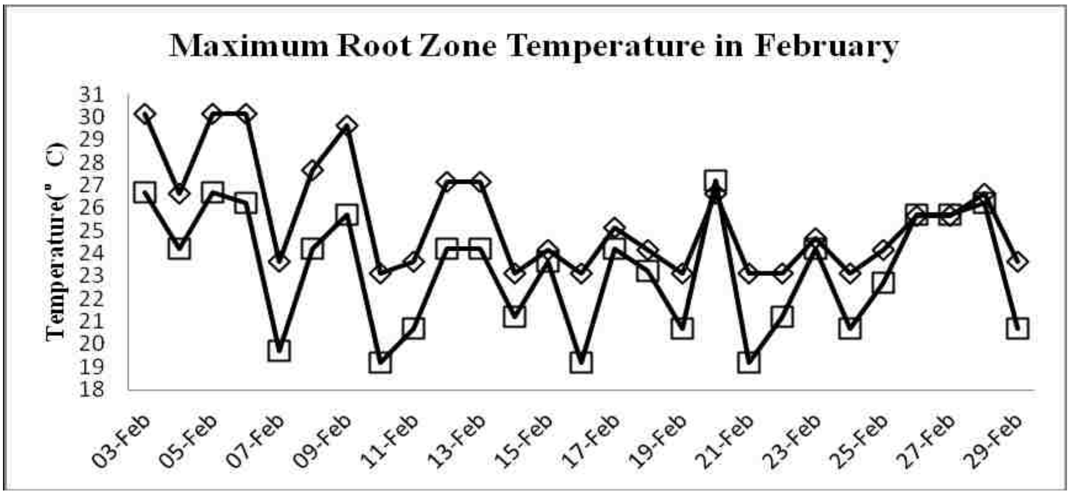


(b)

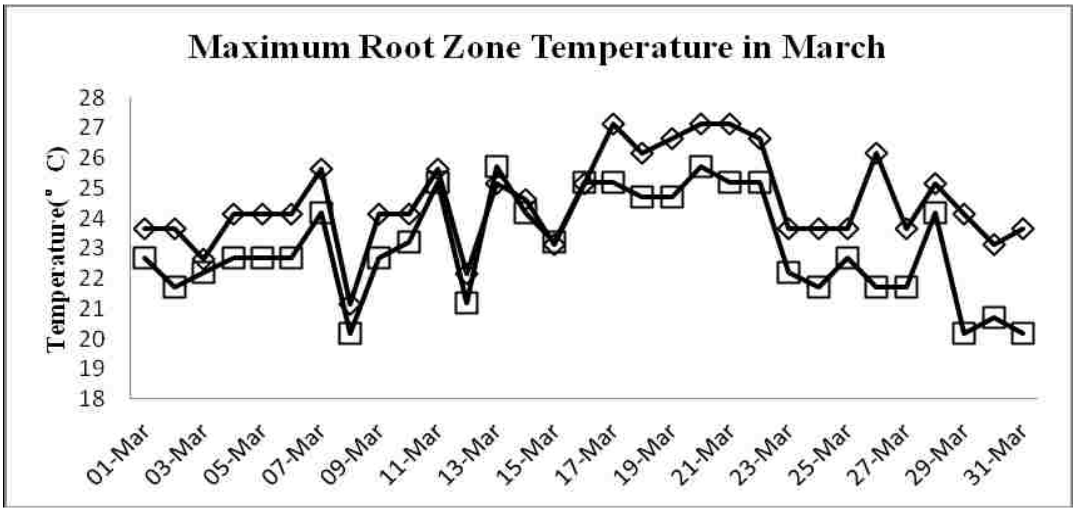


(c)

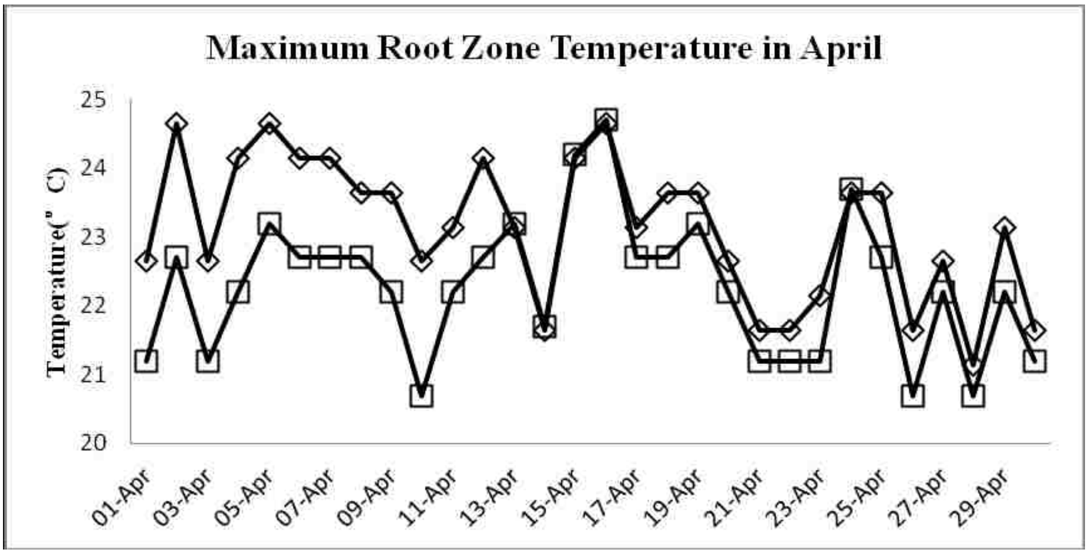
Figure 20: Min. temperature comparison in (a) February, (b) March, (c) April (root zone: F6-◊, C3-□)



(A)



(B)



(C)

Figure 21: Max. temperature comparison in (A) February, (B) March, (C) April (root zone: F6-◊, C3-□)

4.2 Yield and Other Parameters

Other than the root zone temperature, many other factors were regularly measured, e.g., water content (WC %), conductivity (EC) and PH. However, not much difference in these parameters was observed between the experimental lines and the control line.

Table 3 tabulates the total weight of tomato yield harvested over the growth period. The yield data indicated that there was no gain in total yield from this bench-top heating system. However, the production of tomatoes was accelerated by about one week, which means that the product is available for the market one week earlier. This supports Harssema's work [3] and Went's research [5] which may be an indication that the greenhouse in which our experiment was being conducted was operating at near optimal conditions.

	Feed Line	Return Line	Control Line
Total Weight (kg)	4,302	4,401	4,472

Table 3: Total weight of tomato yield

4.3 Additional Experiments

The results shown previously indicate that the root zone temperature management system appears to perform well in maintaining a temperature range most suitable to promote plant growth. Furthermore, the system was also shown to be effective in maintaining the required range throughout the length of the heated lines. However, the results did not indicate tomato yield efficacy for the greenhouse. To further investigate these concepts, additional experiments have commenced in a different greenhouse. Some preliminary results are presented in Appendix C.

CHAPTER 5

SIMPLE MATHEMATICAL MODELS

5.1 General Introduction to the CFD Model

Computational Fluid Dynamics (CFD) modeling can be an extremely valuable tool in the analysis of fluid flow and heat transfer. It is able to solve many problems without the huge amount of time and expensive investment required for experimental investigations. To more fully explore the key characteristics of the bench-top heating system using the PVC duct to transport heated water along the bench, a CFD model was developed using the commercial software ANSYS FLUENT [44]. A CFD model opens the possibility of investigating the impact of many parameters, such as flow rate, inlet temperature and geometry of the PVC rectangular duct, on the temperature in the growth medium. In the field or laboratory setting, changing any one of the above parameters in order to compare the heat transfer performance could be very costly and/or time consuming. A CFD model can be a great help for optimizing the design parameters for heat transfer performance.

For the purposes of this thesis, a CFD model was built to help assess the appropriateness of some of the assumptions made about the greenhouse environment. Figure 22 illustrates the schematic diagram of the PVC duct and growth medium. The dark block at the top represents the growth medium, while the lighter gray block at the bottom indicates the rectangular plastic duct. When setting up the model, several factors which affect the simulation need to be considered. For instance, one must decide whether the physical phenomenon can be captured in a two-dimensional (2D) simulation or if a three-dimensional (3D) model is required, whether the flow is steady or unsteady, what are the correct boundary conditions, etc.

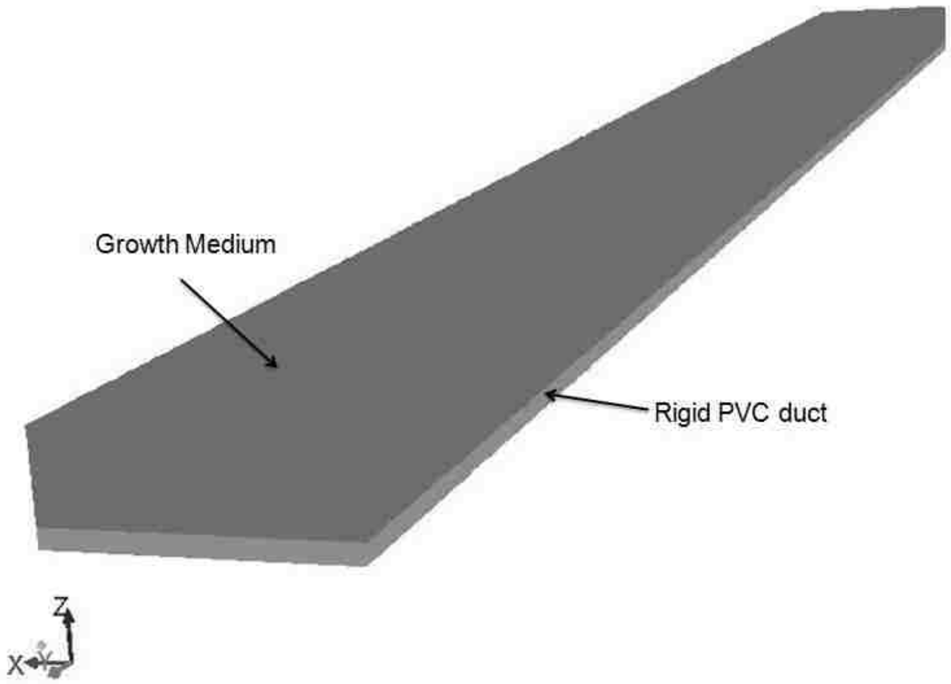


Figure 22: Schematic diagram of the PVC duct and growth medium

5.2 Two-dimensional Model

Hardware and software both affect the size of the model selected for the simulation. Besides the available computer resources and processor speed, computational cost in terms of CPU time is also important. By utilizing the combination of creating an interface between two materials (plastic and growth medium) and the shell condition method, a three-dimensional model (see Figure 22) can be created to calculate the heat transfer across the boundaries. However, considering the long length of the plastic duct (76 m), a two-dimensional model (see Figure 23) is preferred in order to reduce simulation cost.

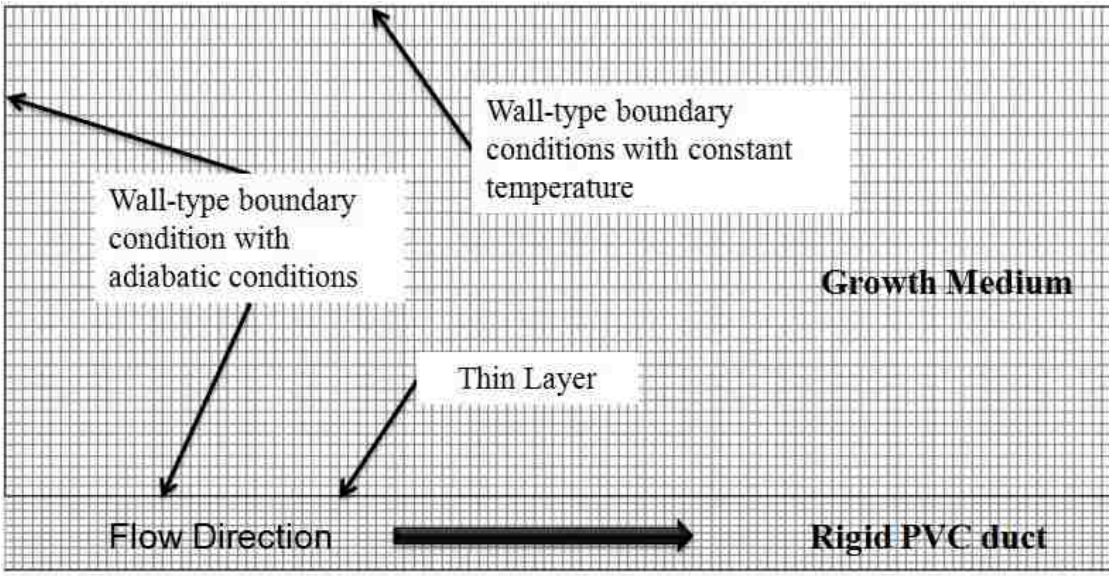


Figure 23: 2D model

5.3 Boundary Conditions

The whole 2D domain, divided into two blocks (the growth medium and the PVC duct) as illustrated in Figure 23, was generated according to the physical dimensions of the greenhouse experiment. From the general grid specifications, a structured mesh with appropriate successive ratio for grid clustering was used to acquire accurate computations at the boundaries and minimize calculations in uniform flow areas.

FLUENT required input variables associated with the properties of the water and boundary conditions [43]. The flow velocity and the inlet temperature were set as 0.95 m/s and 22°C, respectively. An outlet boundary condition was assigned for the outlet flow. Subsequently, the heat loss over the duct length and the outlet temperature can be determined from the results of the FLUENT simulation. As presented in Figure 23, for this 2D model, wall-type boundary conditions were applied for three surfaces of the growth medium (top and two side surfaces) and the bottom surface of the duct. The small gap between the two materials was neglected and only one line which represented the contact surface was generated. Usually, a wall will have a thickness of zero. However, in order to model the effect of a thin layer between two solid regions in conjunction with the thermal conditions, a value of 0.001m was assigned to the thickness of the contact surface. With this specification, FLUENT solves a 1D conduction equation to compute the thermal resistance offered by the wall and the heat generation in the wall [44]. Rigid PVC and stone wool were specified as the material of the duct and the growth medium, respectively. Moreover, the thermal boundary conditions imposed constant temperature (20°C, ambient temperature) on the top surface of the growth medium and adiabatic conditions along the side walls of the growth medium and the bottom surface of the duct.

It is important to point out that the heat transfer coefficient of the growth medium used in the greenhouse varies day by day, being strongly affected by the radiation, the ambient temperature, humidity, nutrient injection and other parameters. However, the heat transfer coefficient of the growth medium used in the CFD model is assumed to be constant (equal to the heat transfer coefficient of stone wool) in order to simplify the problem.

5.4 Various Other Settings

The simulation was identified as steady state and the pressure-based solver was used, since water in the duct was considered as incompressible flow. Moreover, the energy equation was activated and k-ε with enhanced wall treatment (thermal effects) was employed to model the turbulent flow in the duct. Convergence criteria on the residuals were set at 1E-07 for continuity, momentum and energy equations. The SIMPLE algorithm with spatial discretization using second order upwind for momentum and energy were chosen.

5.5 Post-Processing

Figure 24 represents the water temperature distribution at half height of the duct along the horizontal direction. Similarly, Figure 25 indicates the temperature distribution in the middle position of the growth medium along the row direction. Both figures demonstrate that the temperature in the duct and the growth medium hold constant along the full length of the bench. This implies that, neglecting the impact of radiation, the ambient variation and other parameters, utilizing the PVC duct is an effective method to maintain the temperature in the growth medium and the heat loss in the longitudinal direction is small.

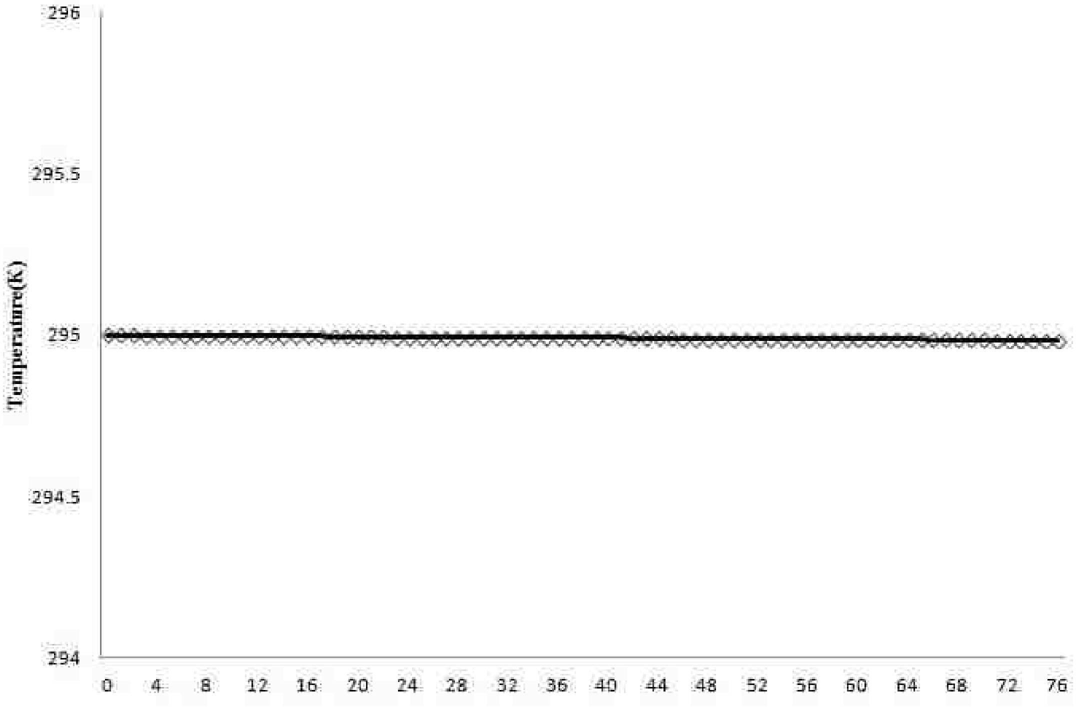


Figure 24: Water temperature distribution along the horizontal direction

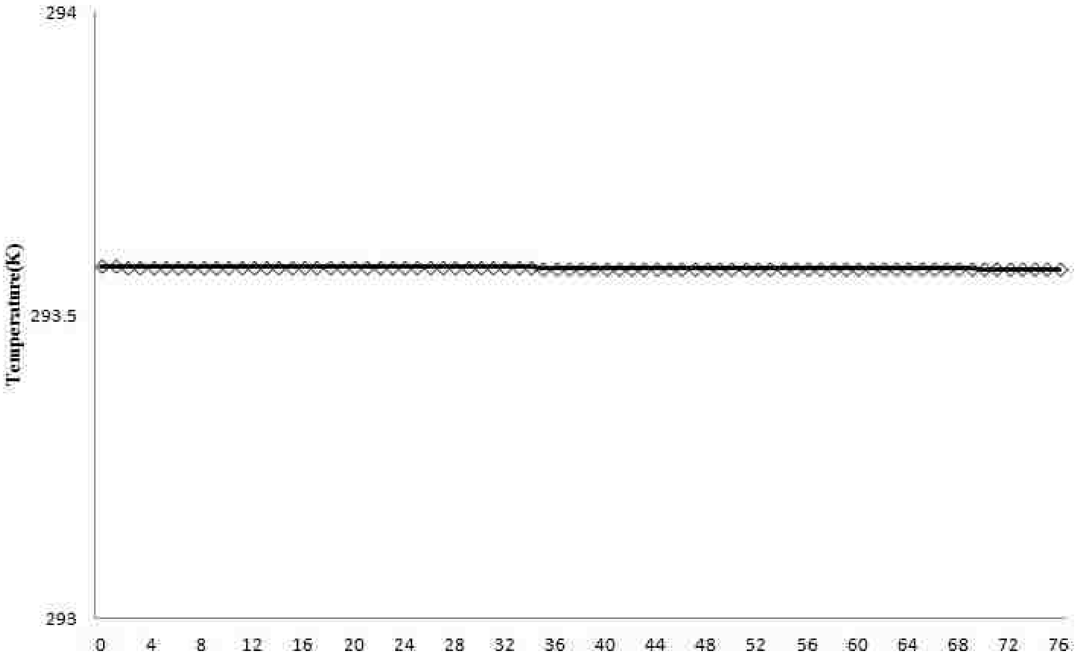


Figure 25: Growth medium temperature distribution along the horizontal direction

Figure 26 illustrates the static temperature contours in the PVC duct and the growth medium. It is easy to notice that heat transfer across the boundary has occurred and the temperature decreases gradually from 22°C (inlet temperature) to 20°C (ambient temperature) along the vertical direction.

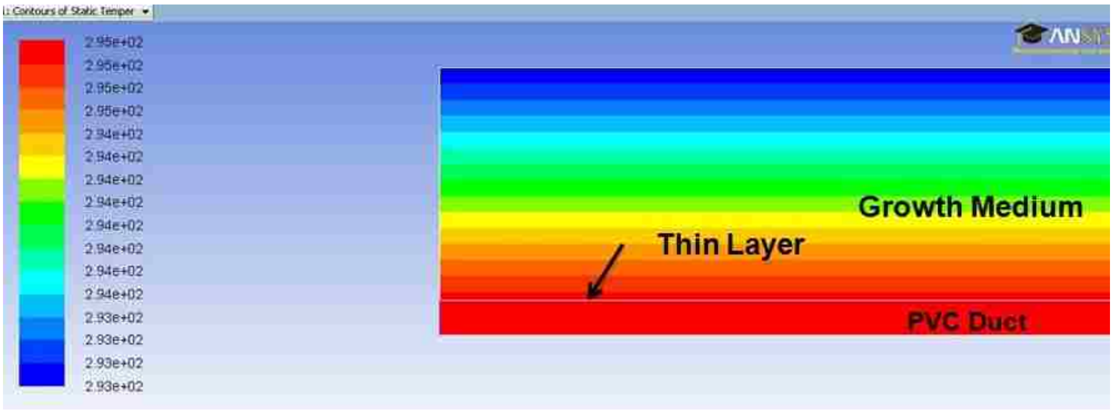


Figure 26: Static temperature contours

Figure 27 indicates the temperature variation from the bottom of the duct to the top surface of the growth medium. As can be seen clearly from this figure, the temperature maintains a constant value along the height from the bottom of the duct to the upper surface position at 0.019 m. After this point, up to the top surface of the growth medium, the temperature decreases linearly to the ambient temperature.

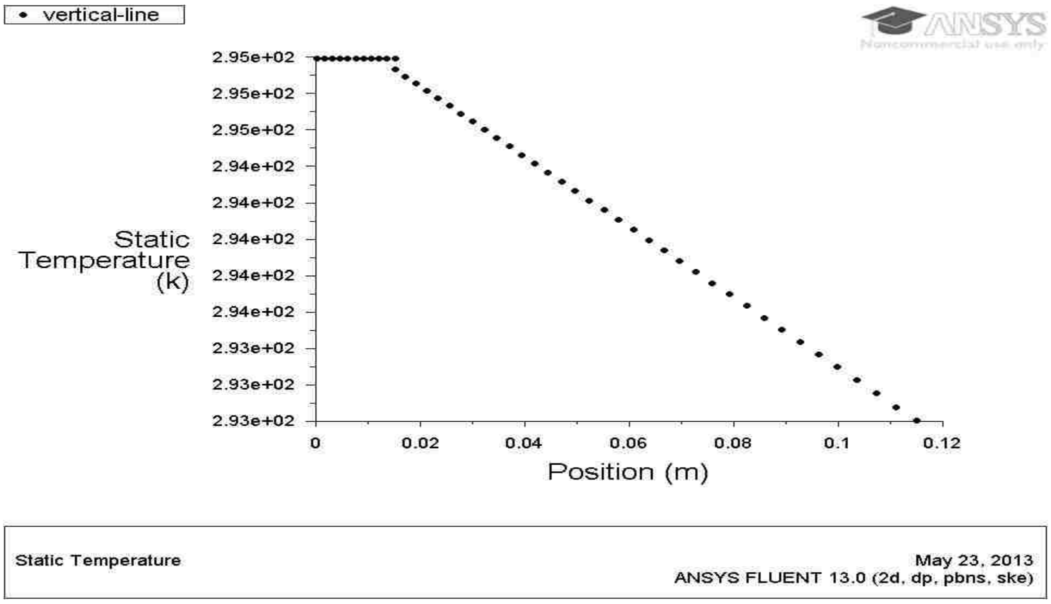


Figure 27: Static temperature along the vertical direction

5.6 1D Heat Conduction Model

As mentioned above, the experimental data (Figure 13) and the CFD model (Figures 24, 25, 27) both suggest that there is only a small drop in temperature in both the duct and slab along the length of the bench. Furthermore, to assess the potential for heat transfer through the sides of the duct (i.e., in lateral direction), a 3D model was tested and, upon comparison with the 2D simulation, showed negligible lateral heat loss. These observations suggest that the heat flow is essentially one-dimensional in the vertical direction, which can be modeled by the 1D heat conduction equation,

$$\frac{d}{dz}\left(K\frac{dT}{dz}\right)=0 \tag{5.1}$$

where T is the temperature, z is the vertical direction measured downward from the top of the growth medium and K is the thermal conductivity. A schematic of the model is shown in Figure 28.

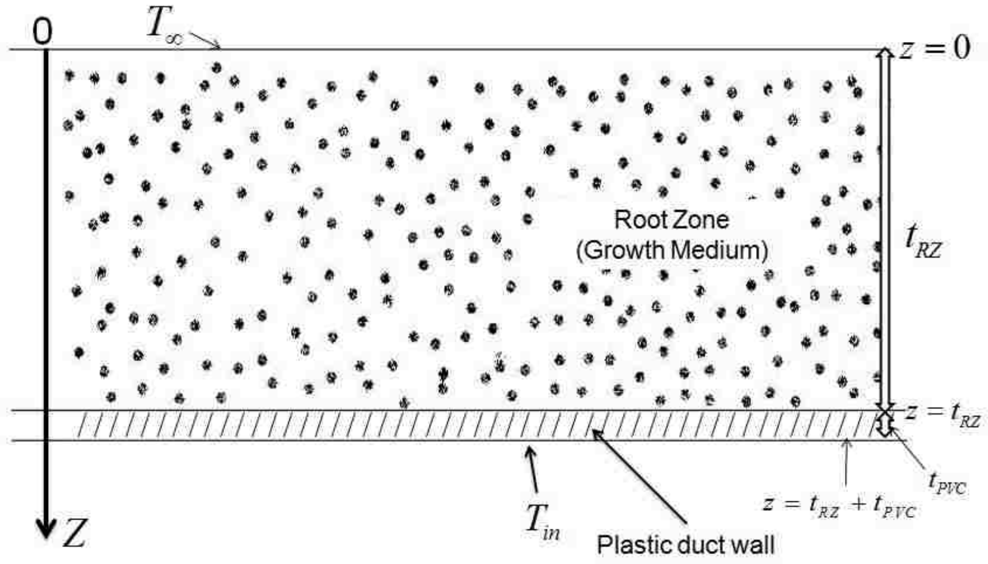


Figure 28: Schematic of 1D model

The boundary conditions associated with equation (5.1) are

$$T=T_\infty \quad \text{at } z=0; \tag{5.2}$$

$$T=T_{in} \quad \text{at } z=t_{RZ}+t_{PVC}; \tag{5.3}$$

As illustrated in Figure 28, T_∞ is the ambient room temperature, T_{in} is the water temperature in the duct, t_{RZ} is the thickness of the root zone slab and t_{PVC} is the plastic duct wall thickness. Since the thermal conductivity of the growth medium and the plastic are different, the integration of equation (5.1) must be separated into two parts, with a requirement that the temperature at the interface between the growth medium and the plastic wall is continuous, i.e.,

$$\lim_{z \to t_{RZ}^-} T(z) = \lim_{z \to t_{RZ}^+} T(z) \tag{5.4}$$

Integrating equation (5.1) across the root zone, the root zone temperature $T_{RZ}(z)$ is given by

$$T_{RZ}(z) = \frac{A_1}{K_{RZ}} z + B_1$$

where K_{RZ} is the thermal conductivity of the growth medium and A_1, B_1 are constants. Applying boundary condition (5.2) implies that $B_1 = T_\infty$. Thus,

$$T_{RZ}(z) = \frac{A_1}{K_{RZ}} z + T_\infty; \qquad 0 \le z \le t_{RZ} \tag{5.5}$$

Integrating equation (5.1) across the duct wall, the duct temperature $T_{PVC}(z)$ is

$$T_{PVC}(z) = \frac{A_2}{K_{PVC}} z + B_2$$

Applying boundary condition (5.3), the expression for duct temperature can be written as

$$T_{PVC}(z) = \frac{A_2}{K_{PVC}} [z - t_{RZ} - t_{PVC}] + T_{in}; \qquad t_{RZ} \le z \le t_{RZ} + t_{PVC} \tag{5.6}$$

Imposing the continuity condition (5.4) at the interface implies that

$$A_1 \frac{t_{RZ}}{K_{RZ}} + A_2 \frac{t_{PVC}}{K_{PVC}} = T_{in} - T_\infty \tag{5.7}$$

To determine A_1 and A_2, an additional condition is required. Assuming continuity of heat flux across the interface, i.e.,

$$K_{PVC} \frac{dT_{PVC}}{dz} = K_{RZ} \frac{dT_{RZ}}{dz} \tag{5.8}$$

and using equations (5.5) and (5.6), implies that $A_1 = A_2$. Thus, using equation (5.7), and substituting into equation (5.5), we get the root zone temperature

$$T_{RZ}(z) = T_\infty - \frac{T_\infty - T_{in}}{K_{RZ}[\frac{t_{RZ}}{K_{RZ}} + \frac{t_{PVC}}{K_{PVC}}]} z, \quad 0 \le z \le t_{RZ} \tag{5.9}$$

To simplify this expression, define

$$t^* = t_{RZ} + \frac{K_{RZ}}{K_{PVC}} t_{PVC}$$

then,

$$T_{RZ}(z) = T_\infty - [\frac{T_\infty - T_{in}}{t^*}] z, \quad 0 \le z \le t_{RZ} \tag{5.10}$$

For our purposes, equation (5.9) [or (5.10)] can be used to relate the inlet temperature T_{in} to the ambient temperature T_∞, in order to achieve a desired root zone temperature. For example, suppose we want to maintain a root zone temperature of T_0 at the mid-point ($z = 0.5 t_{RZ}$) of the growth medium. Then, from equation (5.9), the relationship between T_{in} and T_∞ is

$$T_{in} = 2[1 + \frac{K_{RZ}}{K_{PVC}} \frac{t_{PVC}}{t_{RZ}}] T_0 - [1 + 2 \frac{K_{RZ}}{K_{PVC}} \frac{t_{PVC}}{t_{RZ}}] T_\infty \tag{5.11}$$

The result of this analysis is illustrated in non-dimensional form in Figure 29.

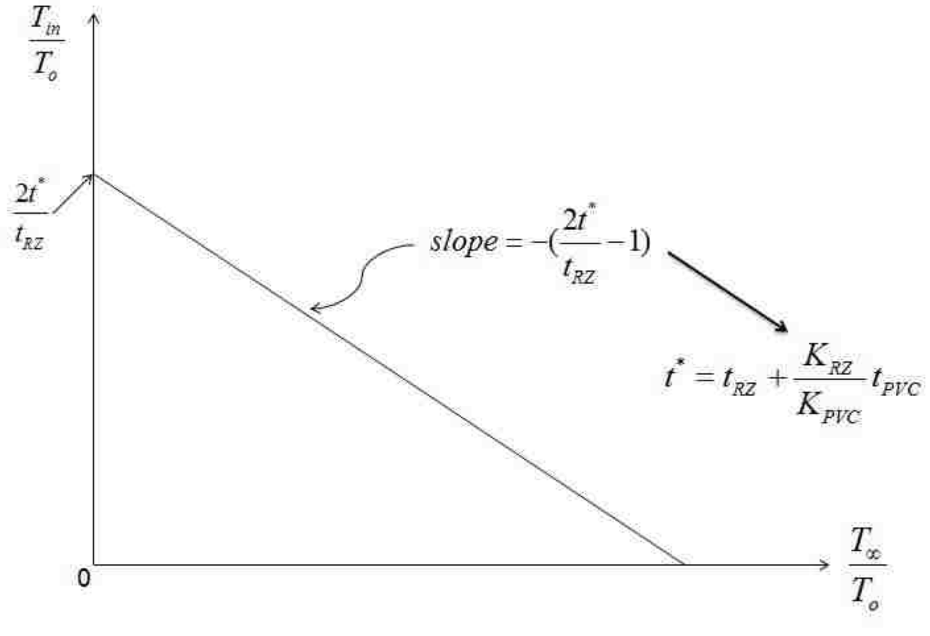


Figure 29: Variation of inlet water temperature as a function of ambient greenhouse temperature

Figure 30 illustrates the comparison between the computational result and 1D model result for the temperature distribution in the growth medium along the vertical direction when the ambient temperature was set at 15°C. Clearly, the result obtained from the 1D heat conduction model shows excellent agreement with the simulation result.

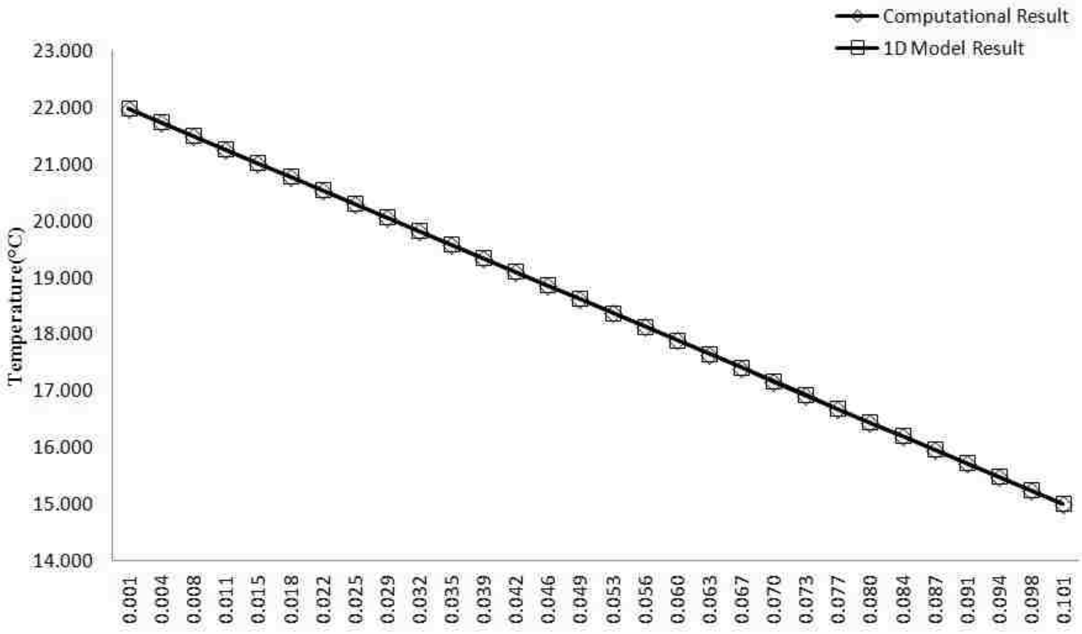


Figure 30: Results comparison

If the 1D model adequately captures the essential physics, equation (5.11) can be used to adjust the heated water temperature at the duct inlet, based on a current reading of the ambient temperature in the greenhouse, in order to maintain the root zone at a prescribed temperature. To validate this simple model, further tests are needed.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The bench-top heating system has been used to perform experiments in a greenhouse to examine the performance and study the relationships between root zone temperature and yield on tomato plants. Temperature measurements indicate that utilizing this type of bench-top heating method is an effective method for maintaining the root zone temperature in the desired range regardless of the variation of the ambient temperature, radiation and humidity. Although the impact of bench-top heating on tomato productivity was not significant, the positive effect on the time of tomato fruit maturation was observed. This might be an indication that the ambient temperature, which was being controlled by the greenhouse operator, maintained the appropriate comfort zone for the plant roots. Thus, the bench-top heating system did not contribute to the overall production of tomatoes. It is also important to point out that other environmental factors outside of our control have an influence on tomato growth and yield, such as ventilation, sun radiation, nutrient supply and humidity. In our experiments, the water temperature was controlled to achieve root zone temperature of 18°C - 25°C, which may not be optimum for tomato plants. Perhaps most significantly, the bench-top heating system was able to maintain the desired root zone temperature, even when the room temperature dropped well below the minimum desired temperature. This suggests that the bench-top heating system allows the grower to cultivate the plants at a lower ambient room temperature without harming the plants, which may reduce energy costs.

6.2 Future Work

While the temperature in the growth medium has been studied, further investigation on energy conservation and the impact of the variation of the ambient temperature, radiation and humidity on the root zone temperature is of interest. In order to accomplish this goal, a controlled environment chamber is recommended for future study. Further, as presented in Figure 13, this system is capable of delivering the same amount of heat to each foot of bench top, which indicates the current system has potential for future development. Future work, therefore, will be conducted on refinements of the system to expand its capabilities. A chiller would be added into the system to avoid super-high root zone temperatures during the summer. Possible future applications of this system include conducting the experiments in a small-scale greenhouse environment to verify the effects on energy demand and study the relationship between root zone temperature and yield on additional crops (e.g. cucumbers and peppers). Also, further tests should be conducted to validate the 1D model, since it may provide a simple relationship between the water temperature in the duct system and the ambient room temperature to ensure a desired root zone temperature.

REFERENCES

[1] Emmert, E.M., 1973, "Greenhouses and Post Harvest Technology", AENG 252. Final Lectures Notes, http://www.angrau.ac.in/media/10964/aeng252finallecturenotes.pdf

[2] Cook, R. and Calvin, L., 2005, "Greenhouse Tomatoes Change the Dynamics of the North American Fresh Tomato Industry", Economic Research Report, 2, pp. 3-4.

[3] Harssema, H., 1977, "Root Temperature and Growth of Young Tomato Plants". Doctoral Thesis, Agricultural University, Veenman (publ.), Wageningen, Netherlands.

[4] Linacre, E.T., 1964, "A Note on a Feature of Leaf and Air Temperatures", Agric. Meteor, 1, pp. 66-72.

[5] Went, F.W., 1944, "Plant Growth under Controlled Conditions. I. Thermoperiodicity in Growth and Fruiting of the Tomato", Am. J. Bot., 31, pp. 135-150.

[6] Richards, S.J., Hagan, R.M. and McCalla, T.M., 1952, "Soil Temperature and Plant Growth". In: Soil Physical Conditions and Plant Growth. B.T. Shaw (editor), Academic Press, New York.

[7] Brouwer, R. and Levi, E., 1969, "Responses of Bean Plants to Root Temperatures; IV. Translocation of ^{22}Na Applied to the Leaves", Acta Bot. Neerl., 18, pp. 58-66.

[8] McAvoy, R.J. and Janes, W.H., 1984, "The Effects of Root Zone Heating in Conjunction with Standard and Cool Night Conditions on the Growth of Chrysanthemums", ISHS Acta Hortic., 148, pp. 843-852.

[9] Moorby, J. and Graves, C.J., 1980, "Root and Air Temperature Effects on Growth and Yield of Tomatoes and Lettuce", Acta Hortic., 98, pp. 29-44.

[10] Cannell, G.H., Bingham, F.T., Lingle, J.C. and Garber, M.J., 1963, "Yield and Nutrient Composition for Tomatoes in Relation to Soil Temperature, Moisture,

and Phosphorus Levels”, Soil Sci. Soc. Am. Proc., 27, pp. 560-565.

[11] Rosenthal, E., 2002, “Root Zone Temperature”, http://www.pot.tv/articles/2565.html

[12] Pianta, C., 2012, “Is Root Zone Heating Really Necessary?”, Maximum Yield, USA. pp. 152-158.

[13] Bodnaruk, W.H. Jr., Mills, T.W. and Ingram, D.L., 1981, “Response of Four Foliage Plants to Heated Soil and Reduced Air Temperatures”, Proc. Fla. State Hort. Soc., 94, pp. 104-107.

[14] Adebooye, O.C., Noga, G.J. and Lankes, C., 2009, “Root Zone Temperature Affects Emergence and Growth Traits of Snake Tomato”, Central European Agriculture, 10, pp. 240-243.

[15] Jaworski, C.A. and Valli, V.J., 1964, “Tomato Seed Germination and Plant Growth in Relation to Soil Temperatures and Phosphorus Levels”, Proc. Fla. State Hort. Soc., 77-78, pp. 178-183.

[16] Christenbury, G.D., 1990, “Energy Management with Root-Zone Heating”, Miscellaneous Publication #295, University of Georgia, pp. 1-2.

[17] Brouwer, R., 1964, “Responses of Bean Plants to Root Temperatures; Ⅰ: Root Temperatures and Growth in the Vegetative Stage”, Jaarb. Inst. Boil. Scheik. Onderz. LandbGewass. pp. 11-22.

[18] Eguchi, T., Kitano, M. and Eguchi, H., 1994, “Effect of Root Temperature on Sink Strength of Tuberous Root in Sweet Potato Plants”, Biotronics, 23, pp.75-80.

[19] David, W., 2011, “Plant Growth Factors: Temperature”, Colorado State University Extension. Notes #143.

[20] David, S., 2002, “Root Zone Heating for Greenhouse Crops”, Appropriate Technology Transfer for Rural Areas (ATTRA). http://www.mnproject.org/resourcecenter/Utlizing%20Root%20Zone%20Heating.pdf

[21] Falah, M.A.F., Wajima, T., Yasutake, D., Sago, Y. and Kitano, M., 2010, “Responses of Root Uptake to High Temperature of Tomato Plants (Lycopersicon esculentum Mill.) in Soil-less Culture”, Agricultural Techn.,

6(3), pp. 543-558.

[22] Kramer, A.J., 1983, "Water Relations of Plants", Academic Press, New York, pp. 1-143.

[23] Diczbalis, Y. and Menzel, C.M., 1998, "Low Temperatures Decrease CO2 Assimilation and Growth in the Tropical Rambutan", J. Hort. Sci. Biotechnol., 73, pp. 65-71.

[24] Lingle, J.C., Cannell, G.H., Bingham, F.T. and Garber, M.J., 1963, "Yield and Nutrient Composition for Tomatoes in Relation to Soil Temperature, Moisture, and Phosphorus Levels", Soil Sci. Soc. Am. Proc., 27, pp. 560-565.

[25] Locascio, S.J. and Warren, G.F., 1960, "Interaction of Soil Temperature and Phosphorus on Growth of Tomatoes", Proc. Am. Soc. Hort. Sci., 75, pp. 601-610.

[26] Burton, A.J., Bouma, T.J., Pregitzer, K.S., Zogg, G.P. and Zak, D.R., 1996, "Latitudinal Variation in Sugar Maple Fine Root Respiration", Canadian Forest Res., 26, pp. 1761-1768.

[27] BassiriRad, H., 2000, "Kinetics of Nutrient Uptake by Roots: Responses to Global Change", New Phytologist, 147, pp. 155-169.

[28] Abd el Rahman, A.A., Kuiper, P.J.C. and Bierhuizen, J.F., 1959, "Preliminary Observations on the Effect of Soil Temperature on Transpiration and Growth of Young Tomato Plants under Controlled Conditions", Meded. Van de LandbHoogesch. Wageningen, 59(15), pp. 1-12.

[29] Nkansah, G.O. and Tadashi, I., 1995, "Effect of Air and Root Zone Temperatures on Physiological Characteristics and Yield of Heat Tolerant and Non Heat-tolerant Tomato Cultivars", J. Japan. Soc. Hort. Sci., 64(2), pp. 315-320.

[30] Jones, D.A.G., Sandwell, I. and Talent, C.J.W., 1978, "The Effect of Soil Temperature when Associated with Low Air Temperatures on Cropping of Early Tomatoes", Acta Hortic., 76, pp. 167-171.

[31] Sandwell, I., 1977, "Warm Rooted Tomatoes Crop Satisfactorily at 5°C", Grower, 88, p. 605.

[32] Gosselin, A. and Trudel, M., 1983, "Interactions Between Air and Root Temperatures in Greenhouse Tomatoes: Growth, Development, and Yield", Am. Soc. Hort. Sci., 108, pp. 901-905.

[33] Cooper, A.J., 1973. "Root Temperature and Plant Growth". Commonwealth Agricultural Bureaux. Slough, England.

[34] Fujishige, N. and Sugiyama, T., 1968, "Effect of Soil Temperature on Growth of Seedlings of a Few Fruit Vegetables (a Preliminary Report)", J. Hort. Assoc. Japan, 37, pp. 221-226.

[35] Canham, A.E., 1966, "Raising Young Tomato Plants with Soil Warming and Supplementary Light", Acta. Hortic., 4, pp. 81-88.

[36] Ingram, D.L., Basford, B.H., Foster, W.J. and Ramcharan, C., 1990, "Electronically Controlled Root Heating Tubes", Hort Science, 25(6), pp. 693-694.

[37] "Greenhouse Heating Efficiency Design Considerations", National Greenhouse Manufacturers Association, 1998.J

[38] Jenkins, B.M., Sachs, P.M., Forister, G.W. and Sisto, I., 1989, "Thermal Response of Greenhouses under Bench and Perimeter Heating", ASAE Paper, No. 89-4038.

[39] Sachs, R.M., 1992, "Plant Response and Energy Savings for Bench-top Heated Greenhouses", Scientia Horticulturae, 49(1-2), pp. 135-146.

[40] iButton User Manual, http://www.maximintegrated.com/

[41] http://www.onsetcomp.com/products/sensors/s-tmb-m006

[42] Wilkerson, E.G. and Gates, R.S., 2003, "Controlled Environment System for Studying Root Zone Temperature Effects on Cutting Propagation", Am. Soc. of Agricultural Engineers, 19(4), pp. 483-489.

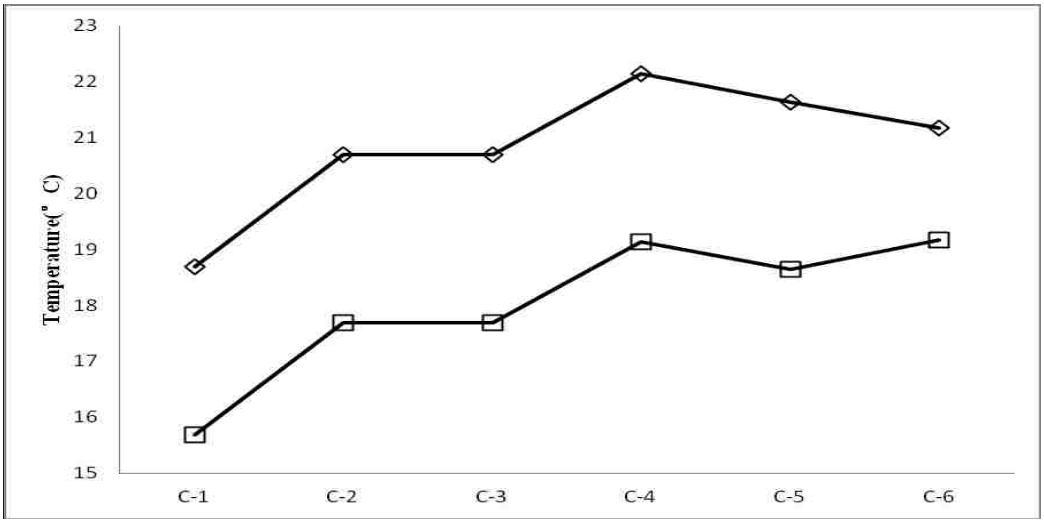
[43] Hou, C. and Ma, C., 2008, "Boundary Setting in Simulating Greenhouse Ventilation by Fluent Software", IFIP International Federation for Information Processing, 259, pp. 1391-1395.

[44] ANSYS FLUENT User's Guide, ANSYS Inc., Canonsburg, PA, 2006.

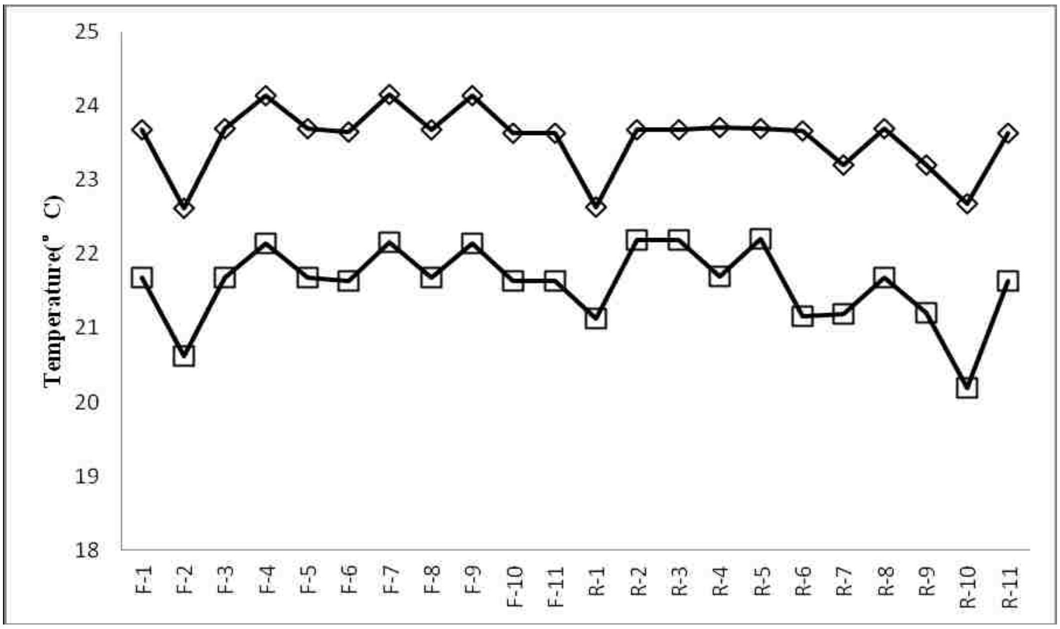
APPENDIX A

TEMPERATURE DISTRIBUTION ALONG THE ENTIRE LINE

A.1 Temperature Distribution along the Entire Line at 2:30 PM and 10:30 PM on February 11 (Ambient temperature is not available.)



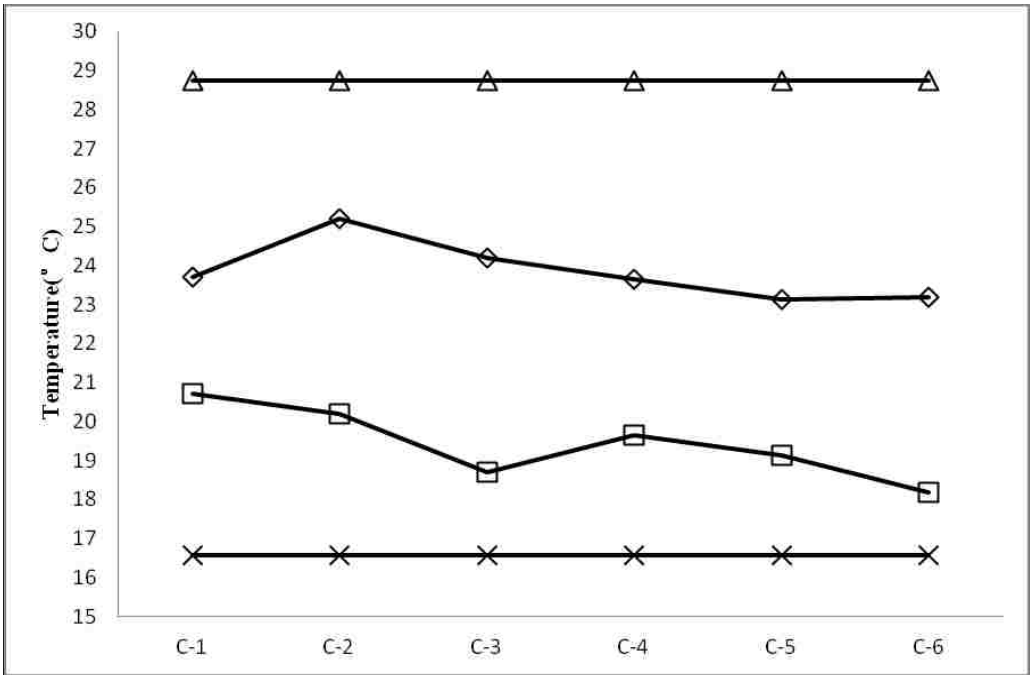
(A)



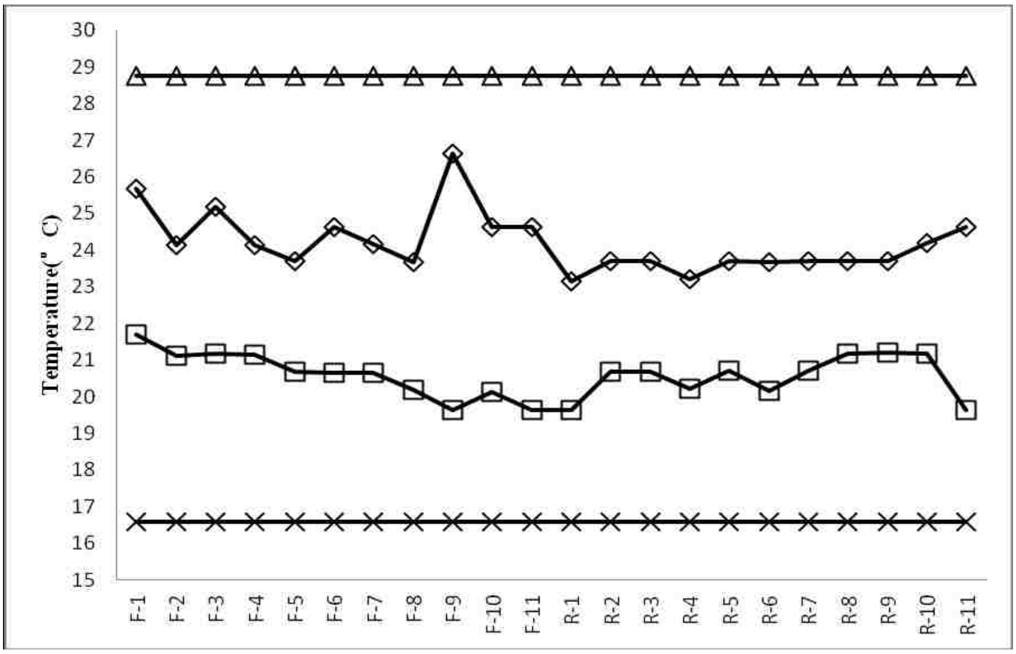
(B)

Figure A.1: Temperature distribution along (A) control line, (B) experimental line (root zone: 2:30 PM - ◊, 10:30 PM - □)

A.2 Temperature Distribution along the Entire Line at 2:30 PM and 10:30 PM on March 11.



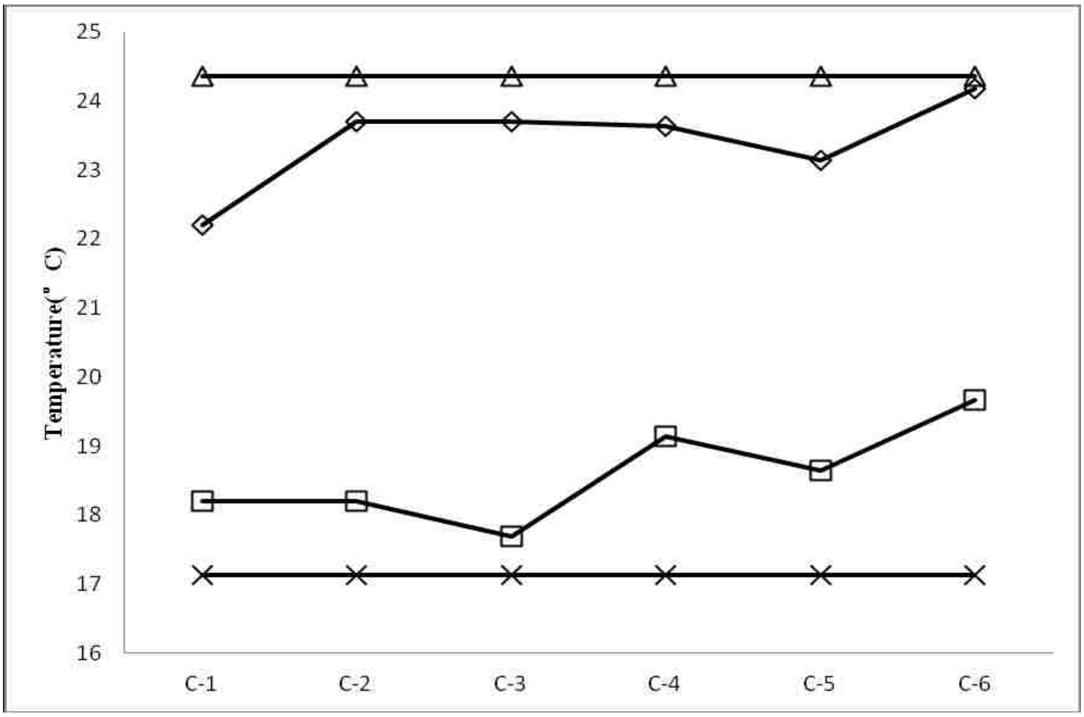
(A)



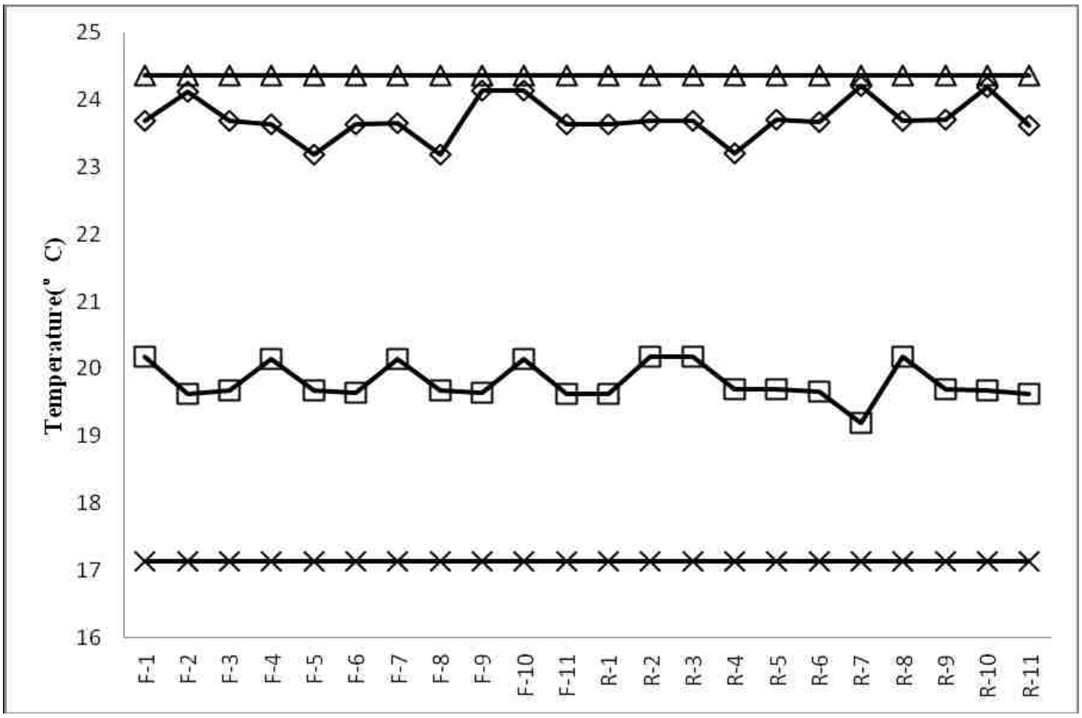
(B)

Figure A.2: Temperature distribution along (A) control line, (B) experimental line (ambient: 2:30 PM - Δ, 10:30 PM - x; root zone: 2:30 PM - ◊, 10:30 PM - □)

A.3 Temperature Distribution along the Entire Line at 2:30 PM and 10:30 PM on April 24.



(A)



(B)

Figure A.3: Temperature distribution along (A) control line, (B) experimental line (ambient: 2:30 PM - Δ, 10:30 PM - x; root zone: 2:30 PM - ◊, 10:30 PM - □)

APPENDIX B

DAILY TEMPERATURE AT SENSORS F6 AND C3

B.1 Daily Temperature at sensors F6 and C3 on February 15. (Ambient temperature is not available.)

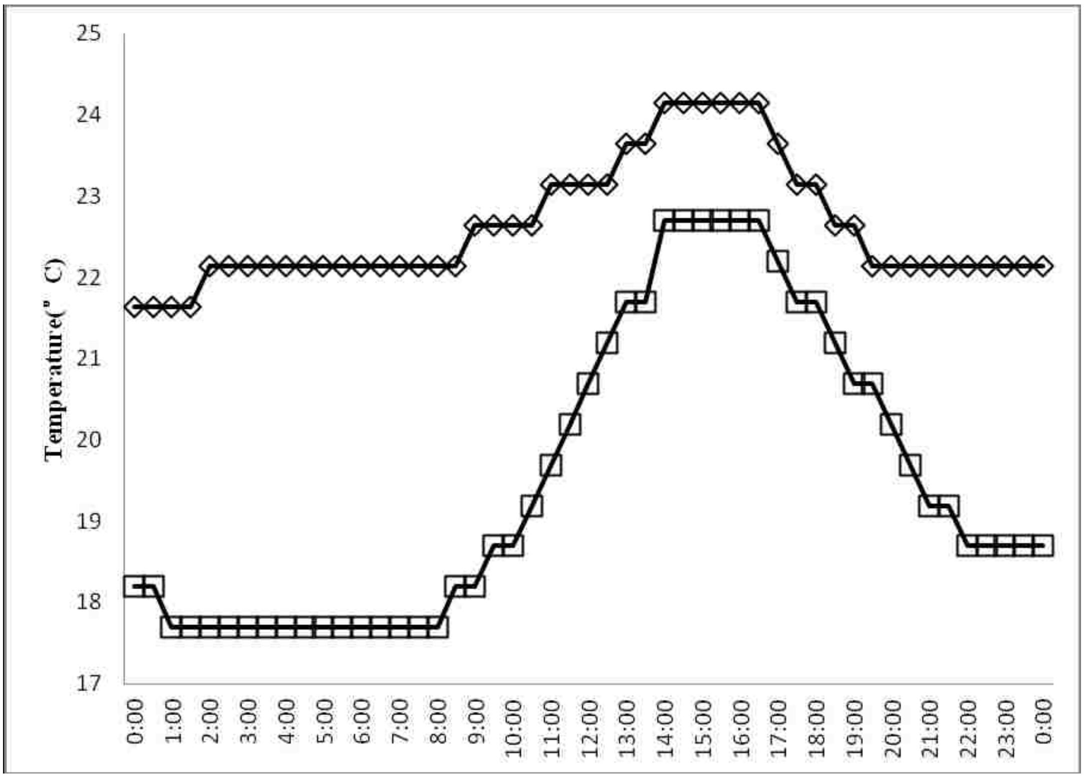


Figure B.1: Daily (Feb. 15) temperature at sensors F6 and C3
(root zone: F6-◊, C3-□)

B.2 Daily Temperature at sensors F6 and C3 on March 15.

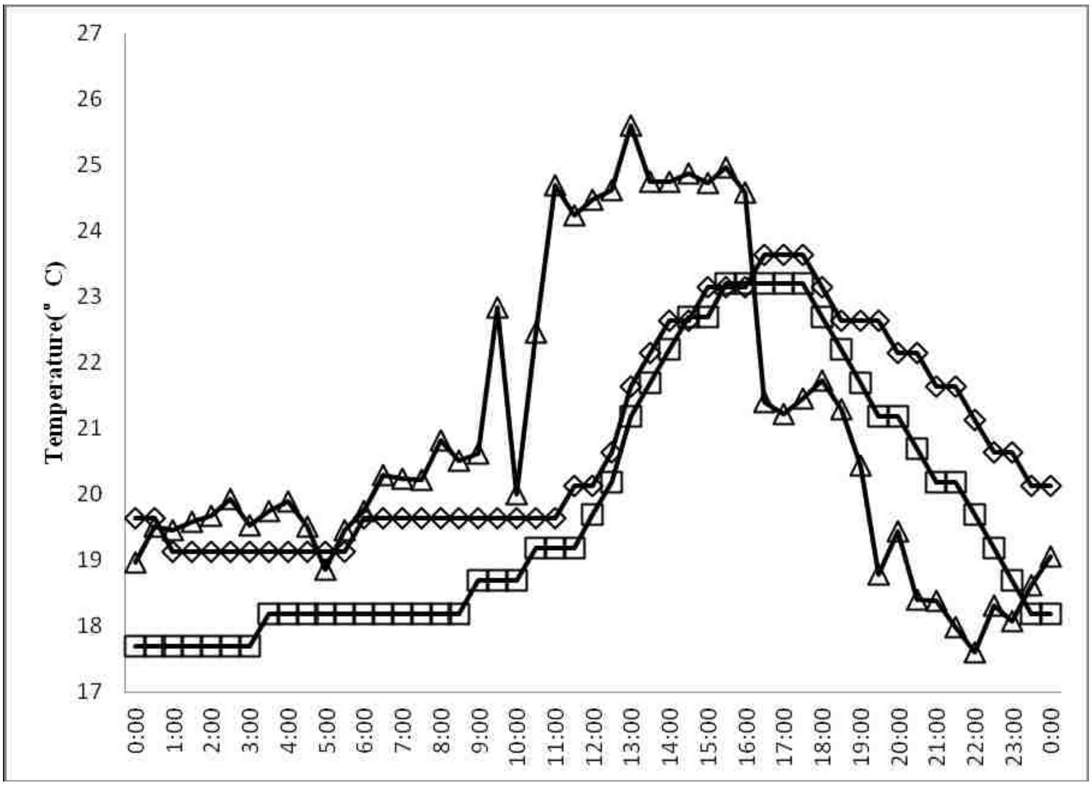


Figure B.2: Daily (Mar. 15) temperature at sensors F6 and C3
(ambient: Δ; root zone: F6-◊, C3-□)

B.3 Daily Temperature at sensors F6 and C3 on April 15.

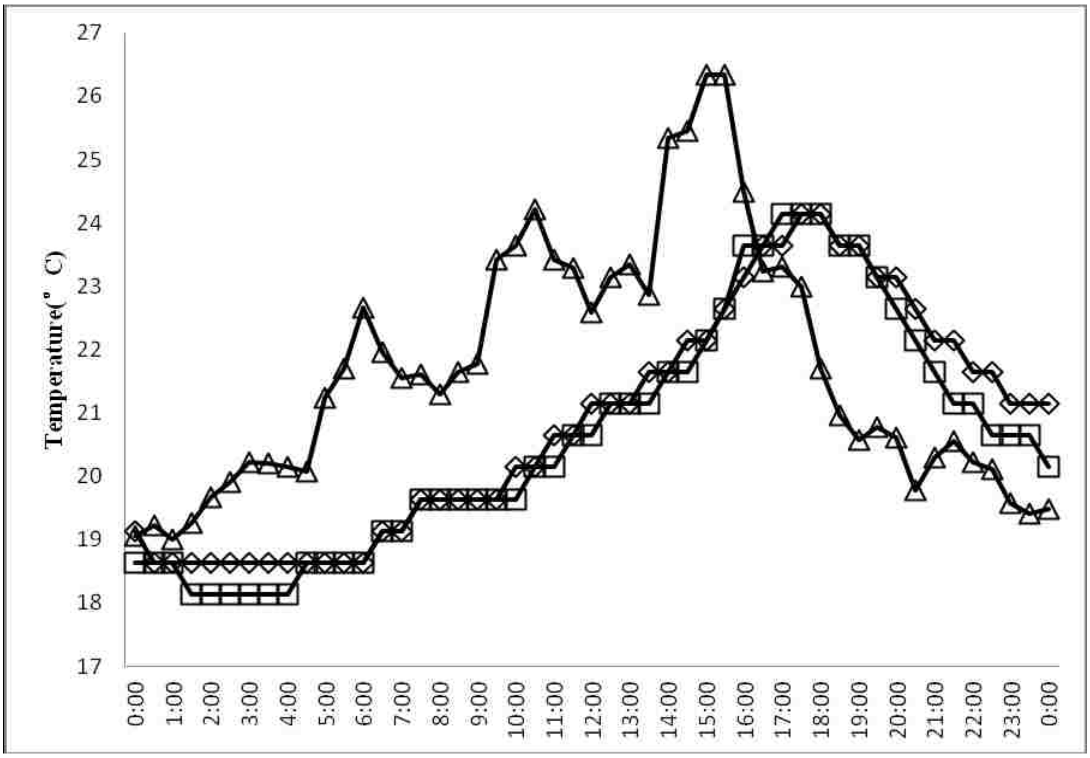


Figure B.3: Daily (Apr. 15) temperature at sensors F6 and C3
(ambient: Δ; root zone: F6-◊, C3-□)

APPENDIX C

ADDITIONAL EXPERIMENTS

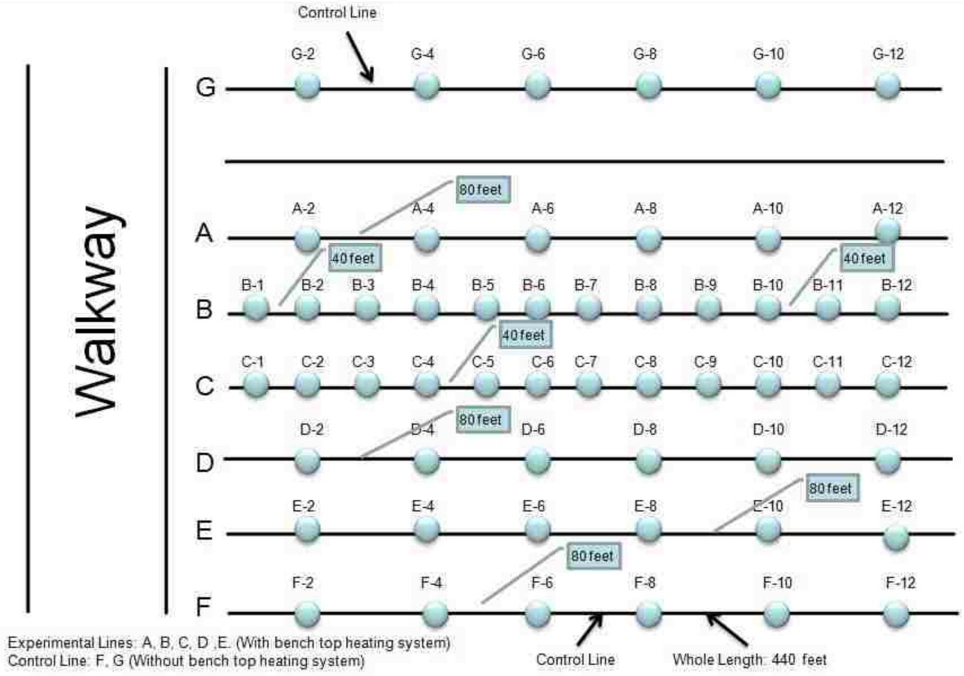


Figure C.1 Schematic of the location of the iButtons

Figure C.1 shows a schematic of the location of the iButtons in the greenhouse. Lines A to E have the root zone temperature managed with the bench-top heating system, while lines F and G are the control lines. Further, three other iButtons are located in the ambient air to measure room temperature, placed near F-6, A-6 and G-6.

Figure C.2 and Figure C.3 show the variation of room temperature at various locations in the greenhouse over one single day and one week, respectively. All three locations display a similar pattern, which indicates the ambient temperature distribution along the across-row direction is comparatively uniform. Specifically, on March 9th, the temperature gradually increased at about 8 AM from the overnight value of 20°C to a maximum value of 42°C at around 11 AM. The temperature remained more or less constant until about 4 PM, from which point it gradually reduced to the overnight value of 20°C at around 7 PM. Beyond 7 PM, the room temperature remained constant until the following morning. The cycle appears to repeat day-after-day (see Figure 31). It is also interesting to note that the peak room temperatures can be as high 50^{o}C. This is a good indicator that there is excess heat available in the greenhouse that can be used more efficiently to regulate the overall heat use.

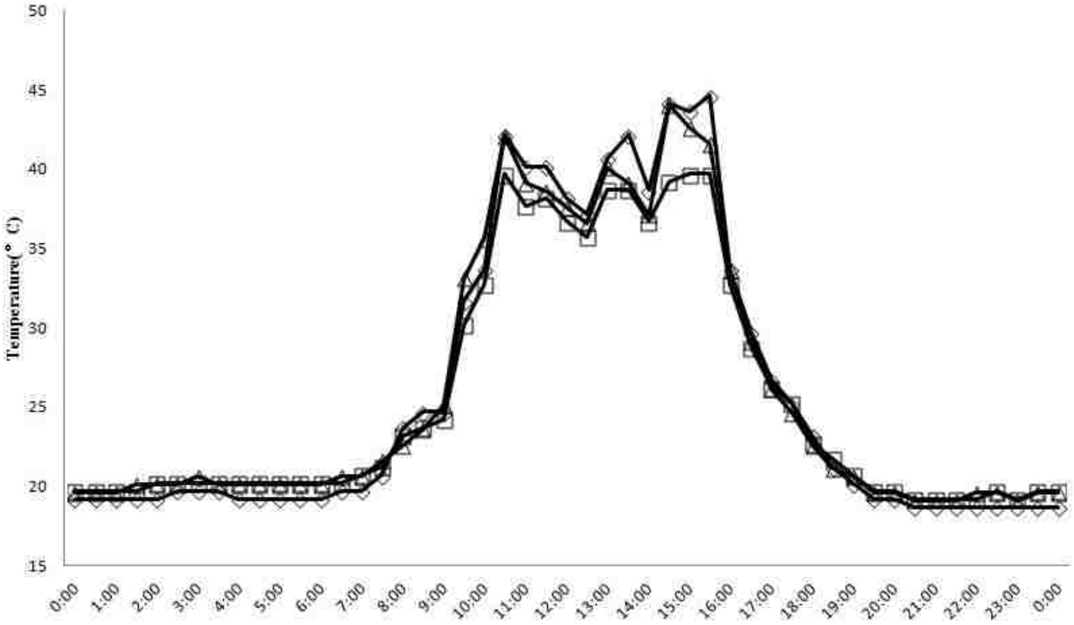


Figure C.2: Room temperature comparison on March 9

(sensor 1-◊, sensor 2-□, sensor 3-Δ)

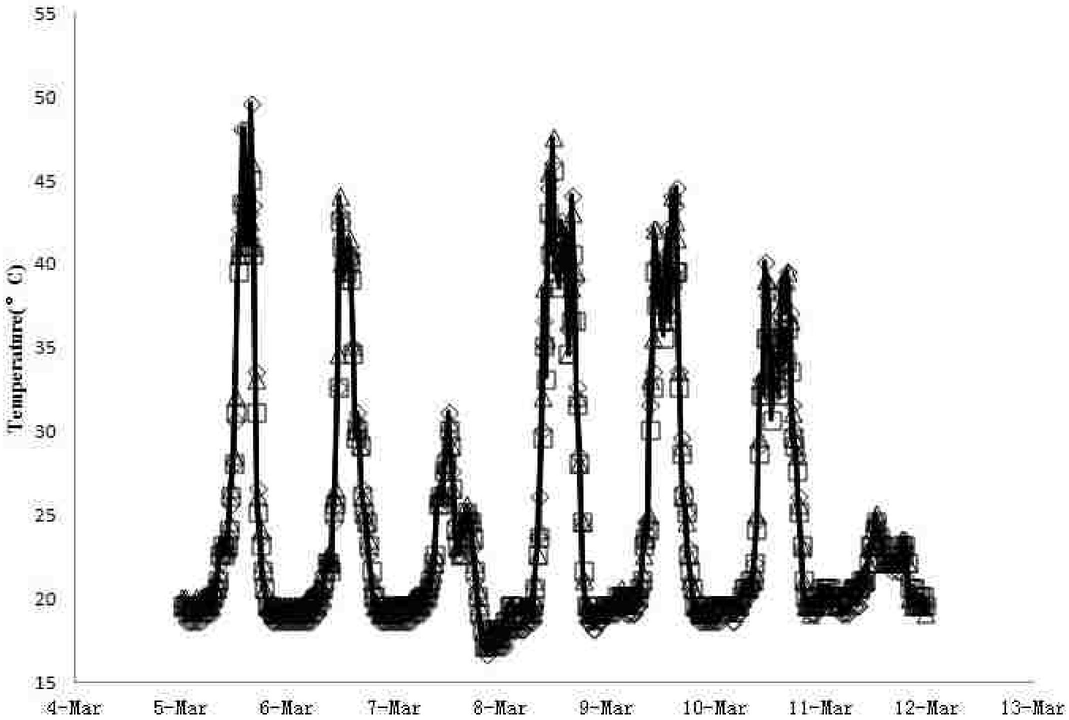
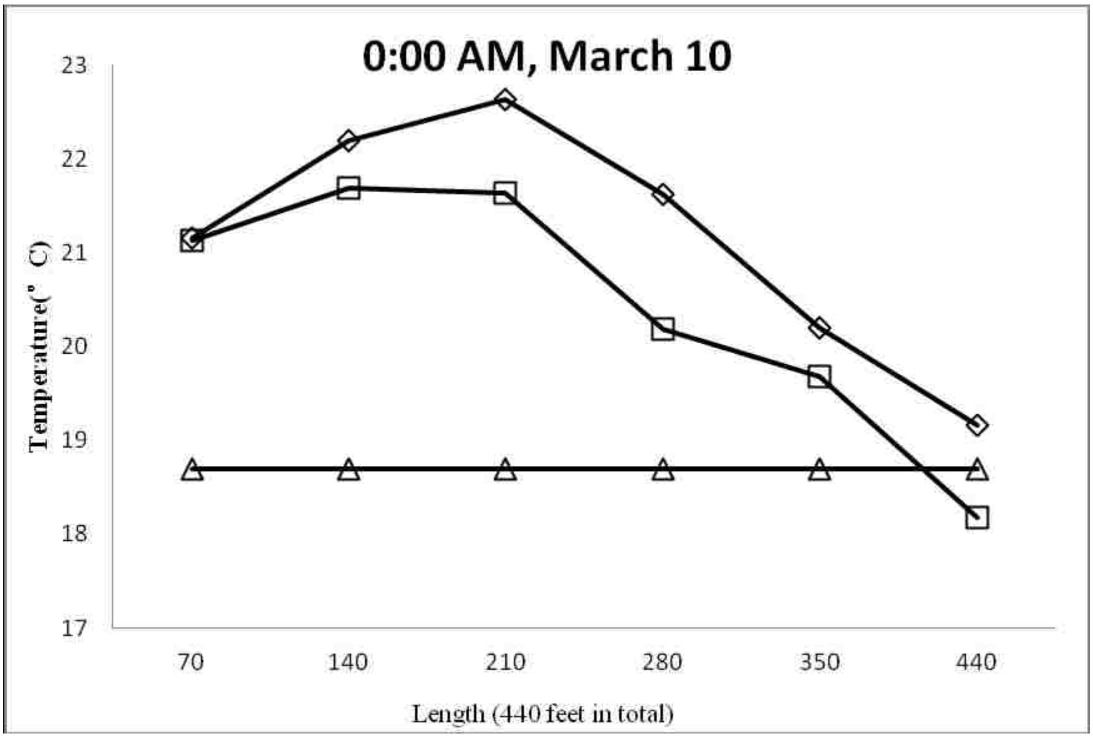


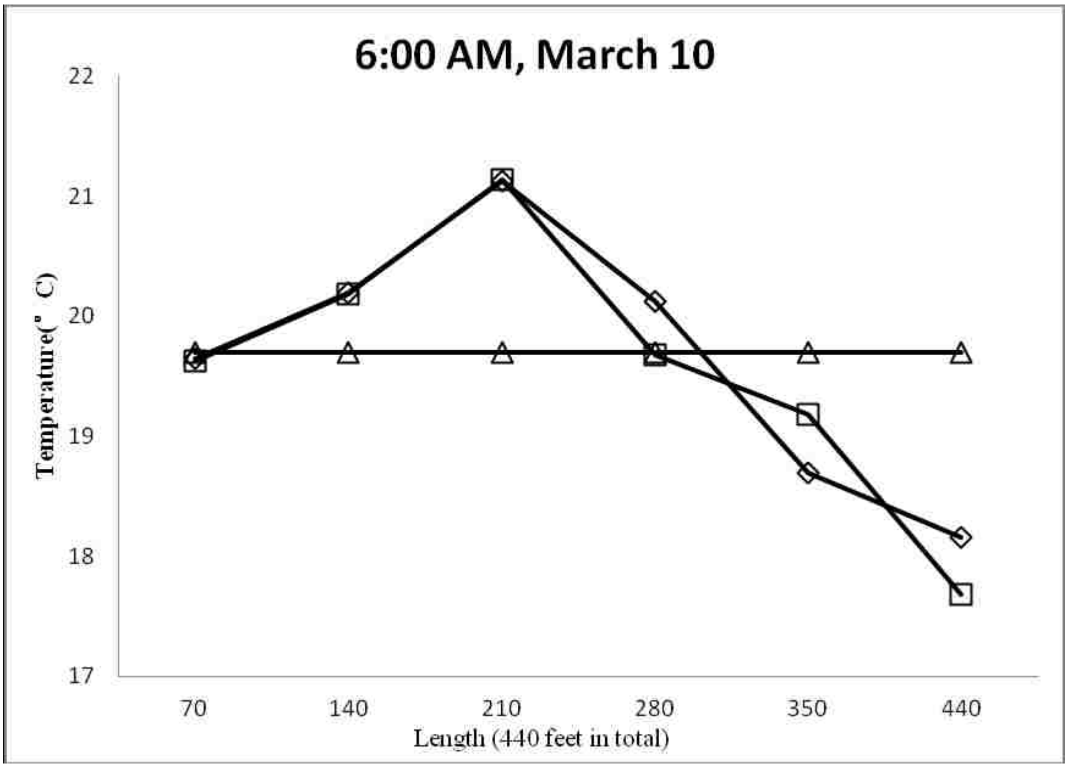
Figure C.3: Room temperature comparison over one week

(sensor 1-◊, sensor 2-□, sensor 3-Δ)

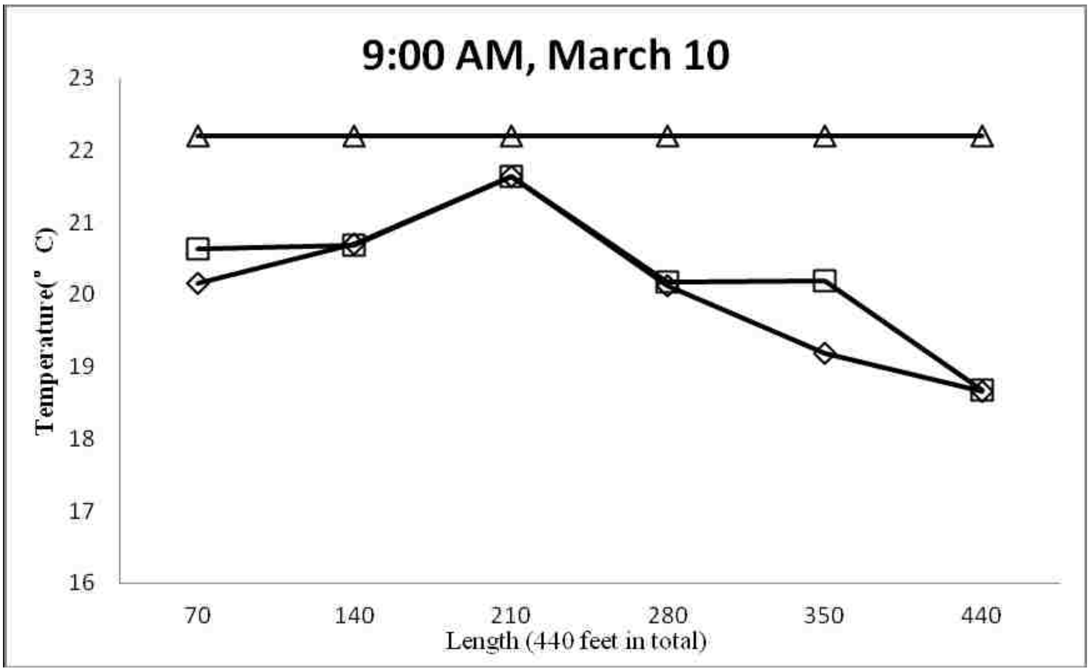
Figure C.4 (a - f) shows the temperature variation in heated line E, and control line F along with the room temperature. Each graph in Figure C.4 shows the temperature variation at a different time ranging from midnight to 9 PM. Clearly the root zone temperatures tend to stay within a narrow band while the room temperature changes significantly. Furthermore, the root zone temperatures in the heated lines tend to have less variation compared to the control lines. The large changes in the room temperature will clearly influence the plant growth. The present results and the preliminary results presented herein indicate that a scientific approach is needed to regulate the root zone temperature while minimizing the large changes seen in the room temperature.


0:00 AM, March 10
Temperature(° C)
23
22
21
20
19
18
17
70
140
210
280
350
440
Length (440 feet in total)

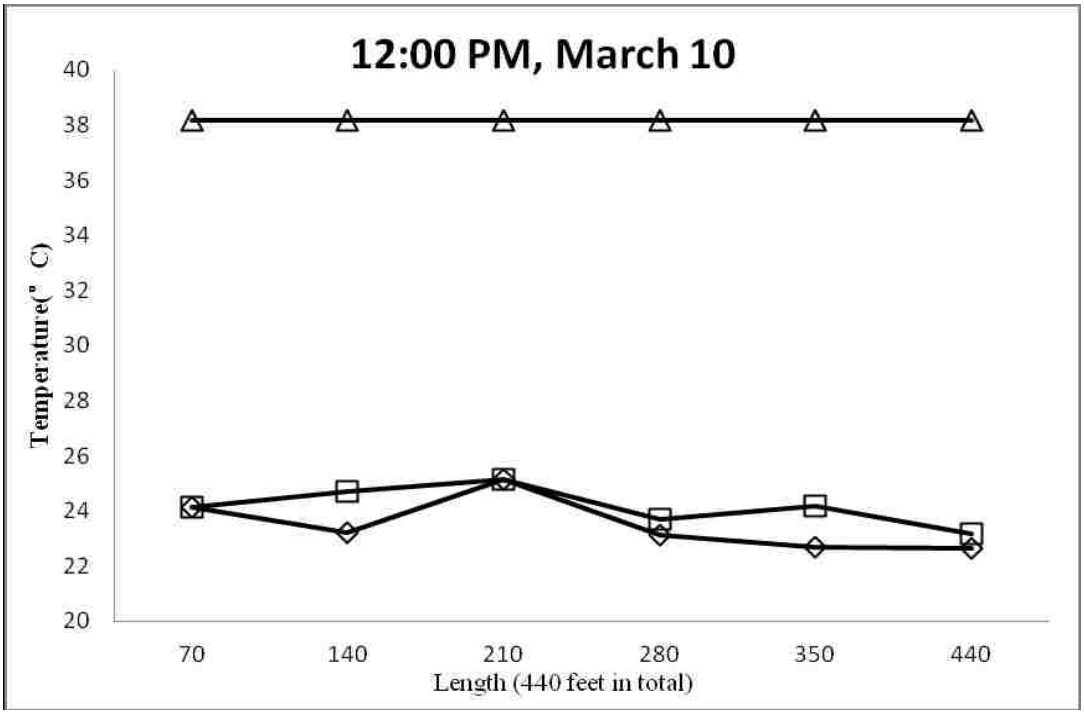
(a)


6:00 AM, March 10
Temperature(° C)
22
21
20
19
18
17
70
140
210
280
350
440
Length (440 feet in total)

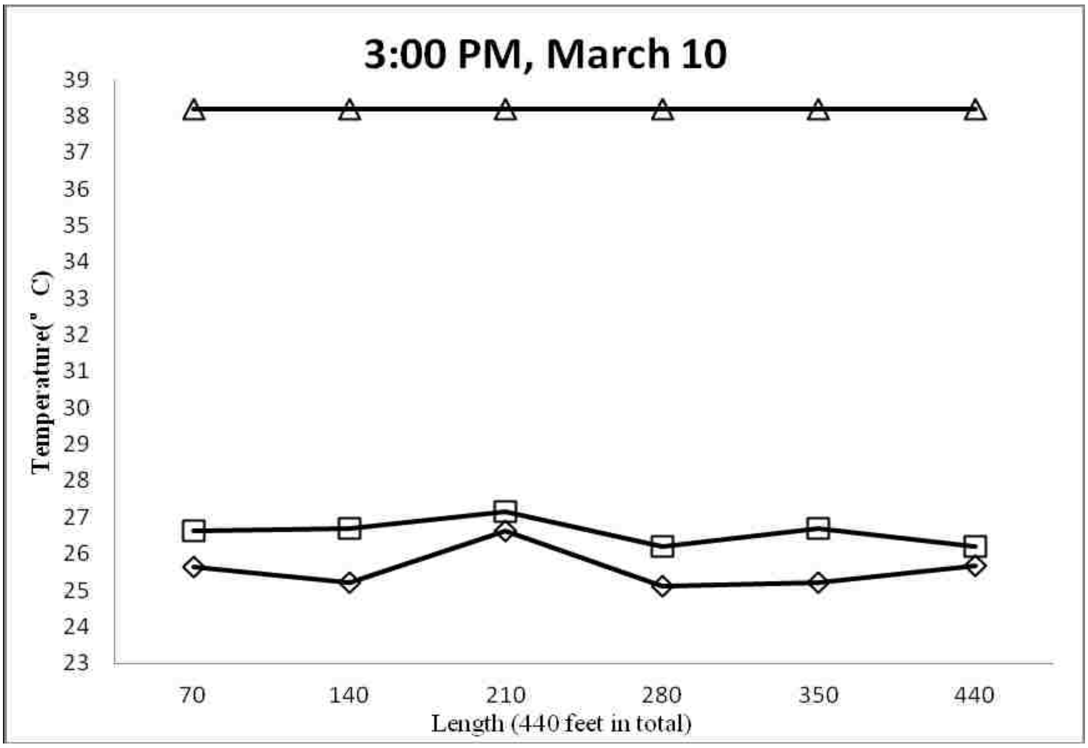
(b)


9:00 AM, March 10
Temperature(° C)
23
22
21
20
19
18
17
16
70
140
210
280
350
440
Length (440 feet in total)

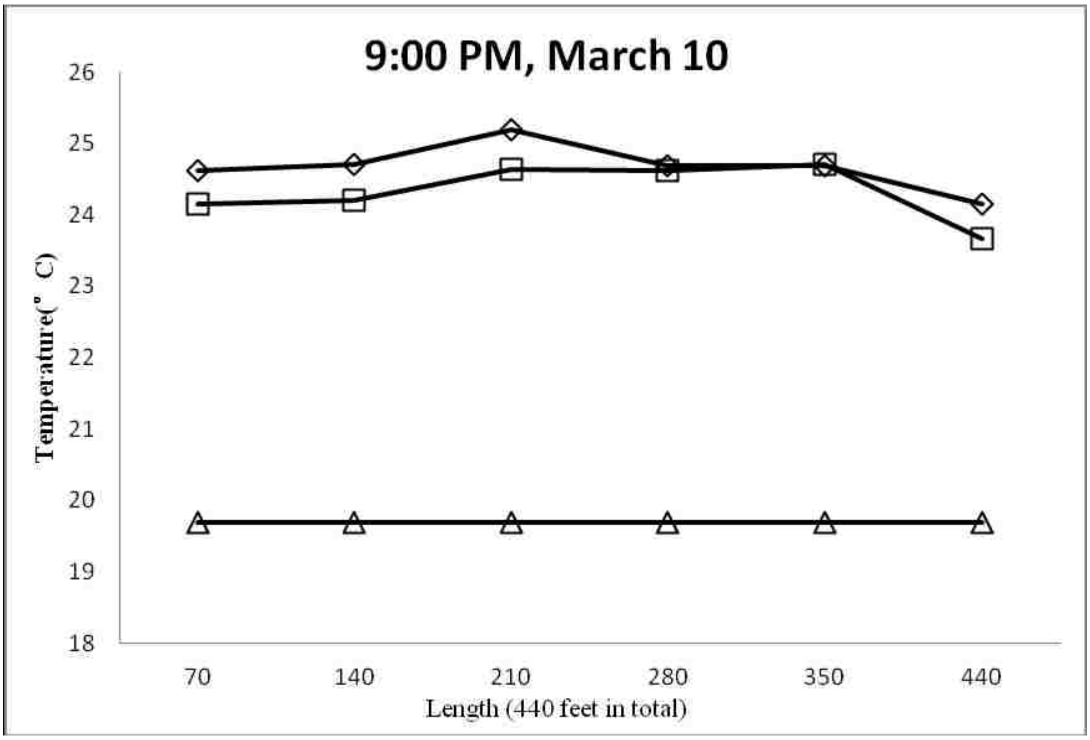
(c)


12:00 PM, March 10
Temperature(° C)
40
38
36
34
32
30
28
26
24
22
20
70
140
210
280
350
440
Length (440 feet in total)

(d)



(e)



(f)

Figure C.4: Temperature comparison
(ambient: Δ; root zone: E line-◊, F line-□)

VITA AUCTORIS

NAME: Han Wang
PLACE OF BIRTH: Nan Chang, China
YEAR OF BIRTH: 1986
EDUCATION: University of Huaqiao
2003-2007 B.A.Sc
University of Windsor, Windsor
2010-2011 MEng