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HEAT TRANSFER PROBLEMS IN PLASTIC COVERED TOMATO GREENHOUSES WITH GROUND BEDS IN MANITOBA

by

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CHAPTER I

INTRODUCTION

1.1 The Potential Market for Greenhouse Tomatoes in Manitoba

Most people like big, fresh tomatoes for making sandwiches and salads. The major supply of tomatoes for Manitoba is produced in Ontario, the United States or Mexico. Unfortunately, these tomatoes do not have the flavorful quality of vine-ripened tomatoes. The transportation expenses and the damage done in transit add to the final cost to the consumer.

A marketing study found that consumers were willing to pay a higher price of up to twenty cents per pound more for greenhouse tomatoes compared to storage ripened tomatoes (21).* Manitoba greenhouse tomato producers can profitably fill the shortage in the local supply of high quality tomatoes if technical information is available.

1.2 Engineering Aspects of Greenhouse Tomato Production

1.2.1 Basic Structure

The plastic covered greenhouse has some advantages over glass covered greenhouses (53). These advantages are:

(a) Less heat loss (double layer assumed).

(b) Diffusive light transmission resulting in less fruit cracking.

*Number(s) in parenthesis refer to the number in references.

(c) Lower capital cost of construction.

(d) More airtight for efficient and economical carbon dioxide enrichment.

Various types of structural designs can be used. Glue laminated, wooden arch rafters are modest in cost and offer clear spans for the growing area. Rafter size and spacing should be selected so as to minimize shading. The use of plastic covering materials results in a very lightweight structure. Thus only small footings or grade beams are required for foundations.

Many types of outer coverings are available but maximum transmission of incident radiant energy is important. The inner lining, required for minimizing heat loss and condensation, can be of polyethylene film (see figures 1-1 and 1-2).

1.2.2 Temperature Control

The optimum temperatures for different stages of tomato growth are summarized in table 1 (53).

When the temperature is low the rate of cell division and growth is also low. At relatively high temperatures growth is rapid and sugars do not accumulate but are used in respiration and growth. For accurate control of temperature, a thermostat should be installed where it is screened from direct radiation and forced air movement.

Tomato seedling temperatures range from 60 to 65F. In order to promote the development of large cotyledons (seed leaves) and thick stems, a cold treatment is given. Cold treatment tends to double the number of flowers in the first and often the second clusters, and to

FIGURE 1-1 Exterior View of Experimental Greenhouse at University of Manitoba

FIGURE 1-2 Interior Design of Greenhouse at University of Manitoba

TABLE 1

Night and Day Temperatures for Tomatoes

Growth Stages	Sunlight Conditions	Night (F)	Day (F)
1. Seed Germination	Not critical	65 - 70	65 - 70
2. Cold treatment: 10 days to 2 weeks	Sunny or partly cloudy	52 - 56	55 - 60
2 to 3 weeks	Cloudy or dull	52 - 56	55 - 58
3. After the cold treatment and until plants are transplanted into beds	Sunny or partly cloudy	58 - 62	65 - 75
	Cloudy or dull	58 - 60	60 - 62
4. During flowering and fruiting	Sunny or partly cloudy	60 - 65	65 - 75
	Cloudy or dull	60 - 62	60 - 62

increase the early and total yield. The young tomato plants are exposed to night temperatures from 52 to 56F for ten days to three weeks. Following this cold treatment temperatures during day and night should be raised to 58 to 75F (see table 1 for details).

1.2.3 Humidity Control

The relative humidity inside the greenhouse should be kept below 90 percent to control leaf mold disease which is very destructive to greenhouse tomato plants (44). Humidstats are available to control the opening of ventilators (26,41) for humidity control. Double layer covered greenhouses tend to have less condensation on internal surfaces in cold weather than single layer covered greenhouses (49).

Relative humidity of 55 to 65 percent at 70 to 75F is considered to be optimum (4). Most pathogenic spores will not germinate unless the relative humidity is 96 percent or higher (37). Relative humidity levels in the range of 70 percent or higher are necessary for the continued growth of most pathogens (42).

The upper leaves will be dried by solar radiation and induced air currents, whereas the lower leaves will still remain moist. A fan with a perforated plastic distribution tube will maintain more uniform temperature and humidity, and prevent cold and moist spots (12).

1.2.4 Soil Moisture and Nutrients

If fruiting plants become deficient in moisture or nutrients, top yields of high-quality greenhouse tomatoes cannot be obtained. Warm, soft water is required for irrigation. Automatic irrigation systems can be controlled by solar evaporimeters or tensiometers (41).

The required nutrients are best determined by soil and tissue tests. The accepted method of supplying nutrients is to supply appropriate soluble fertilizers. Required nitrogen, phosphorus, potassium, calcium, magnesium and trace elements in dilute form are applied with the irrigation water.

1.2.5 Light

The energy for photosynthesis is provided by radiant energy. The quantity of energy, the spectral distribution of energy and the relative light and dark periods determine the rate and type of growth.

The portion of the electromagnetic spectrum that is involved in photochemical reactions in plants is from 290 nanometers to 850 nanometers (1 nanometer (nm) = 10^{-9} meters) (17). The energy in the spectrum band, 380 nm to 760 nm, can be detected by the human eye and is defined as light. Natural daylight (sunlight) has the correct spectral balance for proper growth of tomatoes.

Photosynthetic reactions in tomato plants under natural conditions saturate at light levels of approximately 1500 foot-candle (ft-c) (17). Sunlight intensity on a clear June day at noon is approximately 10,000 ft-c.

To avoid pathological conditions, tomato plants need a dark period of at least 7 hours. The natural diurnal cycle provides the needed dark period.

1.2.6 Carbon Dioxide Enrichment

Normally air contains about 0.03 percent or 300 ppm (parts per million, volume basis) of carbon dioxide. The optimal concentration is from 1000 to 1500 ppm (53).

From 10 A.M. to 4 P.M. on bright sunny days is the most beneficial period to increase the concentration of carbon dioxide because of the high rate of photosynthesis.

Perforated plastic air distribution tubes can be used with a fan to distribute and circulate supplementary carbon dioxide. Carbon dioxide can be supplied from solid dry ice, pressurized liquid carbon dioxide or from burning hydrocarbon fuels of low sulphur content.

A simple, cheap and reliable colorimeter for measuring carbon dioxide concentration is available (40).

1.2.7 Disease Control

Good air circulation, fresh air and optimal temperatures in the greenhouse will control fungus diseases. The heating and air circulating system should be designed to avoid cold air pockets and high moisture levels around the base of the plants. Removing leaves to the level of the ripening fruit will improve air circulation (53).

Soil sterilization prior to planting is necessary for control of soil-borne diseases and detrimental microorganisms. Soil in small quantities can be sterilized with heat from electrical heaters. Soil in growing beds is usually sterilized with steam or chemicals.

1.3 Objectives

The scope of this investigation was limited to areas where immediate problems existed. The main problem area was steam sterilization of the ground beds using portable steam generators. The other problem areas were the design of the heating system and the design of the ventilation system. The objectives were:

1. To evaluate steam sterilization of the soil beds and to compare with chemical sterilization.

2. To compare estimated heat losses with that estimated from the measured fuel consumption.

3. To estimate solar heat gains and to evaluate the ventilation system design for removal of excess solar heat.

CHAPTER II

REVIEW OF LITERATURE

2.1 Steam Sterilization

2.1.1 Benefits of Steam Sterilization

The bacterial destroying capacity of steam is a combination of moisture and heat. Dry heat sterilization requires much higher temperatures and longer heating times than moist heat. Bacteria are killed by protein coagulation. Much higher temperatures are needed to coagulate protein when moisture content is low. With dry heat this necessitates the destruction of the bacteria by actual burning (29, 36).

Effective soil sterilization with steam is fundamentally dependent on the type of pathogens or harmful organisms present as well as soil moisture, soil density, soil parent material, and soil structure. These factors affect the treatment temperature and the temperature distribution which determines the sterilization effectiveness.

Steam sterilization is faster, easier, cheaper and more effective than other methods of destroying fungi, bacteria, nematodes, weeds and insects (13). Steam releases a large quantity of heat at the point to be heated and provides the most efficient method for treating a large stationary soil mass (13).

2.1.2 Sterilization Temperatures and Times

Fungi are relatively sensitive to heat. Most pathogenic fungi are destroyed by time-temperature relationships of the order of 140F for 30 minutes. Hot water treatment would control fungi diseases (14).

Most bacteria that cause plant diseases can be killed at 140F for 10 minutes since these bacteria do not form heat resistant spores as do some animal pathogens and some food-spoiling bacteria (14).

Most nematodes will be killed at 130F for 10 to 15 minutes (14). Insects and mites in the egg stage cannot survive at temperatures exceeding 160F. Worms, slugs, centipedes and similar animals will be killed at 140F for 30 minutes using moist heat (14).

Viruses do not persist in soil but they do live in dried infected plant tissue that is left in the soil. These viruses can survive for at least 2 years and some can even survive 200F for 10 minutes (14).

Under ideal sterilizing conditions most of the organisms of concern can be killed by heating the soil to 140F for 30 minutes. Because clods or lumps require a heating time that is proportional to the square of their diameters (34), recommended temperatures are higher than 140F. Soil that is turned should be heated to a final temperature of 180F for 30 minutes and stationary soil masses should be heated to 212F for 30 minutes (14,15).

2.1.3 Sterilization Methods

Soil may be sterilized either by using a stationary soil mass method or a moving soil mass method. The choice of method depends on the efficiency, dependability, cost and chance of reinfection.

If steam is used as the heat source a stationary soil mass method will prove best in most cases. Where the source of heat is dry heat a moving soil mass method will be much more efficient and easier to control (1,15,19).

The Thomas or surface method of steaming is usually limited to 8 inch soil depths but with underground tiles the method can provide efficient steaming for soil beds with depths of 24 inches or greater (15).

2.1.4 Heating of Soil Clods

Heat conduction in soils improves as porosity and pore size decrease, and moisture content increases. Convection increases with large pores, but decreases in wet soil because of reduced pore size and permeability to air. Heat transfer by radiation increases with small pores and wet soil (14). Dry soils ranked in order of thermal conductivity from highest to lowest would be sand, loam, clay and peat (14, 16,30).

Steam moves through the air spaces in the soil mainly by molecular diffusion, micro-convection, and macro-convection. The heating process inside clods is mainly due to diffusion and condensation of steam, but also partly due to thermal conduction. According to Morris and Winspear (34), it has been shown that the time required to raise the temperature at the center of a spherical clod was proportional to the square of the clod diameter. The assumed modes of heat transfer were diffusion and condensation as well as conduction (34).

2.1.5 Condensation of Steam in Soil

Even if steam were at high pressure and high temperature in buried clay tiles, the pressure quickly drops to approximately atmospheric on release from the tiles into the soil mass. The steam temperature will also reduce on contact with the cool soil particles and the cool soil air. Thus, the soil and soil air will be heated by released latent heat as the steam condenses.

The amount of heat released at any radial location is determined by the temperature differential of the steam mixture and the soil and soil air in the advancing condensation zone (14).

The heat transfer and mass transfer between the steam mixture, soil air and the surfaces of the soil particles could be represented by the enthalpy potential difference, the convective coefficient and the specific heat of the steam mixture (43).

2.1.6 Steam Movement from Buried Clay Tile

According to Baker and Roistacher (13) steam expands from buried tile orifices in a pattern of spheroids with elongated tops. They based this conclusion on research of Morris (33) and Bunt (20). They concluded that:

> If the distance of movement above the outlet is 1d, then that below it is approximately ½d and that to the sides is ½d to 5/8d.

This is illustrated in the diagram on the following page.

For fine soil, the heat front forming a boundary between cold and hot soil is about 0.27 inches thick (34).

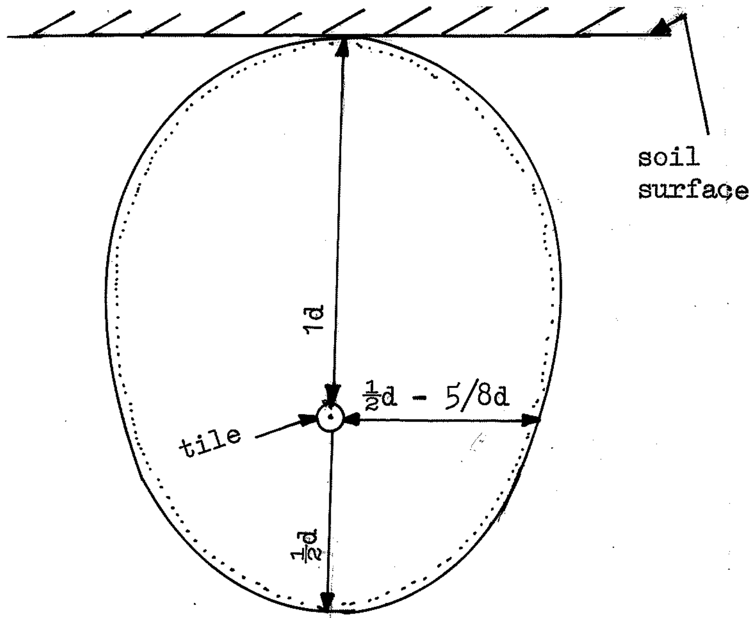

FIGURE 2-1. Cross Section View of Steam Expansion

2.2 Estimating Heat Losses

2.2.1 Heating Methods

Under Manitoba conditions it is important to provide a suitable heating system for successful greenhouse operation. Practical designs are based on the requirements of (41):

(a) Uniform temperature distribution.

(b) Low capital and/or operating costs.

(c) Reduced overhead obstruction and space taken up by heating equipment so that greater sunlight is transmitted to the growing crop and there is more space available for the crop.

(d) Heating ducts or pipes arranged to permit growing of crops in rows or beds.

Heat for greenhouses may be supplied from direct or indirect sources. In direct systems the heat is supplied directly to the heating medium for transfer to the house interior. In indirect systems the heat is supplied to an intermediate medium that transfers it to the house in general. Examples of the two systems are hot air electric systems and steam systems respectively (28).

Recommended electrical tubular heaters are those which are waterproofed and made from aluminum. These are fixed around the walls of the greenhouses with the lowest heater about 4 to 6 inches above the soil level to provide for an efficient air circulation while taking up minimum space. Copper-sheathed electrical cables insulated with mineral wool can also be fitted in a similar position in place of the tubular heaters (24).

Gas-fired or oil-fired air heaters can also be used. The maximum temperature of exit air from these heaters must be no more than 130F (41). Natural gas is the preferred fuel for gas-fired furnaces but manufactured gas or propane gas may also be used. If gas is not available, fuel oil can be used but great care must be taken to insure that exhaust fumes are kept out of the greenhouse. The high levels of carbon dioxide and sulphur dioxide in the exhaust fumes are fatal to plants (53).

There is a trend to the use of steam boilers for greenhouse units larger than three-quarters of an acre (41). Heating pipes are used throughout the greenhouse to distribute either steam or hot water for heating. For high-pressure systems high-level pipes are considered safer than low-level pipes because of the possibility of accidental burns with low-level systems. The high operating temperature (300F) of high-pressure systems requires fewer overhead pipes and therefore gives less shading.

None of the above heating methods provides an absolutely uniform temperature distribution throughout the greenhouse. A perforated plastic tube with a circulating fan installed at the end of the greenhouse will improve the temperature distribution within the house (12).

2.2.2 Determination of Heat Losses

The maintenance of uniform desired temperatures is very important in greenhouses. Heat losses from the greenhouse are due to thermal radiation and convection losses from the covering, conduction through the walls and soil, and condensation on the inner surface and plant transpiration. A reliable heating system must be supplied to the greenhouse since the heat gains from solar radiation, accessory equipment and biological respiration are rather erratic (48).

Takakura et al.(45), have developed a dynamic greenhouse model which considers the difference between leaf temperature and inside air temperature, moisture balance, heat storage in the floor, effects of radiation and convection on the plant leaf temperature, convective heat transmission coefficients of outside surfaces as a function of wind speed, and the solar transmissivity due to wall orientation.

In general a steady state method is used to design greenhouse heating systems (Appendix 1). For steady state conditions the rate of heat input at any point to the system must be exactly equal to the rate of heat loss if there is no net storage or loss of energy in the system. In lightly-constructed plastic-covered greenhouses this assumption is approached (3).

The following equation for calculating heat loss is recommended by the National Greenhouse Manufacturer's Association (25):

$$Q = (A_1 + A_2 \times R) \times \Delta T \times G \times W \times C \qquad (2\text{-}1)$$

where

Q = heat loss, Btu/hr

A_1 = exposed glass area, ft^2

A_2 = exposed wall area other than glass, ft^2

R = resistance of curtain wall to transmission of heat (in relation to transmission through glass), dimensionless

ΔT = highest temperature to be maintained in greenhouse minus outside design temperature, F

G = coefficient of transmission of glass Btu/hr-ft^2-F

W = wind factor, dimensionless

C = construction factor, dimensionless

Commercial heating installers size greenhouse heating systems using a "rule-of-thumb" based on experience. The "rule-of-thumb" value for Winnipeg conditions is 7 Btu/hr-ft^3. This value is used to calculate the required heat input to the furnaces.

2.3 Estimating Solar Heat Gain

The total shortwave radiation, I, reaching a terrestrial surface is the sum of the direct solar radiation, I_D, the diffuse sky radiation, I_d, and the solar radiation reflected from the surroundings, I_r. If the