THE UNIVERSITY OF MANITOBA

PREDICTING THE EFFECTS OF GREENHOUSE ORIENTATION AND INSULATION ON ENERGY CONSERVATION

by

PITAM CHANDRA

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ABSTRACT

Vegetable greenhouses in the province of Manitoba are usually constructed as transparent structures with a double layer of plastic covering materials so that necessary illumination can be made available to the plants. These covering materials have poor thermal resistance characteristics and the local climate is such that greenhouse operation has to be abandoned for a period in winter because high heating costs make production uneconomic. Greenhouse heating is probably one of the most inefficient uses of fuel for heating applications.

A number of studies have been conducted in different parts of the world with a view to reducing heating costs for greenhouse structures and a number of different schemes have been proposed. A solution valid for the cold Canadian climate is yet to be obtained. It has been observed that at northernly latitudes, the north side of a greenhouse receives little illumination during winter months. Insulating the north side of the structure could result in a substantial saving in heat lost from the greenhouse with little change in natural illumination available to the plants.

This theoretical study was undertaken to investigate the effect of insulating the north side of a greenhouse. A mathematical model was developed to study the effect of specific changes in greenhouse design on the greenhouse heat balance. In this model a more accurate method to determine solar radiation incident on a surface was incorporated. Variables studied were orientation, shape, size, and different levels of north-side insulation. Winnipeg was assumed as the location of the greenhouses and heat balance in greenhouses was studied for two arbitrarily selected summer and winter conditions. Gothic arch, gable, and circular shapes were analysed with two ground-bed sizes (15 m x 10 m and 200 m x 12 m). The greenhouses were assumed to be oriented either east-west or north-south. The necessary climatic data were obtained from the local meteorological office for December 21, 1974 and June 21, 1974 representing winter and summer conditions, respectively. The three levels of fiberglass insulation assumed in the insulated north side of greenhouses were R = 0.70, 1.41, and 2.11 $(m^2 \cdot K)/w$.

In most cases, the north side of a greenhouse was found to be contributing less than 3.0 percent to the total solar heat gain of a greenhouse on December 21. A gothic arch greenhouse was found to be superior to gable and circular greenhouses with respect to heating and ventilation requirements. An east-west oriented greenhouse maintained greater thermal environment efficiency in comparison to a north-south oriented greenhouse. Reductions of almost 50 percent in heating requirements on December 21, 1974 and at least 15 percent in ventilation requirements on June 21, 1974 were predicted when the north side of a greenhouse was insulated.

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LIST OF SYMBOLS

A	Area, m^2
A_z	Solar-azimuth angle (measured from South), rad
a	Atmospheric extinction coefficient
B	Ratio of the instantaneous diffuse solar radiation on horizontal surface to the instaneous direct normal solar radiation
b	Width, m
C_o	Conductance, $w/(m^2 \cdot K)$
C_p	Specific heat, $J/(kg \cdot K)$
C_a	Air conductance, $w/(m^2 \cdot K)$
D	Day of a year ($1 \leq D \leq 365$)
d	Solar declination angle, rad
de	Solar declination angle on June 21, rad
FS	Shape factor
f	Edge-loss factor
H	Solar hour angle, rad
HO	Daily total extraterrestrial solar radiation, w/m^2
h	Surface heat transfer coefficient, $(w/(m^2 \cdot K)$
I	Intensity of solar radiation, $w/(m^2 \cdot h)$
IO	Apparent solar constant, $w/(m^2 \cdot h)$
JC	Cloudless radiation index
KC	Cloud cover coefficient
KD	Ratio of daily direct solar radiation to daily direct extraterrestrial solar radiation
KS	Percent of possible sunshine expressed in fraction

KT	Daily cloudiness index
k	Thermal conductivity, w/(m • K)
L	Latitude of a place, rad
ℓ	Length, m
MH	Ratio of the hemispherical diffuse radiation on a surface to the hemispherical diffuse radiation on a horizontal surface
MS	Ratio of the circumsolar diffuse radiation on a surface to the circumsolar diffuse radiation on a horizontal surface
N	Number of days from January 1 to the desired date
n	Number of surfaces in a greenhouse
P	Perimeter, m
pw	Atmospheric vapour pressure, m Hg
pws	Atmospheric saturation vapour pressure at a given temperature, m Hg
Q	Rate of heat transfer for a whole greenhouse, w/h
q	Rate of heat transfer for a part of greenhouse, w/h
R	Resistance to heat transfer, $(m^2 \cdot K)/w$
RA	Actual solar constant, $w/(m^2 \cdot h)$
RH	Relative humidity expressed as fraction
r	Radius, m
S	Number of transparent surfaces
sw	Area of structural members in a wall section expressed as a decimal fraction of the area of the wall section
T	Local civil time
TL	Local watch time
TR	Sunrise time (local civil time)
t	Temperature, C
X	Value of rectangular coordinate in horizontal direction
XY	A point in rectangular coordinate

Y	Values of rectangular coordinate in vertical direction
z	Height, m
α	Wall-azimuth angle (measured from South), rad
β	Solar-altitude angle, rad
Δ	Curtain factor
δ	Stefan-Boltzmann constant, $w/(m^2 \cdot K^4)$
ε	Emissivity
γ	Wall-solar azimuth angle, rad
ω	Absorptance
ϕ	Surface inclination angle (measured from horizontal), rad
ψ	Transmittance
ρ	Reflectivity
σ	Curtain effect
τ	Atmospheric transmission coefficient for solar radiation
θ	Incidence angle i.e., angle between incident solar beam and the normal to the surface, rad

SUBSCRIPTS

A	Absorbed component of solar radiation
a	Air
c	conductive heat transfer
D	Direct component of solar radiation
DH	Direct component of solar radiation incident on a horizontal surface
DN	Direct normal component of solar radiation
d	Diffuse component of solar radiation

db	Dry-bulb temperature
dh	Diffuse component of solar radiation incident on a horizontal surface
dp	Dew-point temperature
e	Equipment
f	Floor level
g	Ground
h	Furnace
i	Indoor
ins	Insulation
j	Index to indicate surface number in a greenhouse
o	Outdoor
p	Photosynthetic
ply	Plywood, 1 cm thick
r	Respiratory
s	Surface
T	Transmitted component of solar radiation
t	Thermal radiation
u	Solar radiation
v	Ventilation
w	Wood
x	Lateral direction
y	Vertical direction
1	Clear sky
2	Cloudy sky

CHAPTER I

INTRODUCTION

Greenhouses are a means of assuring year-round production of certain agricultural products in areas of severe climate. For any given region, design should consider the local climate so that the greenhouse operation can be kept within permissible limits of economy.

The climate in most parts of western Canada is such that greenhouse operation has to be abandoned for a period in winter because high heating costs make production uneconomic. Vegetable greenhouses in the province of Manitoba are usually constructed as transparent structures with a double layer of plastic-covering materials. A number of studies have been conducted in different parts of the world with a view to reducing heating costs for greenhouse structures and a number of different schemes have been proposed to achieve this goal (23, 32, 35, 36, 42). An amicable solution valid for the cold Canadian climate is yet to be obtained.

A greenhouse is built using transparent materials, such as glass or plastic, to admit the light necessary for plant growth. These materials exhibit poor thermal resistance characteristics and thus tremendous heat losses occur, especially at night. From a study of the contribution of natural illumination from the various sides of a transparent greenhouse structure, it is inferred that the north side of the structure contributes little illumination during winter months (16) while the heat loss to the atmosphere from this side is comparable to any other side of the structure. Insulating the north side of the structure could result in a substantial saving in heat lost from the greenhouse with little change in natural illumination available to the plants.

For a greenhouse with a length-to-width ratio greater than one, the fraction of the surface area in the most favourable position to receive incoming solar energy depends upon the orientation, therefore, the surface area facing north is also dependent on it. Thus, the magnitude of the effect of insulating the north side of a greenhouse will depend upon the orientation of the greenhouse.

A theoretical study was proposed to investigate the effect of insulating the north side of a greenhouse on its thermal balance. A mathematical model was developed to study the effect of specific changes in greenhouse design on the greenhouse heat balance. Intended variables for study were orientation, shape, size, and levels of north-side insulation of greenhouse. Climatic conditions were arbitrarily selected for the model.

The specific objectives of this thesis were:

1. to develop a mathematical model which would adequately account for specific changes in greenhouse design on the thermal balance of the structure,
2. to determine the contribution of solar radiation from the north side of a greenhouse,
3. to compare gothic arch, gable, and circular greenhouse shapes for their heat loss property,
4. to compare north-south and east-west orientations of greenhouses with and without insulating the north side, and
5. to study thermal balance of greenhouses with and without insulating the north side in both winter and summer conditions.

CHAPTER II

REVIEW OF LITERATURE

2.1 System of Units

SI (Systems International d' unites) units have been used in this thesis as far as possible. Where the cgs system is more understandable, i.e., degrees Celsius (C) for temperature, this substitution has been made. A table for quantities used in this investigation is given for the convenience of the reader with conversion factors from the British system of units to the SI, Table 2.1.

TABLE 2.1

Conversion Factors

Quantity	Unit in British System	Conversion Factor	Unit in SI
Length, ℓ	ft	0.3048	m
Area, A	ft^2	0.0920	m^2
Temperature, t	F	(F-32·0)(5/9)	C
Coeff. of Heat Transfer, U,			(K=C+273.16)
and Conductance, C_o	Btu/(hr·ft^2·F)	5.6783	w/(m^2·K)
Res. to Heat Transfer, K	(hr·ft^2·F)/Btu	0.1761	(m^2·K)/w
Thermal Conductivity, k	Btu/(hr·ft·F)	1.7296	w/(m·K)
Rate of Heat Transfer, Q	Btu/hr	0.2929	w
Specific Heat, C_p	Btu/(lb · F)	4184.0	J/(kg·K)
Intensity of Radiation, I	Btu/(hr · ft^2)	3.152	w/m^2
(Stefan-Boltzmann	Btu/(hr·ft^2·R^4)	33.0788	w/(m^2·K^4)
constant, δ)	(0.1714×10^{-8})		(5.6697×10^{-8})

2.2 Necessity of Reducing Energy Intensiveness of Greenhouse Operation

A basic criterion for designing a greenhouse has been that the structure should admit the maximum possible amount of sunshine during the months of lowest light. The structural system must have a minimum opaque area and a maximum transparent area, and yet be strong enough to support itself and predicted wind and snow loads. The structure must be made of transparent material such as glass or plastic to supply the necessary light for plant growth (2). Unfortunately, these materials have poor thermal resistance characteristics. As a result, a great deal of heat will be required to maintain the necessary temperature inside the structure in most regions of Manitoba. Excessive heating will render the whole greenhouse operation uneconomical during the most severe part of the winter. Greenhouse heating is probably the most inefficient use of fuel of most heating applications (36).

During summer, a transparent greenhouse admits more sunlight than necessary and, therefore, increases the ventilation requirements. At a time when energy is becoming more costly and scarce, it is very important to research ways so that the energy intensiveness of the greenhouse industry is reduced.

2.3 Techniques to Reduce Heat Losses from Greenhouses

Price <u>et al.</u> (36) have laid guidelines to minimize thermal wastage from greenhouses. Their most critical recommendations include leak-proof greenhouse construction, using a double layer in plastic-covered greenhouses, and drawing a black curtain between the greenhouse covering and the plant canopy at night. Substantial savings (20 to 25 percent) in fuel are projected if these guidelines are followed. They have presented other suggestions which would reduce the energy demand of greenhouses such as insulating the greenhouse during the night and removing the insulation during sunshine hours; or using an opaque, insulated structure with artificial lighting.

The use of curtains in greenhouses at night to reduce heat losses has also been studied by Amsen (3) and Simpkins et al. (42). Amsen mathematically evaluated the effect of using curtains in greenhouses on radiative heat loss to the atmosphere at night. He introduced the 'curtain effect' which is defined as: the radiative difference in net heat radiation from a plant canopy before and after a curtain, with a specified 'curtain factor' $(\Delta = \psi_t - \rho_t)$, is placed between the plant canopy and the greenhouse roof. Mathematically, the 'curtain effect' is:

$$\sigma = 1.0 - 2.0 \left(\frac{1 + \Delta}{3 + \Delta}\right) \tag{2.1}$$

Using the above formula, it is possible to evaluate and compare the effect of using curtains of different materials on radiative heat loss from the plant canopy to the atmosphere. An aluminum curtain would give a curtain effect as high as 90 percent because of its high reflectance, 0.9.

Simpkins et al. (42) conducted experimental studies to determine the coefficients of heat transfer through the walls and roof of a double-layer air-inflated polyethylene greenhouse with an internal curtain added. Various materials and installation techniques were studied and several proposed curtain materials evaluated. Tests were conducted in an environmental chamber and in a small prototype greenhouse. Based on the results of their tests, they observed that conduction due to thin curtains depends, primarily, upon the method and position of fastening and not upon the curtain material. A curtain fastened horizontally from eave to eave was more effective than one fastened from eave to peak. Installing a curtain with the edges sealed with no contact between the curtain and the greenhouse structure, except at the edges, maximized the added resistance to heat transfer by conduction. It was also observed that a curtain with higher reflectivity saved more radiation heat loss. A highly reflective curtain fastened tightly from gutter to gutter, with similar side wall and end wall curtains, could save half of the energy currently required to heat a double-layer air-inflated multi-span polyethylene greenhouse.

Both Amsen (3) and Simpkins et al. (42) assumed that the curtains were thin and, therefore, offered no appreciable conductive resistance in themselves. The observation of Simpkins et al., that a curtain with higher reflectivity saves more radiative heat loss, is consistent with Amsen's prediction of curtain effect. The former researchers also note the importance of the method and position of fastening the curtain to achieve better results.

Perry (35) has developed a 'clicon' system consisting of pairs of mylar tubes. Half of the outer surface of each pair is aluminized for light and radiation control. These tubes can be inflated to make contact as a ceiling at night or be partially or fully deflated and hung vertically in the day. The 'clicon' system has been reported to have reduced night roof heat losses by 48 percent. It minimum light obstruction is 15 percent at solar noon. It should be noted that the 'clicon' system was adopted taking into consideration, the climatic conditions at 34°

latitude where a 15 percent reduction in sunlight could be tolerated. Applying the 'clicon' system at 50° or higher latitudes, common in Canada. would probably result in an intolerable loss of sunlight during winter and early spring. Daily operation of either 'clicon' or night curtain would also add to the responsibilities of the operator.

Lawand et al. (23) developed an environmentally designed greenhouse for colder regions, Fig. 2.1. The east-west oriented greenhouse has its inclined north-facing wall insulated with a reflective cover on the interior face. The angles of each inclined roof were designed to permit optimum transmittance of solar radiation and maximum reflection of this radiation on the plant canopy. The shape of such a greenhouse is very different from the traditionally built symmetrical (about the ridge line) greenhouse shapes. Heat loss savings reported are promising in this greenhouse, but adoption by growers would require assessment of structural and economic performance of this greenhouse, relative to traditional shapes.

Musard (32) has carried out experimental trials with discontinuous fixed transparent screens located between the plants and the ceiling of the greenhouse. These screens must be discontinuous to allow for ventilation. They could, however, be continuous in a greenhouse fitted with a forced ventilation system. The screens in the trial were 1.5 m wide cut from 50 micron thick polyethylene film placed across the greenhouse span. Separation between screens varied from 10 to 15 cm. Installation of the discontinuous screens is shown in Fig. 2.2. Recorded temperatures under the screens were 0.7 C higher than those recorded above the screens when the control temperature was set at 13 C and 1.2 C with the control temperature set at 15 C. In the middle of the gaps

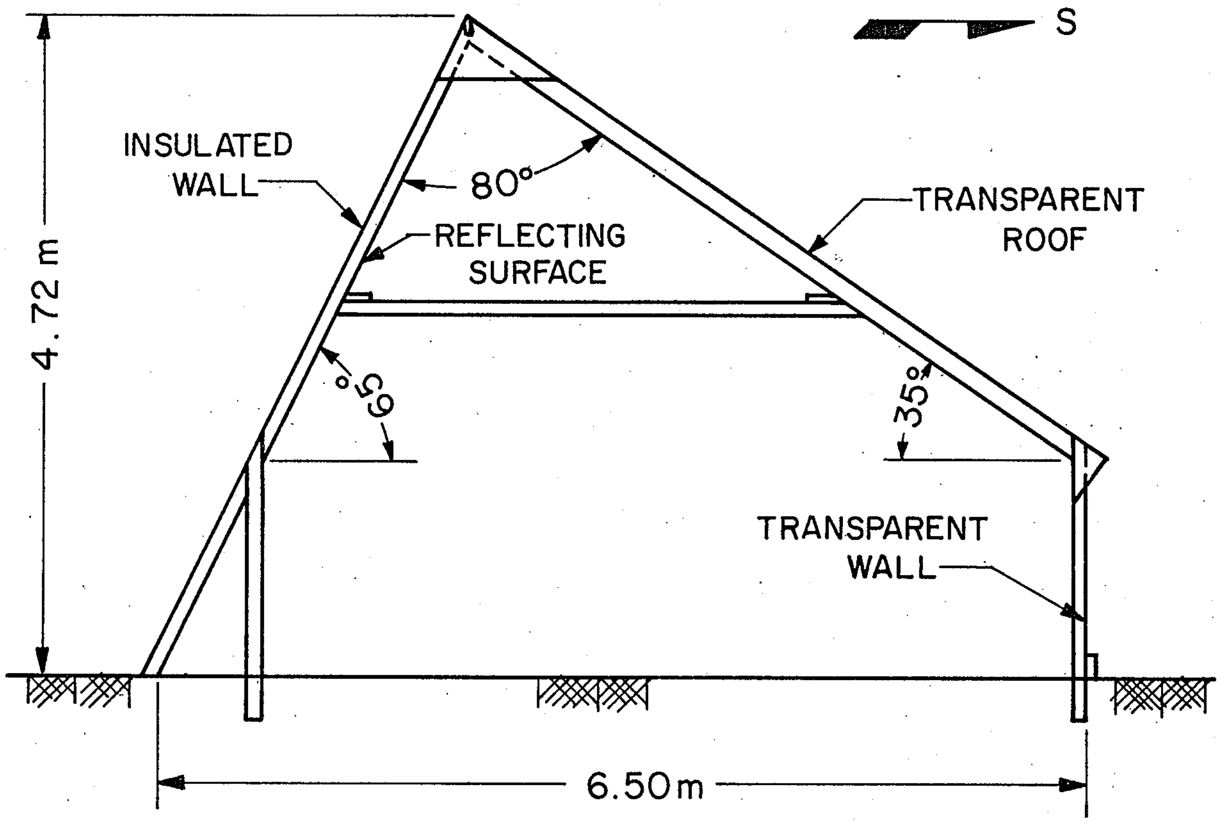

Fig. 2.1 Greenhouse for colder regions designed by Lawand et al. (23)

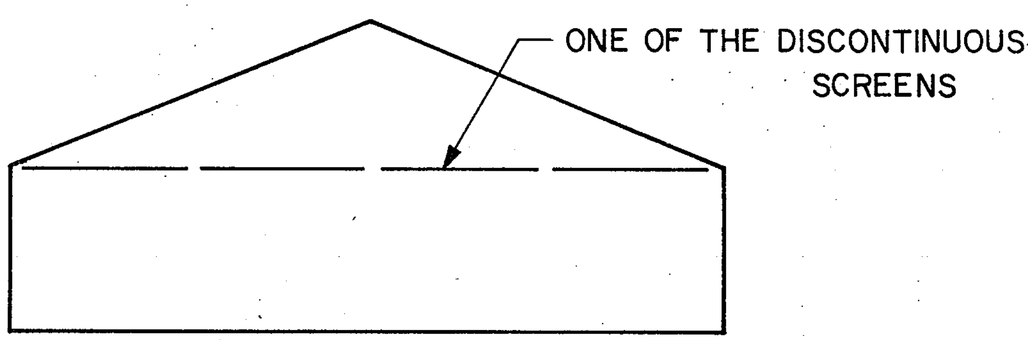

Fig. 2.2 Position of the discontinuous screens in a greenhouse as suggested by Musard (32)

between the films, a difference of 0.5 C between the temperature taken at 0.5 m below the level of screen and at 0.5 m above had been observed. These trials, carried out in glasshouses in France, showed that in spite of the reduction in luminosity there was some saving in heating and an improvement in the yield of early tomatoes. The author suggested that three to four percent energy savings were possible with such an arrangement.

Use of screens, as suggested by Musard (32) results in a reduction in solar radiation intensity at crop level that may not be tolerated in Canadian winter conditions. As well, these screens when installed would also restrict the cultural operation inside the greenhouse. Musard also noted that the improvement in the insulation of the walls exposed to the north or to the prevailing wind will result in a saving of energy. The suggested use of a double layer of plastic materials having low transmission to longwave radiation for greenhouse walls and the use of carbon dioxide between the two films of plastic instead of air should result in a better greenhouse effect.

According to trials carried out in Great Britain (7), using black polyethylene screens during nocturnal periods results in energy consumption savings of 33 percent. Taken over the total cultivation period this saving becomes 20 percent. If the screen is not continuous and has a gap of even one metre, the effect is almost completely lost.

2.4 Previous Studies on Greenhouse Thermal Environment

An analysis of greenhouse thermal environment was done by Morris (31) as early as 1956. Using a simple calculation procedure and a number of simplifying assumptions he computed design ventilation requirements for various sizes of gable greenhouses. Since this initial work, there have been a number of studies which have resulted in more accurate