

Solar radiation transmission and capture in greenhouses

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Lau, A. K. and Staley, L. M. 1989. **Solar radiation transmission and capture in greenhouses.** *Can. Agric. Eng.* **31**: 204–214. Solar radiation transmission and capture in single-span greenhouses were evaluated by means of computer modeling and simulations. The quantity of solar radiation incident on an inside surface is governed by the geometry of the greenhouse through the interception factor for direct radiation and configuration factor for diffuse radiation. Simulated results were found to agree reasonably well with actual data obtained from a shed-type glasshouse and a conventional glasshouse. Computer runs using long-term average solar radiation data revealed that the greenhouse shape and cover material had an obvious effect on the effective transmissivity of the greenhouse. Results of this study would be useful in applications where the monthly average hourly solar radiation level inside the greenhouse enclosure needs to be accurately estimated for design purpose.

INTRODUCTION

Mathematical modeling of the greenhouse thermal environment provides an effective means in studying energy utilization of greenhouses. In the energy balance, solar radiation absorbed by the various component surfaces constitutes the major heat term and therefore it should be calculated as accurately as possible. Seginer and Levav (1971) made a thorough review of the models existing at that time, pointing out the need to develop models which only include primary boundary conditions that are easy to measure and unaffected by the existence of the greenhouse. Kindelan (1980) adopted this approach, and he recommended the use of more elaborate models of solar radiation transmission. Cooper and Fuller (1983) and Arinze et al. (1984) modeled the environment of greenhouses equipped with thermal storage.

A number of greenhouse steady-state and even unsteady-state modeling studies adopted a simple method to estimate the inside solar radiation level. An average value of the transmittance of the greenhouse cover material is used regardless of greenhouse construction, orientation, location, and time of the year. While this approach might be appropriate for the determination of an adequate ventilation rate required to maintain healthy plant growth based on maximum solar heat input at noon (Walker et al. 1983), it is not applicable for the purpose of studying the thermal environment of solar greenhouses. Large errors could be induced in the estimation of hourly solar heat gain, and subsequently affect the accuracy of predicting energy flows and utilization in the greenhouse environment.

The purpose of this paper is the determination of solar radiation transmission and capture in greenhouses by means of computer simulations. Results of this investigation would be useful in applications where the monthly average hourly inside solar radiation level needs to be estimated, such as the simplified design procedure for greenhouse solar heating systems developed by Lau (1988) and in the prediction of greenhouse crop

canopy photosynthesis (Charles-Edwards 1981). More precise values of solar radiation transmissivity may be used in estimating the ventilation requirements of greenhouses. Greenhouses with alternative design variations may also be compared from a solar utilization efficiency standpoint.

LITERATURE REVIEW

Many studies have been carried out to evaluate the performance of greenhouses in transmitting light, and results were generally presented with regard to the glazing level transmittance, τ , or more frequently the effective transmissivity, τ_e . Whereas τ showed mainly the effects of the optical properties of glazing materials, sky clearness and solar angle of incidence, τ_e is strongly influenced by the greenhouse geometric configuration and internal structures. Though various authors used different terminologies in reporting their research outcomes, τ_e can generally be defined as the amount of solar radiation (broad-band or PAR) received on an inside horizontal surface as a percent of that falling on an outside horizontal surface of the same area. The inside horizontal surface may be taken at any height, but the plant canopy (gutter height) level is the most appropriate reference while floor level measurements have also been reported.

Walker and Slack (1970) made a comparative summary of the optical properties of selected rigid and film plastic covers. Polyvinyl, polyester, fiberglass and rigid PVC show a reduced transparency in the 735-mm wavelength, which would have a significant effect upon flowering and stem elongation of plants. Transmittance of global (direct and diffuse) solar radiation for all materials with the exception of standard fiberglass was about 90%; fiberglass exhibited a marked difference between direct and global transmittance.

Later in the decade, Godbey et al. (1979) carried out extensive experimental work to determine values of τ for a variety of glazing materials. Global as well as direct solar energy transmission were measured for six angles of incidence ranging from 0° to 67°. Results were presented for single-layer samples and two-layer combinations.

In his comprehensive study of the greenhouse climate, Businger (1963) introduced a daylight coefficient which related inside and outside short-wave radiations, taking into account the optical losses through glass and the influence of the construction, the orientation and the location of the greenhouse on a lumped basis. This coefficient varies from 0.55 under diffuse light conditions to 0.75 when direct light predominates.

Edwards and Lake (1965) measured solar radiation transmission in a large-span 1800-m² east-west oriented greenhouse. Obstructions to diffuse radiation caused by various components of the structure were determined by making measurements on overcast days at various stages of construction. The

mean daily transmissivity of the diffuse component was found to be 64–69%; that of the direct component, 57% in summer and 68% in winter. They pointed out that changes in shape rather than structure could lead to improvements in transmission, particularly that of direct radiation.

Manbeck and Aldrich (1967) attempted to generalize direct visible solar radiation transmission in greenhouses using an analytical procedure. Computational results showed that at a latitude of 45°N, an E-W oriented gable-roof surface transmitted more solar radiation in the winter months and slightly less in early fall and spring than one oriented N-S.

A more generalized analytical method was outlined by Smith and Kingham (1971) for computing the solar radiation components falling within a single-span glasshouse located at Kew, England. They introduced an angle-factor and separately evaluated this factor using geometric and trigonometric analyses for the direct and diffuse radiations transmitted by a glass surface (roof or wall) and subsequently intercepted by the floor of the house. The calculated values of τ_e ranging from 0.66 in June to 0.70 in January were in agreement to within 5% with the observed values of Edwards and Lake (1965).

Experimental rigid plastic greenhouses ranging in size from 20 m² to 40 m² were used by Aldrich and White (1973) to study the relationship between structural form and quality and quantity of transmitted solar energy in such greenhouses. Measurements were taken on 9 days during two winter growing seasons. Results showed that there is an insignificant difference in τ_e due to single acrylic sheet cover or glass, with a value of 0.72 ± 0.06 (acrylic) and 0.72 ± 0.03 (glass), compared to that of a fiberglass cylindrical vault which was found to be 0.67 ± 0.05 .

The Brace Research Institute style greenhouse was proposed by Lawand et al. (1975) as an unconventionally shaped greenhouse for colder regions. The basis for the new design was to maximize solar radiation input while reducing high heat losses. The greenhouse is thus oriented on an E-W axis, with transparent south-facing roof and wall (air-inflated polyethylene), and the inclined north wall is insulated with a reflective cover on the interior face. Tests with a 40-m² experimental unit showed that solar irradiance at the north side of the house was higher than that on the south side by as much as 60% when direct light predominates. When diffuse light predominates, north side light levels are lower than on the south side. Based on the entire horizontal surface, average τ_e value was 0.54 in April and 0.90 in December.

Kozai et al. (1977) developed a computer model to predict the effects of orientation and latitude on the overall transmissivity of a free-standing conventional glasshouse. He concluded that the difference in greenhouse direct radiation transmissivity between E-W and N-S oriented greenhouses is larger at high latitudes; the E-W orientation was greater by 22% for Amsterdam (52.3°N) and 7% for Tokyo (35.7°N).

Turkewitsch and Brundrett (1979) used the computer simulation technique to predict solar energy admission of four single-span glasshouses of different shapes. Their results reinforced the Brace style greenhouse design concept that reflecting insulation walls augment winter light levels and reduce summer ventilating heat load. Yet, its disadvantage was found to be the higher penalty under completely overcast conditions compared to Greensol (an asymmetrical glasshouse retaining the north roof and insulating only the north wall); the latter has a larger transparent cover area to floor area ratio. In this regard, though, Lawand et al. (1975) suggested that new greenhouse designs

should have every effort made to reduce the exposed transparent cover surface area and hence the conductive heat loss, while maximizing solar gain.

Light intensity measured directly above the top heating pipes was compared by Amsen (1981) for double glass and double acrylic greenhouses with reference to a single glasshouse. No absolute values of τ_e were reported, rather light level was found to be 20 and 22% less under double glass and double acrylic respectively.

Ferare and Goldsberry (1984) reported values of τ_e measured at plant level (1 m above floor) under double glazings. The percent of global radiation transmitted ranged from 0.55 to 0.65 for double polyethylene (Monsanto 603) and 0.62 to 0.72 for double PVC (4 mil) between October and April.

In Hannover (52.5°N), Bredenbeck (1985) measured light transmissivity at the plant canopy level in three N-S oriented greenhouses each covered with single glass, double glass and double acrylic over a period of 2 yr. The transmissivity of the single glass house was about 0.60 in summer and 0.55 in winter. It was noted that the transmissivity for diffuse radiation in winter time was higher than that for direct radiation, a well known connection between greenhouse orientation and light transmissivity. The corresponding values for the double glass house were about 0.10 less. Double acrylic cover had a transmissivity ranging from 0.60 to 0.64 with no significant difference between summer and winter months. τ_e for double acrylic was better than double glass and was attributed to the placing of fewer bars (aluminum with rubber profiles) in the roof area and the treatment of the cladding material with a 5% "sun-clear" solution.

Ben-Abdallah (1983) analyzed solar radiation input to conventional and shed-type glasshouses by means of the "total transmission factor, TTF" defined as follows:

$$\text{TTF} = \frac{\sum_k A_k (I_{bt} + I_{dt})_k}{A_f I_o} \quad (1)$$

The numerator represents the sum of beam and diffuse radiations transmitted through all glazing surfaces, while the denominator is global solar radiation incident on an outside horizontal surface. Geometric losses are excluded in this expression. He used this factor to compare solar input efficiency of conventional and shed-type greenhouses. The concept behind the TTF is important in that the transmitted solar radiation at the glazing level is an essential secondary quantity that leads to the computation of tertiary quantities such as solar radiation falling onto plant canopy and floor levels.

The research work carried out by Ting and Giacomelli (1987) dealt with both τ and τ_e . They found that air-inflated double polyethylene transmitted a higher percentage when measured in the broadband range (0.83) than in the PAR range (0.76). However, effective transmissivity based on the PAR range is much reduced at the canopy level, and is only 0.48, which is indeed a very low value compared with findings by other authors.

Coffin et al. (1988) built and tested scale models of conventional and insulated multispan greenhouses at Montreal. The E-W models were found to have higher overall light levels (average $\tau_e = 0.67$) than the N-S (average $\tau_e = 0.61$) during the winter months from October to March, though no apparent differences were observed for the rest of the year.

COMPUTER MODELING AND SIMULATIONS

The foremost requirement for computing the capture of solar radiation is the transmittance of the cover material of known

refractive index, n and extinction coefficient k . Values of n for most glazing materials is published in handbooks (International Technical Information Institute 1976; Bolz and Ture 1979), but values of k for plastics are not immediately available. This problem was resolved by iteratively calculating the value of k using Fresnel's relation and Bouguer's law of attenuation (Duffie and Beckman 1980), along with the measured values of direct transmittance at various incident angles (Godbey et al 1979). k was thus estimated to be 400 m^{-1} and 10 m^{-1} for polyethylene and acrylic, of thickness 0.1 mm and 16 mm (two 2-mm sheets with 12-mm air space) respectively. Also, using the total and direct transmittance values determined by Godbey et. al. (1979) in the same study, the diffusing power of polyethylene was estimated to be 10% for an angle of incidence θ_i below 60° , and 15% when θ_i exceeds 60° .

For model validation purpose, solar radiation incident upon the various surfaces — greenhouse cover, plant canopy, floor, and absorber plate (for the solar shed only) are computed from measured global and diffuse irradiances incident on an outside horizontal surface. Beam irradiance is the difference between the two quantities. Diffuse and beam components were each transposed to radiation incident upon an inclined plane (the cover). Transmitted solar irradiance is then calculated for each hour using the incidence angle at mid-hour, by means of Fresnel's relations and Bouguer's law of attenuation that account for reflectance and absorptance, respectively. The diffuse component is relatively independent of the sun's position and is assumed to be incident at a constant 60° . The above computational formulae are presented in detail by Duffie and Beckman (1980). The total solar energy input is the sum of beam radiation, I_{bt} and diffuse radiation, I_{dt} , transmitted at the glazing level through the roof, the wall and gable ends. The latter originates from I_d , the sky diffuse irradiance and ground reflected irradiance, assumed perfectly diffused. An anisotropic model (Klucher 1979) was used to transform I_d to I_{ds} ; this model approximates partly cloudy sky conditions, and may vary from clear skies on one extreme to entirely cloudy skies on the other.

The admitted solar radiation has to be traced further to arrive at quantities of solar energy incident on an inside surface. Two separate factors are required, one called the "interception factor (P_{kj})" for beam radiation, the other is the well-known "configuration factor (F_{kj})" for diffuse radiation. The interception factor is necessary because the dimensions of the greenhouse dictate the percentage of transmitted direct sunrays that is captured by an inside surface, whereas the configuration factor accounts for diffuse radiation that does not reach the surface in question. Based on the method outlined by Smith and Kingham (1971), equations for P_{kj} were formulated by Lau (1988) for each of the inside surfaces; it is a function of the solar altitude, the solar azimuth, as well as the cover surface azimuth and slope, and the greenhouse dimensions. The expression for F_{kj} between two rectangles having a common edge and forming an arbitrary angle was due to Feingold (1966). F_{kj} varies with the greenhouse dimensions and the relevant cover surface area involved in the radiation interchange. Eventually, solar radiations incident on the plant canopy I_p , and the absorber plate I_q are summarized in the following two expressions:

$$I_p = \sum_k A_k \{ (I_{bt} P_{kp} + I_{dt} F_{kp}) + \rho_q F_{qp} (I_{bt} P_{kq} + I_{dt} F_{kq}) \} / A_p \quad (2)$$

$$I_q = \sum_k A_k \{ (I_{bt} P_{kq} + I_{dt} F_{kq}) + \rho_p F_{pq} (I_{bt} P_{kp} + I_{dt} F_{kp}) \} / A_q \quad (3)$$

where k denotes each cover surface. The assumptions made were that only one internal reflection is considered, as subsequent multiple reflections are much weakened because of low albedo values of the various participating surfaces, and that a surface reflects radiation diffusely.

In addition to these two factors, internal structure and overhead mechanical equipment were assumed to cause a lumped 10% blockage of solar radiation due to reach an inside surface. The effect of dirt on the cover is of minor concern here as these research greenhouses were designated for collection of daytime surplus solar heat and thus subject to routine maintenance.

MODEL VALIDATION — RESULTS AND DISCUSSION

Before making any comparison between simulated and measured data, the latter, as collected by Staley and Monk (1984), were analyzed in terms of the total transmission factor, TTF (Eq. 1), and the effective transmissivity, τ_e , defined as

$$\tau_e = \frac{A_p PAR_p / 0.45}{A_f I_o} \quad (4)$$

The constant 0.45 is the conversion factor between photosynthetically active radiation (PAR) and broadband solar radiation (Salisbury and Ross 1982).

Two greenhouses were used to provide actual data. These research units are located at the former Agriculture Canada Saanichton Research Station, Sidney, B.C. (latitude 48.5°N , longitude 123.3°W). A 6.4-m \times 18.3-m shed-type structure is one-half of a conventional 12.8-m-wide gable roof glasshouse that has had its north roof eliminated and north wall insulated. The south roof surface is tilted at 26.6° from the horizontal. Another structure is a conventional glasshouse that serves as the experimental control. Both houses are supported by conventional trusses. All data related to the solar energy experiments were collected on a continuously integrated basis, and recorded hourly. In particular, outside solar radiation was measured by silicon photodiode pyranometers (Li-Cor LI-200SB and 2010S), and transmitted radiation at the glazing level by photovoltaic pyranometers (Rho-Sigma RS-1008). Photosynthetically active radiation on an inside horizontal surface at the plant canopy (gutter height) level was measured by light sensors (Li-Cor LI-190SEB).

Values of TTF deduced from measured solar radiation data inside and outside the greenhouse for the shed-type structure are consistently higher than those for the control house, as shown in Fig. 1. The shed has a TTF ranging from 2.16 in December to 1.03 in June, whereas the control house achieved a value declining from 1.66 in December to 0.93 in July. During the period October 1983 to September 1984, solar energy input into the shed with north wall insulated amounted to 5.11 GJ/m^2 compared to 4.22 GJ/m^2 for the conventional house. Since the two houses have almost the same glazing to floor area ratio (1.98 vs. 2.02), the shed-type glasshouse appears to be more efficient in admitting solar radiation than the conventional shape. This may be attributed to the shed's larger area (131 m^2) of the south roof as the major cover surface compared to 110 m^2 for the control house.

Simulations were carried out using one week's data from each month, and computed values of TTF are plotted in Fig. 1. The very good agreement between measured and predicted values may be credited to the well-established mathematical relations used for calculating transmitted solar radiation through non-diffusing materials.

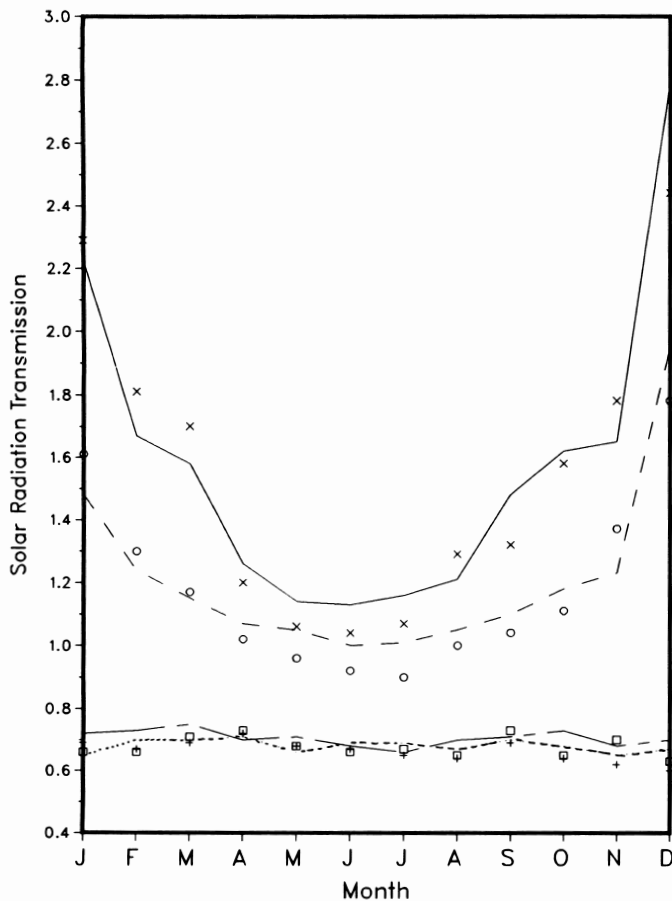


Figure 1. Total transmission factor and effective transmissivity. Experimental and simulated results for the period September 1983 to August 1984. \times , shed-type, measured TTF; —, shed-type, simulated TTF. \circ , conventional, measured TTF; ---, conventional, simulated TTF. \square , shed-type, measured τ_e ; ———, shed-type, simulated τ_e . +, conventional, measured τ_e ; , conventional, simulated τ_e .

Values of τ_e derived from experimental data are also plotted in Fig. 1 along with the TTF values. Two trends that are not possessed by TTF can now be realized. The annual variation of the effective transmissivity of each greenhouse does not vary by more than 25%, and there is no appreciable difference in effective transmissivity between the shed and its conventional counterpart. These results are not particularly surprising, considering the dimensions of the solar shed that limit the percentage of transmitted beam radiation to be intercepted at the plant canopy level. The drastic difference in the magnitudes of TTF and τ_e of the same greenhouse points out the phenomenon that even though the solar shed can admit a substantially greater amount of solar radiation at the glazing level, the loss induced by the greenhouse geometry itself on both the direct and diffuse components eventually erodes this advantage. Further computer simulations produced τ_e values that have a maximum deviation of 13% from the experimental values, and these computed results are found in Fig. 1 as well. Three weeks have been chosen for presenting details of the predicted and measured values of hourly inside solar radiation that forms the basis of τ_e and TTF, as illustrated in Figs. 2, 3 and 4.

The week of 18–24 Feb. 1984 recorded a sequence of medium to low hourly solar radiation ($I_o = 300\text{--}500 \text{ W m}^{-2}$), which was 81% diffuse in nature. Average daily I_o amounted to 6.2 MJ m^{-2} . Conversion of PAR to global solar radiation revealed that the magnitude of solar radiation incident on the absorber

plate was very close to that incident on an inside horizontal surface at the plant canopy level, as demonstrated in Fig. 2. Weekly total I_p is 8421 MJ and is 5% greater than the measured value of 8015 MJ . As for I_q , simulated and actual data differ by 9%.

Global solar radiation averaged 14.4 MJ m^{-2} per day within the week of 25–31 Mar. 1984, and beam radiation constitutes 70% of I_o . The second half of this week had abundant sunshine when I_o attained values of up to 800 W m^{-2} for 3 consecutive days. Figure 3 indicates that predicted and measured inside solar radiation agrees well and are within 7% of one another.

The solar radiation of the week 8–14, Apr. 1984 is characterized by the approximately equal magnitudes of the beam and diffuse components. Simulated values of inside solar radiation fall within 9 and 12% of measured values in regard to that incident on the absorber plate and the plant canopy, respectively. The larger discrepancy between predicted and actual data is likely attributed to heavier condensation taking place on the cover inside surface on some occasions.

On 29 Mar., the plant canopy and absorber plate temperatures had attained maximum temperatures of (39°C and 58°C), but on 8 Apr. they were (32°C and 49°C) as I_o peaked at 760 W m^{-2} on each occasion, and both days recorded total I_o to be in the vicinity of 4850 Wh m^{-2} . This observation demonstrates that the greenhouse thermal environment is influenced, among other factors such as transpiration, by the relative amounts of the diffuse and direct components of the global solar radiation. Whereas the diffuse radiation configuration factor between the cover (south roof) and the vertical absorber plate is only 0.26, the beam radiation interception factor is 0.34 at noon at this time of the year. The shed-type greenhouse actually captures beam radiation more effectively than diffuse radiation during most of the day. Solar radiation on 29 Mar. is predominantly direct (78%) in nature, by contrast, it is 46% diffuse on 8 Apr. Hence, the inside surfaces were heated to a higher temperature in the former case.

SIMULATION FOR LONG-TERM AVERAGE PERFORMANCE

Simulations were extended to predict the long-term average solar input efficiency. Mean (monthly average) meteorological data are used. They include the daily (H) or hourly (I) global solar radiation incident on an outside horizontal surface. Some weather stations also recorded diffuse or direct radiation in addition to global radiation, and these were used as inputs so as to reduce the error incurred by estimating either form of radiation with empirical relations. These weather data are published by Environment Canada (1983) for many Canadian locations. Ground albedo is needed to compute reflected diffuse radiation from the greenhouse surroundings, and mean values measured for large geographic areas were obtained by Hay, as cited by Iqbal (1983).

Unlike the short-term records of outside global and diffuse solar radiation data, there are five possible cases where processing of monthly average solar radiation data are needed.

Case 1. Only hourly global radiation (I) is available.

Hay's method (1979) may be used to compute the hourly diffuse component, I_d . It takes into account the modified daylength which excludes the fraction when the solar altitude is less than 5° , and the clear sky albedo and cloud albedo, having values of 0.25 and 0.6, respectively. I and I_d are the global and diffuse radiations before multiple reflections between the ground and the sky.

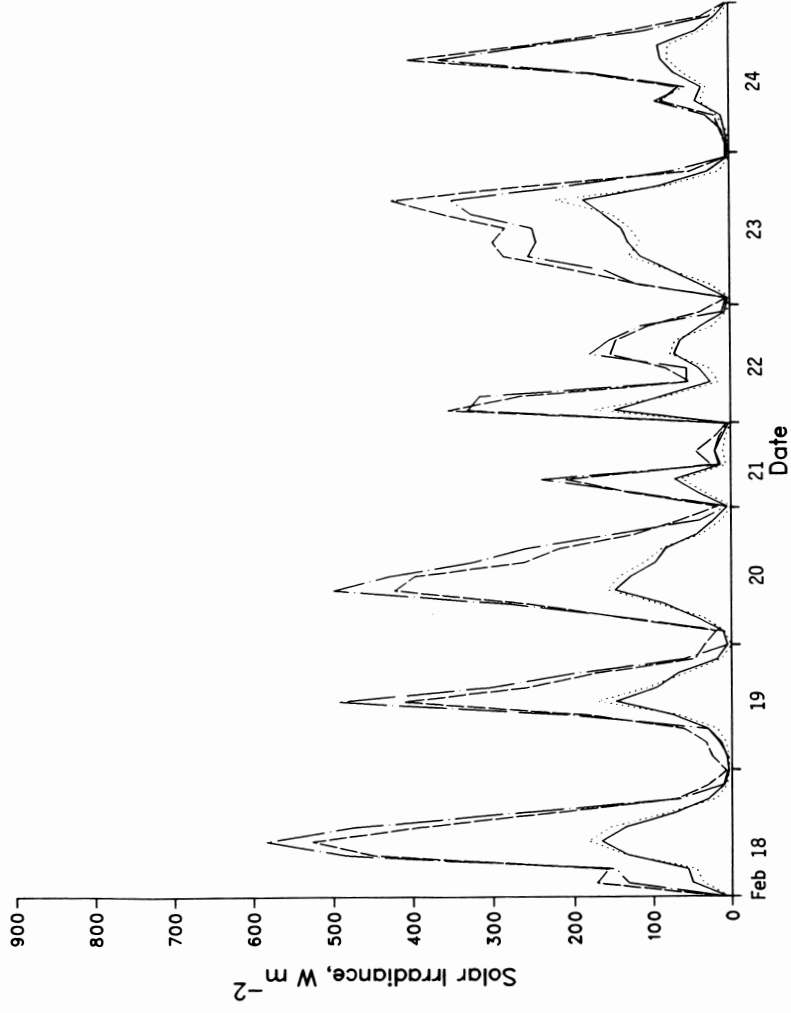


Figure 2. Predicted and measured inside solar radiation, 18-24 Feb. 1984. —, predicted, PAR on horizontal surface; ·····, measured, PAR on horizontal surface; ---, predicted, incident on absorber plate; -·-·, measured, incident on absorber plate.

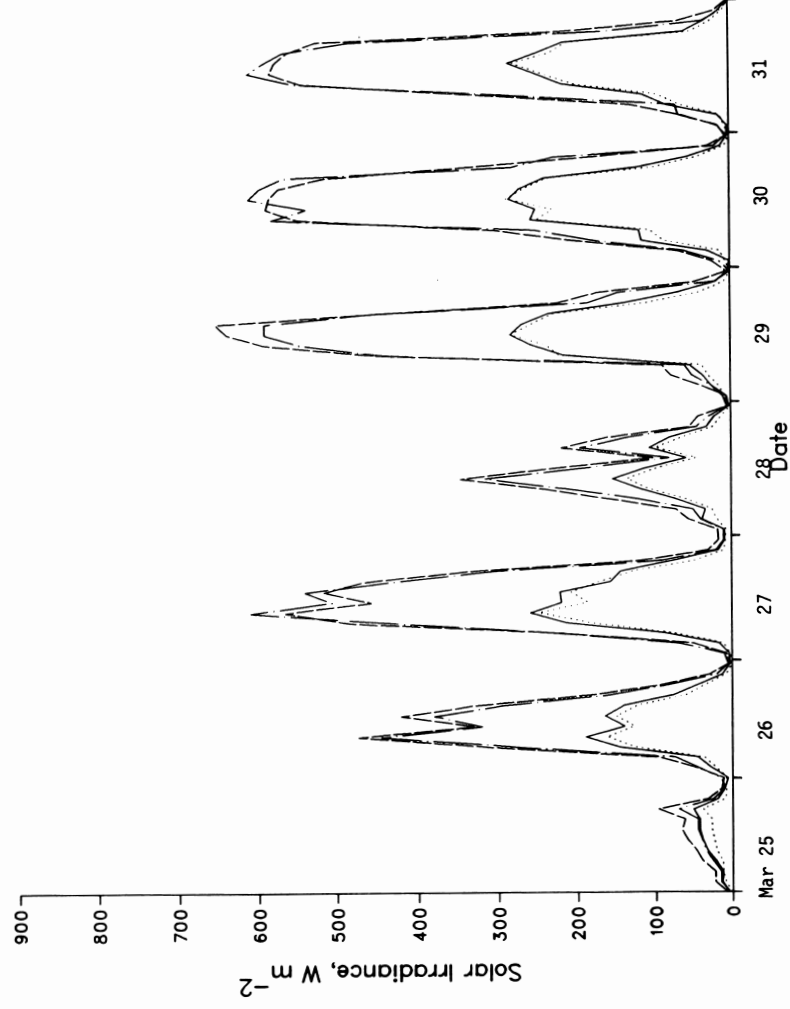


Figure 3. Predicted and measured inside solar radiation, 25-31 Mar. 1984. —, predicted, PAR on horizontal surface; ·····, measured, PAR on horizontal surface; ---, predicted, incident on absorber plate; -·-·, measured, incident on absorber plate.

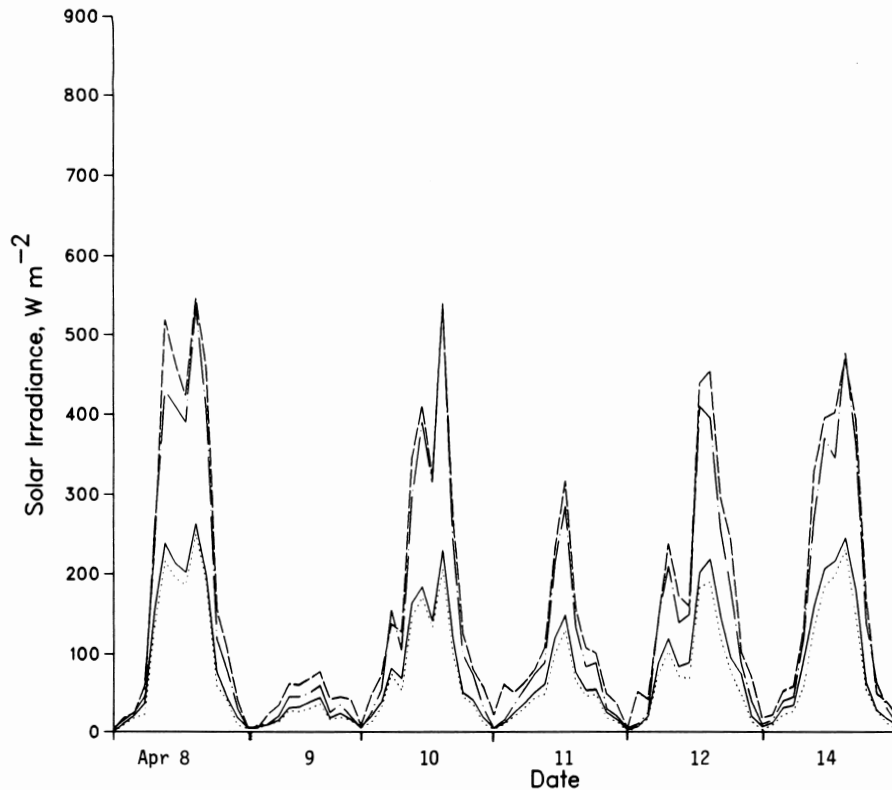


Figure 4. Predicted and measured inside solar radiation, 8–14 Apr. 1984. —, predicted, PAR on horizontal surface; ·····, measured, PAR on horizontal surface; ---, predicted, incident on absorber plate; -·-·, measured, incident on absorber plate.

Case 2. Hourly global and diffuse radiations (I and I_d) are both available.

This is the most straight-forward situation, and no solar data processing is necessary.

Case 3. Only daily global radiation (H) is available.

A few correlations have to be applied in sequence to achieve our aim in this case. First, for locations situated between 40°N and 40°S , the daily diffuse radiation H_d can be calculated from Page's correlation (1979), whereas Iqbal's correlation (1983) may be used for Canadian locations. The next step is to estimate hourly diffuse radiation I_d from H_d using Liu and Jordan's method (1967). Finally, hourly global radiation, I , can be calculated by the expression of Collares-Pereira and Rabl (1979).

Case 4. Only the number of bright sunshine hours (m) is available.

This case applied to locations where solar radiation is not routinely measured, rather, sunshine records are maintained. The correlation due to Rietveld (1978) has been adopted to estimate H . Thence, H_d , I_d and I are estimated as outlined in case 3 above.

For the above cases, hourly beam radiation I_b is calculated simply as the difference between I and I_d .

Case 5. Both hourly global and direct normal radiations (I and I_n) are available.

This case refers to the U.S. locations where I_n is measured by a pyroheliometer (National Climate Center 1981). I_b is related to I_n through the solar

azimuth angle, thus

$$I_b = I_n \sin \beta$$

where:

$$\sin \beta = \sin l \sin \delta_c + \cos l \cos \delta_c \cos h \quad (5)$$

Then I_b is subtracted from I to get I_d .

Design variations considered in this study are those involved in predicting the long-term average system thermal performance of greenhouse solar heating systems using the greenhouse as the solar collector (Lau 1988). A parametric study was undertaken to examine the effects of greenhouse design parameters on both the actual quantity of solar radiation transmitted into the greenhouse enclosure and the solar input efficiency. They are listed as follows:

- Shape: conventional (gable roof and quonset), shed-type and Brace-style.
- Roof tilt: $18.4^\circ(1:3)$, $26.7^\circ(1:2)$ and $33.7^\circ(1:1.5)$.
- Glazing material: glass, polyethylene and twin-walled acrylic.
- Length-to-width ratio: 2, 4 and 8.
- Orientation: E-W and N-S.

The shape and glazing of the greenhouse are the major design parameters that affect the useful heat gain of a greenhouse being used as a solar collector. Embedded in the parameter "shape" is the energy collection or absorption method. The shape SS represents method I that features a shed-type greenhouse with north wall insulation and a vertical absorber plate with high short-wave absorptivity for augmenting heat collection. Method II is implied by the shape CV where a conventional greenhouse (gable roof or quonset type) is built without modification. The curved surface of the quonset house could be approximated by

polygons (Arinze et al. 1984), but the resulting profile would complicate the formulation of interception and configuration factors for computing the effective transmissivity. The quonset shape is assumed to have straight edges like the gable-roof greenhouse. The BS shape refers to energy collection method III whereby a Brace-style greenhouse having an insulated north surface and lined inside with a highly reflective material is used for energy collection. Equation 3, used to compute the solar radiation striking the solar shed's absorber plate, is also applicable to this reflective lining of the Brace profile.

The majority of conventional glasshouses constructed for commercial use have a roof tilt of 1:2 or 1:15. The steeper slope is usually found in greenhouses that are narrower than 8 m (Mastalerz 1979), while a slope less than 1:2 is not recommended for snowfall areas; also, condensate on the inside cover surface will have a higher tendency to drip onto the plants below unless the glazing has been pretreated with products such as the "sun-clear solution" (Bredenbeck 1985) that would permit filmwise condensation.

Unsymmetrical roof tilts are characteristics of the shed-type and Brace-style greenhouses. All three roof tilts (1:1.5, 1:2 and 1:3) were included in the parametric study for the south roof of the shed, while the north wall is at 90°. The roof slopes were fixed at a constant 35° (south side)/65° (north side) configuration for the Brace-style house.

Lastly, this study pertains to single-span greenhouses, but ones with plastic covers such as fiberglass with much light diffusive power have not been included.

PARAMETRIC STUDY — RESULTS AND DISCUSSION

First, the solar energy input to the greenhouse via the total transmission factor was examined. Representative simulated results for various seasons with regard to a conventional gable greenhouse and shed-type greenhouse are presented in Table I. The overall trend of TTF with respect to latitude shows that northern latitudes above 45°N in general attain a higher gross solar input efficiency, which is more consistent for the conventional house. For a conventional greenhouse with a north-south aligned ridge, results are found in Table II. The total solar energy input is lower in the winter but higher in the summer for the N-S orientation compared to the E-W orientation for northern latitudes ($\geq 40^\circ$). Therefore, other things being equal, an east-west greenhouse in northern latitudes requires less supplemental heat during the heating season and less ventilation in the summer if the total heat loss from the greenhouse is assumed to be a weak function of wind direction. For the southern locations (latitude $< 40^\circ$), an E-W aligned greenhouse does not claim an annual superiority over one oriented otherwise.

Though it is an important intermediate quantity, the transmitted solar radiation at the glazing level has little applicability

Table II. Total transmission factor for a north-south oriented greenhouse at various locations

	Feb.	Apr.	Jul.	Oct.	Dec.
Edmonton	1.23	1.03	0.99	1.11	1.32
Winnipeg	1.19	1.01	0.97	1.06	1.28
Vancouver	1.03	0.98	0.95	1.02	1.12
Montreal	1.07	0.99	0.98	1.02	1.13
Guelph	1.08	1.00	0.98	1.02	1.13
Lexington	1.03	0.96	0.96	0.99	1.09
Albuquerque	1.07	0.98	0.96	1.05	1.20
Tucson	1.03	0.97	0.98	1.04	1.13

in terms of greenhouse design. Results of the effects of greenhouse construction parameters on solar radiation capture will now be focused on the greenhouse effective transmissivity.

Table III gives comparable values of effective transmissivity for different greenhouse solar collection methods. A small difference in the magnitude of effective transmissivity and thus inside solar radiation exists between the SS and CV greenhouses, implying that modification of the greenhouse shape alone cannot bring about an appreciable improvement in the effective transmissivity. Over the heating season from September to May, solar radiation at the plant canopy for the SS and CV houses is 10% lower than the BS house. To demonstrate that the better solar radiation at plant level of the Brace-style greenhouse is credited primarily to the reflective aluminum foil mounted on the inside of the insulated north surface rather than the shape itself, a short-wave reflectivity of 0.05 (equal to that used for the vertical absorber plate of the SS house) was then used in the input in the simulation runs involving the BS house. It was noticed that τ_e became even less than that of the SS house. The presence of the absorber plate is beneficial for solar heat gain and collection. The reflective coating characteristics of the BS collection method permits greater luminosity, but is less effective in enhancing convective heat exchange and thus solar energy collection compared to the SS design.

The effect of cover material on solar radiation admission is also shown in Table III. Whereas the effective transmissivity of a polyethylene-covered quonset house is close to that of a gable roof glasshouse, due in part to the assumption of a straight edge for the curved surface, it is about 10% less for a gable roof greenhouse with double acrylic cover. Since the double acrylic cover retards heat loss rate by about 45% relative to single layer glass or polyethylene, the reduction in inside solar radiation level should not adversely affect the energy savings induced by the installation of twin-walled glazing material.

As the roof tilt is lowered from 33.7 to 18.4°, the glazing area is reduced by 10% and greenhouse volume gets smaller as well, hence there is slightly less heat loss. It was found that the effective transmissivity is not appreciably affected over

Table I. Total transmission factor for an east-west oriented greenhouse at various locations

Location	Latitude	Conventional glasshouse					Shed-type glasshouse				
		Feb.	Apr.	Jul.	Oct.	Dec.	Feb.	Apr.	Jul.	Oct.	Dec.
Edmonton	53.5	1.29	0.98	0.96	1.13	1.67	1.87	1.22	1.07	1.63	2.44
Winnipeg	50.0	1.22	0.98	0.94	1.06	1.49	1.80	1.18	1.04	1.47	2.15
Vancouver	49.3	1.08	0.95	0.93	1.03	1.23	1.42	1.12	1.03	1.37	1.59
Montreal	45.5	1.08	0.96	0.95	1.01	1.20	1.50	1.11	1.01	1.31	1.61
Guelph	43.5	1.10	0.97	0.94	1.01	1.19	1.62	1.11	1.00	1.32	1.58
Lexington	38.0	1.01	0.94	0.92	0.97	1.08	1.30	1.05	0.96	1.29	1.42
Albuquerque	35.1	1.03	0.94	0.92	0.99	1.15	1.46	1.09	0.96	1.41	1.73
Tucson	32.1	0.99	0.94	0.92	0.98	1.08	1.39	1.07	0.94	1.35	1.59

Table III. Effective transmissivity of an east-west oriented greenhouse for different collection systems

Shape/cover	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
<i>Vancouver</i>									
SS/GS	0.80	0.80	0.72	0.75	0.71	0.80	0.80	0.77	0.79
SS/DA	0.74	0.74	0.66	0.69	0.65	0.74	0.74	0.71	0.75
CV/GS	0.76	0.76	0.71	0.71	0.71	0.76	0.79	0.77	0.78
	0.66†	0.64	0.65	0.67	0.66	0.69	0.69	0.70	0.72
CV/DA	0.69	0.69	0.65	0.66	0.65	0.70	0.72	0.69	0.71
BS/GS	0.87	0.92	0.85	0.81	0.82	0.91	0.88	0.81	0.82
<i>Guelph</i>									
SS/GS	0.79	0.79	0.77	0.74	0.81	0.81	0.80	0.76	0.77
SS/DA	0.72	0.73	0.71	0.68	0.74	0.75	0.73	0.70	0.70
CV/GS	0.77	0.78	0.75	0.73	0.78	0.77	0.80	0.78	0.79
CV/DA	0.70	0.72	0.69	0.67	0.72	0.71	0.72	0.71	0.70
BS/GS	0.83	0.88	0.88	0.85	0.93	0.92	0.86	0.78	0.84
<i>Montreal</i>									
CV/GS	0.77	0.78	0.76	0.74	0.74	0.77	0.79	0.78	0.71
SS/GS	0.79	0.79	0.78	0.75	0.77	0.83	0.81	0.77	0.73
BS/GS	0.84	0.88	0.90	0.87	0.91	0.93	0.88	0.80	0.81

†North-south oriented greenhouse.

the range of roof slopes studied. Unlike the important role of latitude-dependent collector slope in optimizing the design of flat-plate solar collectors, the greenhouse geometry renders the roof tilt a minor factor in solar heating system design considerations. Figures 5 and 6 illustrate this point when monthly τ_e is plotted for the shed-type and conventional glasshouses at three locations, Vancouver, Edmonton and Winnipeg. For the conventional gable roof house, τ_e increases very mildly with roof tilt during the winter months, when the effect is most obvious for Edmonton, followed by Winnipeg, while Vancouver exhibits the least variation. Similar behavior is observed for the shed. The difference in the pattern between Vancouver and the other two locations may be explained by different composition of solar radiation received at Vancouver, as demonstrated by two indices: K_T , the ratio of global horizontal radiation to extraterrestrial radiation and K_d , the ratio of diffuse to global radiation that are depicted in Table IV. As shown, Vancouver has the highest K_d and the lowest K_T in the winter months, indicating the domination by the diffuse component. Coupled to the fact that the direct radiation interception factor has different values from the diffuse radiation configuration factor, a greenhouse located at Vancouver and Winnipeg therefore differs in solar radiation capture characteristics, though the two locations are at the same latitude.

Solar radiation capture is essentially unchanged when length-to-width ratio (L:W) increases from 2 to 4 or 8. For a 200-m² greenhouse, the shift in house length is from 20 m to 28 m and then 40 m, and correspondingly from 10 m to 7 m and then 5 m in width. With a high L:W ratio, the apparent advantage of relatively greater south facing glazing area is offset by the interception of less direct radiation at the plant canopy level as the result of a narrower greenhouse. From the energy conservation point of view, a low L:W ratio is preferred because of less glazing area.

The effective transmissivity of a greenhouse is reduced by 6% to 15% when it is moved from the E-W to N-S orientation, depending on the time of the year (Table III). The decrease in inside solar radiation is less pronounced in the winter months when diffuse radiation dominates for the Vancouver area. For Albuquerque where direct sunlight constitutes a major part of

the global solar radiation received during most of the heating season, the decrease of 19% in inside solar radiation regime for a N-S aligned greenhouse compared to one oriented E-W is more significant. Coffin et al. (1988) suggested that increased spatial variation in light levels within E-W greenhouses is the reason many growers prefer N-S over E-W orientation even though E-W winter light levels are higher.

Aside from assessing the influence of greenhouse design parameters on solar radiation transmission and capture, the computer model has been tested on its sensitivity to the variation of hourly solar energy input due to different processing algorithms (cases 1 to 5) as described earlier. Results for Montreal, where records of global and diffuse solar radiations and the number of bright sunshine hours are all available, indicated that the greenhouse effective transmissivity is practically unaffected by the method of solar radiation processing. The simulation method used in this study can therefore provide reasonable estimates of solar radiation transmission for locations where solar energy data are less complete than Montreal.

CONCLUSIONS

The computer model for simulating solar radiation transmission and capture in greenhouses yielded reasonably accurate results compared to actual data. As the model is extended to estimate the long-term monthly average transmission characteristics, it may be concluded that of the greenhouse construction parameters investigated, roof tilt and length-to-width ratio have least influence on effective transmissivity. The collection method that comprises the shape, cover material and solar radiation absorption means has obvious effects. In terms of effective transmissivity, solar radiation admission into greenhouses does not differ significantly, regardless of shape, unless internal reflection is increased considerably. The magnitude of captured solar radiation on an inside horizontal surface is only 70–80% of that incident on an outside horizontal surface, suggesting that glazing transmittance should not be used in place of effective transmissivity. Yet, it should be noted that the effective transmissivity of a solar greenhouse does not vary appreciably from month to month, in contrast to the trend of the total transmission factor.

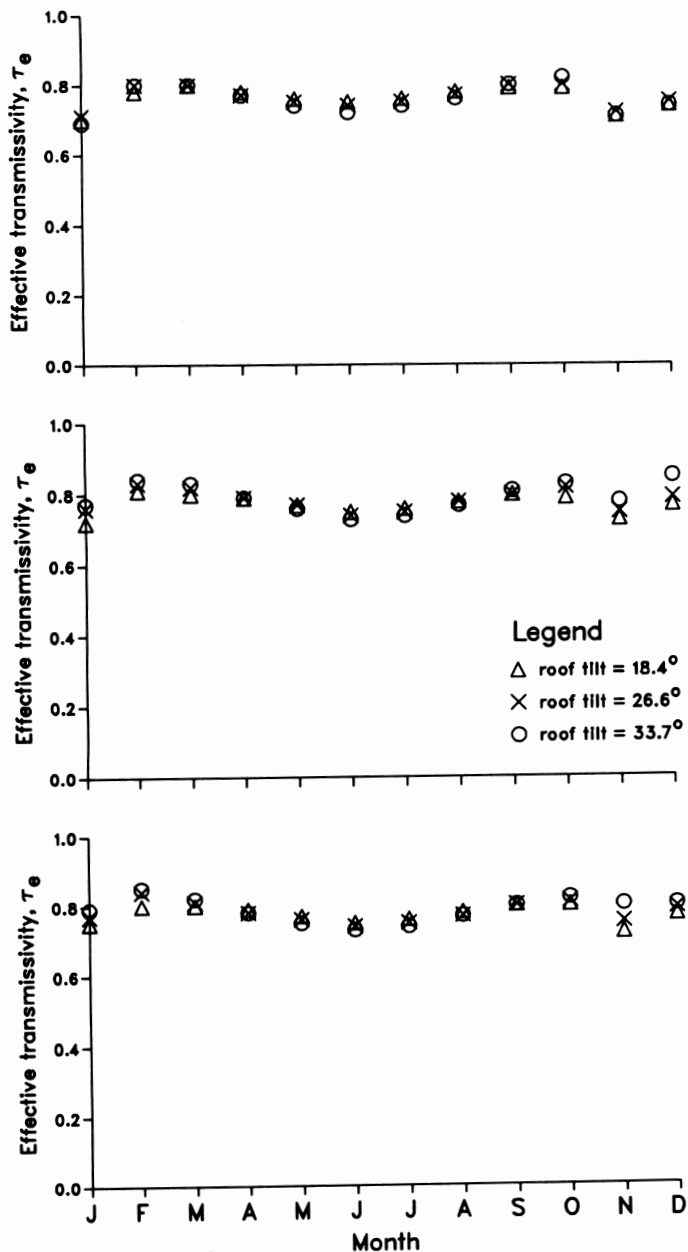


Figure 5. Effective transmissivity for a conventional glasshouse (top, VAN; middle, EDM; bottom, WNG). Δ , $\xi = 18.4^\circ$; \times , $\xi = 26.6^\circ$; \circ , $\xi = 33.7^\circ$.

Table IV. Monthly average of K_d and K_T

Location	Latitude ($^\circ$ N)		Feb.	Apr.	Jul.	Oct.	Dec.
Edmonton	53.5	K_T	0.58	0.58	0.59	0.55	0.49
		K_d	0.39	0.39	0.38	0.42	0.47
Winnipeg	50.0	K_T	0.63	0.56	0.58	0.49	0.50
		K_d	0.34	0.41	0.39	0.47	0.47
Vancouver	49.3	K_T	0.38	0.48	0.57	0.42	0.28
		K_d	0.59	0.49	0.40	0.54	0.68
Montreal	45.5	K_T	0.50	0.49	0.52	0.43	0.37
		K_d	0.47	0.48	0.45	0.54	0.60
Guelph	43.5	K_T	0.56	0.49	0.55	0.46	0.39
		K_d	0.41	0.48	0.42	0.51	0.58
Lexington	38.0	K_T	0.41	0.48	0.52	0.51	0.37
		K_d	0.53	0.46	0.42	0.43	0.58
Albuquerque	35.1	K_T	0.66	0.71	0.70	0.70	0.63
		K_d	0.26	0.20	0.21	0.21	0.29

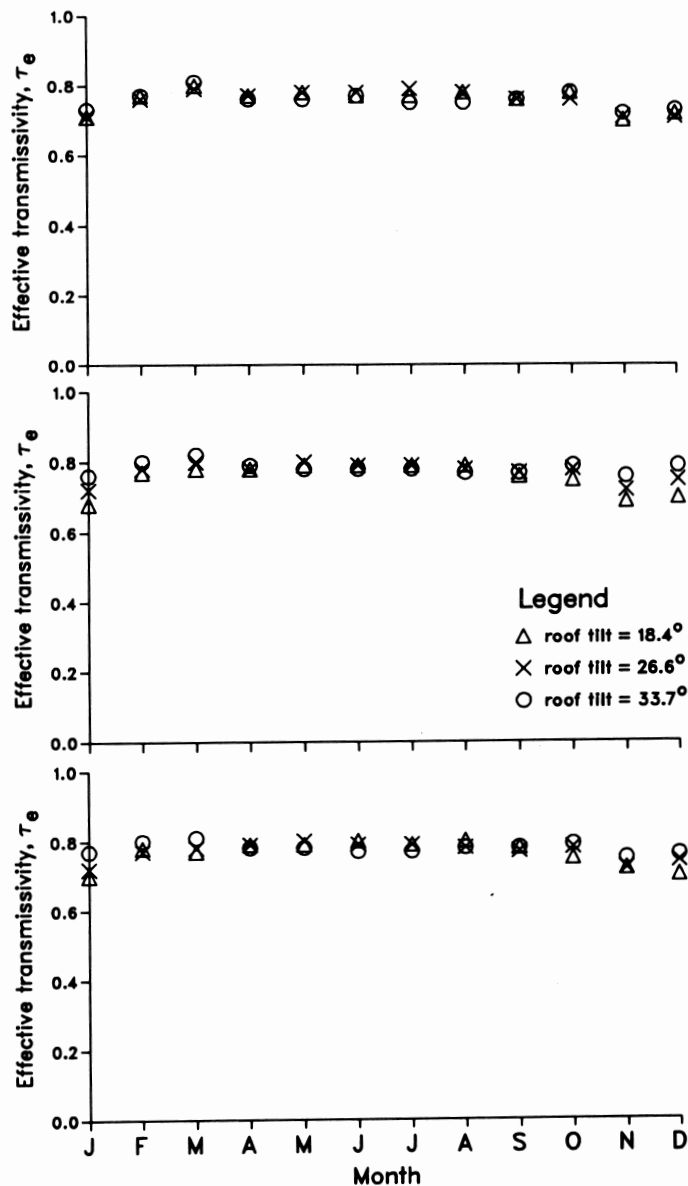


Figure 6. Effective transmissivity for a shed-type glasshouse (top, VAN; middle, EDM; bottom, WNG). Δ , $\xi = 18.4^\circ$; \times , $\xi = 26.6^\circ$; \circ , $\xi = 33.7^\circ$.

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NOTATION

		Dimension
A_f	Greenhouse floor area	m^2
A_k	Area of a greenhouse component surface	m^2
A_p	Area of plant canopy	m^2
A_q	Area of absorber plate	m^2
F_{kj}	Configuration factor between two surfaces	—
H	Daily global solar radiation incident on a horizontal surface	$MJ m^{-2} d^{-1}$
H_d	Daily diffuse solar radiation incident on a horizontal surface	$MJ m^{-2} d^{-1}$
H_{ex}	Daily extraterrestrial solar radiation	$MJ m^{-2} d^{-1}$
I	Hourly global solar radiation incident on outside horizontal surface	$kJ m^{-2} h^{-1}$
I_b	Hourly beam radiation incident on a horizontal surface	$kJ m^{-2} h^{-1}$
I_{bt}	Transmitted beam irradiance through an inclined surface	$W m^{-2}$
I_d	Hourly diffuse radiation incident on a horizontal surface	$kJ m^{-2} h^{-1}$
I_{ds}	Diffuse irradiance incident on an incline surface	$W m^{-2}$
I_{dt}	Transmitted diffuse irradiance through an inclined surface	$W m^{-2}$
I_n	Hourly direct normal solar radiation	$kJ m^{-2} h^{-1}$
I_o	Global solar irradiance incident on outside horizontal surface	$W m^{-2}$
I_p	Solar irradiance incident at plant canopy level	$W m^{-2}$
I_q	Solar irradiance incident on vertical absorber plate	$W m^{-2}$
K_d	The ratio H_d/H_{ex}	—
K_T	Clearness parameter (cloudiness index) = H/H_{ex}	—
L	Length	m
$L:W$	Greenhouse length-to-width ratio	—

P_{kj}	Interception factor between two surfaces	—
PAR_p	Photosynthetically active radiation incident on plant canopy	$W\ m^{-2}$
TTF	Total transmission factor	—
W	Width	m
h	Hour angle at the middle of an hour	Degrees
h_s	Sunset-hour angle for a horizontal surface	Degrees
k	Extinction coefficient	m^{-1}
m	Monthly average number of bright sunshine hours	—
n	Refractive index	—
δ_c	Declination on characteristic days	Degrees
β	Solar altitude	Degrees
θ_i	Angle of incidence	Degrees
ξ	Roof tilt	Degrees
ρ_p	Solar radiation reflectance of plant canopy	—
ρ_q	Solar radiation reflectance of absorber plate	—

τ_c	Effective transmissivity of greenhouse	—
τ	Transmittance of greenhouse cover material	—
l	Latitude	Degrees

Abbreviations

BS	Brace-style greenhouse
CV	conventional gable roof or quonset greenhouse
SS	shed-type greenhouse
DA	twin-walled (double) acrylic
GS	glass
E-W	east-west
N-S	north-south
EDM	Edmonton
VAN	Vancouver
WNG	Winnipeg