LIGHT TRANSMISSION OF ZIGZAG-SHAPED MULTISPAN GREENHOUSES

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Abstract

The light transmission of greenhouses can be improved by either reducing or avoiding construction parts or modifying the covering material itself (e.g. coatings) or modifying the shape of the material. The ideal greenhouse cover does not need construction parts, is self-supporting and of course light transmission and orientation freedom is high. A solution could be the use of pyramidal shaped or zigzag-corrugated cladding material, since light transmission as well as stiffness might increase.
To investigate the light transmission (reflection) of multispan greenhouses cladded with zigzag-shaped materials as well as the transmission (reflection) of multispan greenhouses with large slopes (slope > 45 deg.) a model (ZIGZAG.PAS) based on the tracing of R A Y S was developed.
An other programme, suitable for flat material, one or more (different) layers and for slopes smaller than 45 degrees, was used for verification. This programme, (BUMBLE_BEAM.PAS), based on tracing B A N D S of light, allows the computation of transmissivity (reflectivity, absorptivity) of arbitrary linear polarised light.
Both programmes allow a regressive computation of transmissivity and reflectivity, just by using smooth, averaged values in stead of the actual values determined by the geometry of polarisation. This has a small influence on the computation results as far as tranmissivity for diffuse radiation is concerned. The influence increases when the number of layers or the slope increases. With a proper design greenhouse transmission values for diffuse light of more than 90% can be achieved.

1. Introduction

The light transmission of greenhouses can be improved by either reducing or avoiding construction parts or modifying the covering material itself (e.g. coatings) or modifying the shape of the material. The ideal greenhouse cover does not need construction parts, is self-supporting and of course light transmission and orientation freedom is high. A solution could be the use of pyramidal shaped or zigzag-corrugated cladding material, since light transmission as well as stiffness might increase. To investigate the light transmission (reflection) of multispan greenhouses cladded with zigzag-shaped materials as well as the transmission (reflection) of multispan greenhouses with large slopes (slope > 45 deg.) the use of the computer is unavoidable.

In the early seventies personal computers did not exist. The well known author of 'Photosynthesis of leaf canopies', De Wit (1965) compared the evolution in car driving and electronic calculating by reminding that the chauffeur-driven car had become rare. Nowadays programmes are developed without an intermediary, and ' clear and easy to understand calculation schemes' (de Zwart, 1993) are easier to realise. In stead of experimental validation - only a limited measure of accuracy is attainable- some consequences of statements can be checked in an interactive way. In this study two programmes BUMBLE_BEAM.PAS and ZIGZAG.PAS are developed. The first program computes light transmissivity (T), reflectivity (R) and absorptivity (A) of multispan greenhouses (without construction parts) or 'zigzag' shaped materials. The computation of three components - since T+R+A = 1 - allows a check of internal contradictions when bookkeeping the bands of light. The ultimate result is always an average of 2 figures; the figure in question (T, R or A) relates to the fact whether the beam s(enkrecht=>perpendicular) or p(arallel) to a fictitious plane of incidence (formed by ray direction and the vertical) is polarised. The number of layers is not restricted, as far as thickness of layer-combination remains small compared to span dimension. The sequence of layers, when their physical properties are different, is taken in account. Indeed transmissivity of a combination parallel layers is not influenced by ray direction, absorptivity and reflectivity however does. These effects are marginal when the index of refraction varies between 1.4 and 1.6, but they could become more important when coated materials are involved. The slope of the multispan /material in this model is restricted to values smaller than 45 degrees otherwise a classification in a finite number of geometrical cases is not possible. Computation time is small compared to the time needed by the second programme ZIGZAG .PAS. In this programme the vicissitudes of a number of parallel rays equally distributed over surface are followed, and registered. Computation time increases with slope but principal restrictions in slope value do not exist since a classification in geometrical cases is not needed. In this model we have one extra input variable the slope of the zigzag material itself (SLOPEm). If the computation results of two totally different programs are similar for the conventional 'warenhuis', the credibility of both increases. When the transmissivity of greenhouses cladded with coated materials has to be computed, this needs only a change in one specific procedure.

In the next paragraph a brief description of the method is given.

2. Method

2.1. ZIGZAG

The building ABCDEFGH (Fig.1) is a rectangular parallelepiped. Point A is chosen as a centre of Cartesian co-ordinates (x,y,z), where AD corresponds to x, AB to y and AE to z. The six surfaces are numbered (Fig.3): surface 1 and surface 2 are vertical planes defined by the points ADE and BCF, surface 3 and 4 are the two remaining parallel vertical planes defined by DHC and ABE and surface 5 (ABD) as well as surface 6 (EFH) are horizontally situated. The unit vectors perpendicular to these surfaces get the names Fn[i], where i represents the surface number. (e.g. Fn[1] = {0,1,0}, Fn[2] = {0,-1,0} etc. or Fn[1,1] = 0, Fn[1,2] = 1, Fn[1,3] = 0 and Fn[2,1] = 0, Fn[2,2] = -1, Fn[2,3] = 0.

Let the vertical surfaces (1,2,3,4) be ideal, specular reflecting mirrors and suppose ADFG is a flat transparent material. We have constructed a virtual reality. This reality looks like a Dutch 'warenhuis' without constructionparts. As a matter of fact, such a construction with reflecting mirrors (Balzer Ag-coated surface mirrors) was used by Stoffers, J.A. (1970) to measure the light transmission of a multispan greenhouse model in Hannover (Lichtmessstand Institut fuer Technik im Gartenbau).In this example (Fig.1) the transparent surface (surface 7) is parallel to AD, the x-direction situated.

Fn [7] = {0, cos(slope), sin(slope)} where slope = arc(cos(EF/AF)).

The conventional greenhouse shape can be seen as an infinite number of parallel lines, so the direction of incident radiation (unit vector Ri) can best be defined with cylindrical co-ordinates.

We introduce two angles Beta, Teta (Fig. 2) in such a way that Ri, the direction of incident radiation described in Cartesian co-ordinates becomes:

Ri = {cos(Beta), sin(Beta) . sin(Teta), sin(Beta) . cos(Teta)} or
Ri[1] = cos(Beta), Ri[2] = sin(Beta) . sin(Teta), Ri[2] = sin(Beta) . cos(Teta).

(0<Beta<pi ; -pi/2<Teta<pi/2).

Let Tm(Beta,Teta) be the measured transmissivity of the model.

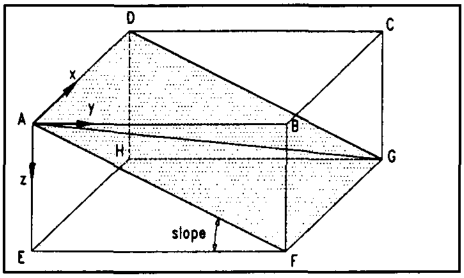

Fig.1.Model Dutch 'warenhuis'.

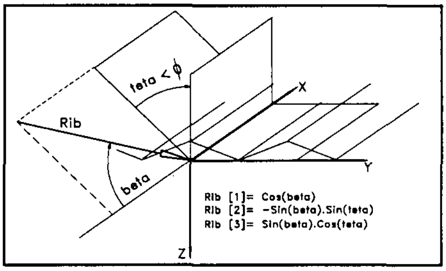

Fig.2. Definition Beta,Teta.

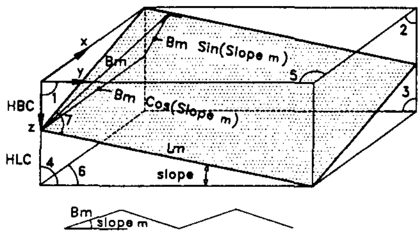

Fig.3. Zigzag in 2 directions.

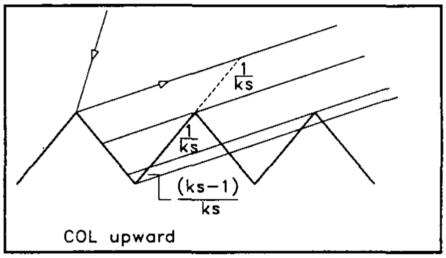

Fig.4.Case Five, ks=u12/(u1-u2).

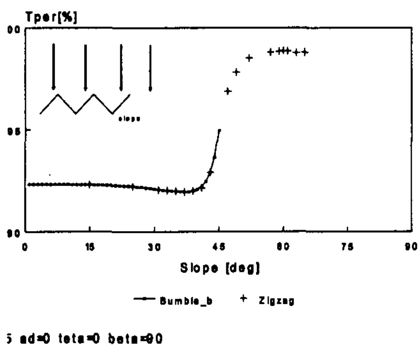

Fig.5 Specular transmissivity.

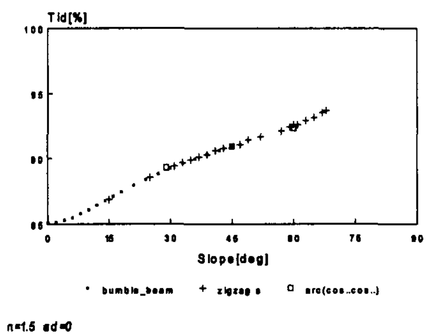

Fig.6.Hemispherical transmissivity.

Then reasons of symmetry urge us to the conclusion that T(Beta,Teta), the transmissivity of the corresponding real multispan becomes:

T(Beta, Teta) = (Tm(Beta, Teta) + Tm(Beta, -Teta))/2

If surface 7 is not parallel to the x-direction (Fig.3.) the model represents a multispan greenhouse, cladded with zigzag corrugated material. The characteristic angle of the folded material is called SLOPEm. Now four model measurements are needed, since the transmissivity of the greenhouse is determined by using the smallest possible model, in fact a simple parallelogram:

[1] T(Beta, Teta) = (Tm(Beta, Teta) + Tm(Beta, -Teta) + Tm(pi-Beta, Teta) + Tm(pi-Beta, -Teta)) / 4

The idea of the smallest possible model between ideal mirrors combined with the relation of symmetry [1] is a very helpful tool, if one wants to compute the transmissivity of a zigzag shaped greenhouse. The tracing of an initial ray of definite direction, sometimes branched in a nearly infinite number of new rays becomes more accessible for the human mind when the rays are locked up between six surfaces.

Apart from Fn[i] the unit vector perpendicular to surface i (1<=i<=7), we define an other vector F0[i] which one could call the 'distance vector'. F0[i] is perpendicular to surface i, starts in a reference point and ABS(F0[i]) is the distance between reference point and surface i. (The reference point is never part of the surfaces 1 to 7.)

SN[i] is a vector connecting the reference point and the intersection of Ri and surface i. This means SN[i].F0[i] = F0[i].F0[i] (scalar multiplication; in the program scal (SN[i].F0[i]) = scal (F0[i].F0[i])).

The initial value of RI is called RIb (b->begin). RIb and Fn[5] are parallel to a fictitious surface of entrance Fn[5] is unitvector in z->direction.)

We have defined a unit vector SPOLb, perpendicular to the fictitious plane of entrance and a unit vector PPOLb parallel to the fictitious surface of entrance. POLb is the initial value of a unit vector called POL.

All computations are made twice: POLb = SPOLb and POLB = PPOLb. During the multiple reflections POL changes but remains unit vector, POL has the same direction as the electrical field vector. The steady diminishing intensity of the ray is registered by curIN[jw] where jw is an integer associated with the (current) ray in question.

For all the seven surfaces a local system of Cartesian co-ordinates is defined. If RI coming from surface Lformer, hits surface L, in the point SN[L], the local Cartesian components of Ri and POL have to be computed in a procedure called INTERACT. Then in the same procedure the s and p component of POL is computed (SPOL and PPOL) and now, depending on whether the ray is reflected (L = 1,2,3,4 or 7) or transmitted (L = 7) the new, local components of Ri, SPOL, PPOL are determined. If L = 5 or L = 6 the tracing of that specific ray 'jw' ends after adding a value curINT[JW] to the summarising entry I5 or I6. If L = 7 the summarising entry Iab7 (absorbed radiation) is brought up to date.

2.2. BUMBLE_BEAM

The program BUMBLE_BEAM is deduced from a part of a greenhouse simulation model SOLANUM.IMAGinatum. (Stoffers, 1990) Some major changes have been made. Calculation of the POL-direction is corrected, the integration procedure for diffuse light is better, the programme is shorter especially in the essential parts in order to approach the already earlier mentioned 'easy to understand calculation schemes'. Now there is taken in account whether a beam hits a surface on the lower or the upper surface, so the programme becomes applicable for coated materials by changing only one procedure.

The program runs about as follows:

Beam direction is defined by unit vector Ri. We distinguish 2 surfaces,their normal unit vector is called Nfl and Nf2, the normal of the horizontal surface is called Nff. Ri1 defines the direction of the beam reflected by surface 1, Ri2 is analogously defined.

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u1  : = scal (ri,Nf1);
u2  : = sca l(ri,Nf2);
u12 : = scal (ri1,Nf2);
u21 : = scal (ri2,Nf1);
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Since the slope is restricted to values smaller than 45 degrees a differentiation into six procedures corresponding to six cases (Table 2.1) leads always to a solution where the collection of absorbed, reflected or transmitted radiation is controlled by only three elementary procedures; the first for case ONE; the second for cases where the reflected beam moves in upward direction along the spans (Fig. 4); and the third when the reflected beam moves in downward direction along the spans.

CASE	u1	u2	u21	u12	u2-u21
1	>=0	<0			
2	>=0	>=0	< 0	< 0	
3	>=0	>=0	>=0	< 0	< 0
4	>=0	>=0	>=0	< 0	>=0
5	>=0	>=0	>=0	>=0	< 0
6	>=0	>=0	=0	>=0	>=0

Table 2.1 Selection beam distribution.

3. Results

If the slope of a zigzag-corrugated non-absorbing material (or the slope a multispan greenhouse without construction parts cladded with a non-absorbing material) approaches 90 degrees the transmissivity approaches 100%. The chosen examples, showing results of computation, are mostly valid for non-absorbing materials. The reader is invited to associate a slope of 90 degrees with 100% transmissivity.

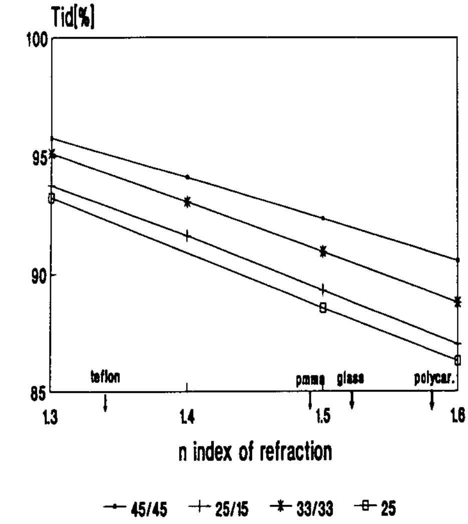
In Hannover (ITG), Montpellier (CEMAGREF) and Wageningen (IMAG) rather large integrating spheres are in use for specific horticultural purposes. What would be the accuracy when the transmissivity of direct light, angle of incidence zero, was measured? Fig. 5 shows computed results. As symbol for the index of refraction in this and all the other Fig.'s is character 'n' in use, 'ad' is the product of materialthickness and coefficient of absorption. Both computing methods show an excellent similarity.

The transmissivity of diffuse radiation is a good measure of greenhouse quality. In Fig. 6 again the similarity is proven. One wonders how the curve for slopes larger than 70 degrees moves toward 100%? For zigzag-corrugated material SLOPE and SLOPEm are combined to a new variable: arc(cos(SLOPE)*cos(SLOPEm)). The Fig. 6 shows how the curve valid for non- corrugated material, remains valid for zigzag-shaped material since all the computed points are caught in the same line.

The influence of the index of refraction on transmissivity is nearly linear as is shown in Fig. 7.

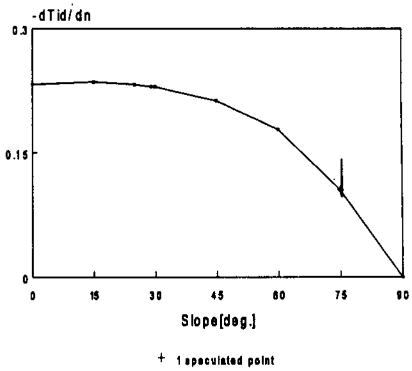
∂Tid/∂n is negative, the absolute value decreases when the slope increases (Fig. 8.) so the material choice becomes less important when the slope increases.

Before we can draw a curve showing 'orientation freedom' we have to define this property. If direct light, azimuth angle 15 degrees, falls on a greenhouse the transmissivity for this light depends on its orientation. The ratio of the minimum and



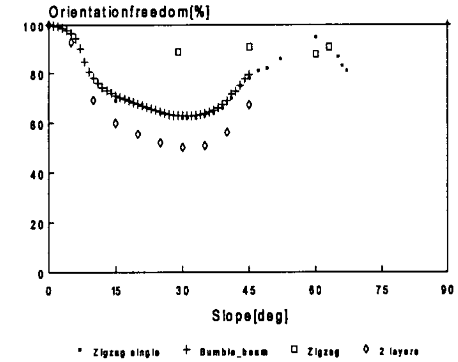
ad=0

Fig.7.Influence index of refraction.



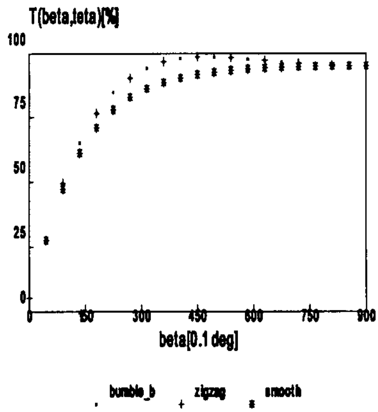
ad=0,nearly independent from n

Fig.8. Deminishing influence index of refraction.



n=1.5 ad=0

Fig.9. Orientation freedom and slope.



n=1.495 ad=0 teta=0
slope 45 deg.

Fig.10. High transmissivity for specific raydirection. Influence 'smooth'.

maximum transmissivity that occurs when the greenhouse is turned around, is here called 'orientation freedom'. We know already: a horizontal non-corrugated surface (Slope=0) or nearly vertical surfaces (Slope=>90) if non -absorbing material is concerned, lead to an orientation freedom of 100%. Fig. 9 shows a typical curve with a minimum for slope angles of about 30 degrees valid for conventional cladding. The improvement caused by zigzag-corrugation is obvious.

Transmissivity for direct radiation T(beta,teta), is not the best measure when describing the quality of the building, but is, as much as the tranmissivity for diffuse light, an important property in greenhouse modelling. An example that shows unexpected values is given in Fig. 10. Again the similarity of results achieved by Bumble_b.PAS and Zigzag.PAS is clear. To demonstrate the effect of the Boolean statement 'smooth: = true' on the result a second line is drawn. For the designer of new greenhouses it must be a relief when he examines Fig. 11 where is shown how ratio Bm/Lm influences the lighttransmissivity. Finally, vertical surfaces e.g. in ridge and gutter part of the roof don't influence the transmissivity whereas the stiffness can be improved.

4. Conclusion

Self-supporting plastic greenhouse decks of which the transmissivity for diffuse light reaches or surpasses the 90% limit, can be obtained even for materials with a relatively high index of refraction (e.g. polycarbonate).

Everyone feels what the architect knows: the use of corrugated material improves the stiffness of the greenhouse building. A provisional calculation, executed by Waaijenberg (1996), which was based on the criterions that the permitted bending should be smaller than 0.001, and the ratio of material thickness (D) to width (Bm) less than 0.01, lead to the optimal thickness/length ratio for PMMA:

D/Lm.0.023*(D/Bm)^0.66

whereas the optimal SLOPEm = 50 degrees.

The influence of ratio Bm/Lm (Fig. 11) on transmittance is not that much that the constructor of zigzag-shaped greenhouses is limited in his choice by aspects of light transmission. Higher Bm/Lm ratios, cause probably higher stiffness. Which value is to choose depends on material properties (like price, n, ad, contact angle water droplets etc.) and indirect influences e.g. dimensions of lorry used for transport of roof segments considerations about savings in labour costs when constructing the greenhouse, etc.

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References

De Wit C.T., 1965. Photosynthesis of leaf canopies, Centre for Agricultural Publications and Documentation, Wageningen.

de Zwart H.F., 1993. Determination of Direct Transmission of a Multispan Greenhouse Using Vector Algebra, J. agric. Engng Res.

Stoffers J.A., 1970. Jaarverslag ITT, Wageningen

Stoffers J.A., 1990. Influence of Material properties on Greenhouse Climate, Acta Horticulturae, nr 281, July.

Waaijenberg D. Internal communication.

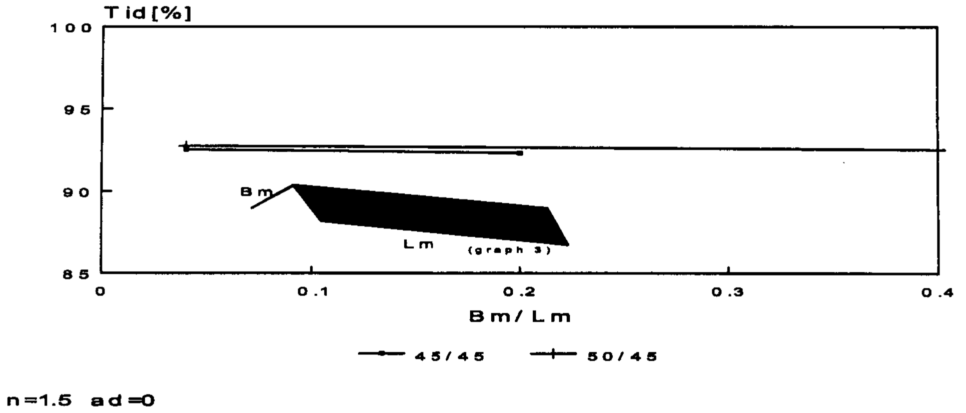

Fig.11.Influence width to length ratio.