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SOLAR RADIATION ON CLOUDY DAYS

BY

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SUMMARY

Solar radiation is one of the most important components of the heat balance at the outside surfaces of buildings, and the solar heat that enters a building through the windows is a major element in the total heat gain by the building. Accurate data on solar intensities are important, therefore, in several phases of building design, particularly in the design of the air conditioning system.

ENSOLEILLEMENT PAR TEMPS COUVERT

SOMMAIRE

Parmi les composantes du bilan thermique des surfaces extérieures des bâtiments, le rayonnement solaire occupe une place importante. La chaleur solaire pénétrant dans les bâtiments par les fenêtres est un élément important de l'apport calorique total au bâtiment. Conséquemment, il est important de posséder des données précises sur l'ensoleillement pour les travaux du bureau d'études, particulièrement dans le domaine de la climatisation de l'air. Le présent article fournit les résultats d'une étude-pilote, effectuée dans le but de déterminer les relations entre l'intensité de l'ensoleillement d'une surface horizontale et les observations horaires de la couche nuageuse à Ottawa, en Ontario.

No. 2106

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Solar Radiation on Cloudy Days

Solar radiation is one of the most important components of the heat balance at the outside surfaces of buildings, and the solar heat that enters a building through the windows is a major element in the total heat gain by the building. Therefore, accurate data on solar intensities are important in several phases of building design, particularly in the design of the air-conditioning system. As solar radiation records are available for only a very limited number of weather stations, it is necessary to find a way of estimating the hourly values of solar intensity for locations where records are not available.

The ASHRAE Task Group on Energy Requirements for Heating and Cooling Buildings is developing a procedure for calculating energy requirements that uses the hourly values of surface observations made at all first class weather stations. These observations include cloud type and amount, but not solar intensity. It is necessary, therefore, to try to infer the hourly values of solar intensity from the cloud observations. This paper presents the results of a pilot study that was made to determine the relationship between solar intensity on a horizontal surface and hourly observations of cloud cover for Ottawa, Ontario.

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CLOUD COVER FACTOR (CCF)

The simplest way of estimating the solar intensity on a horizontal surface on cloudy days is to calculate the intensity that would be obtained if the sky were cloudless and then multiply this clear sky intensity by a factor that depends on the cloud cover. This factor is called the cloud cover factor (CCF). Thus the solar radiation on a horizontal surface for cloudy days, I_{THC}, is given by the expression

$$I_{THC} = I_{TH} \cdot CCF \qquad (1)$$

where I_{TH} is the total solar intensity on a horizontal surface given by the formulas and data in the ASHRAE HANDBOOK OF FUNDAMENTALS [1] (Chapter 28).

The real problem, therefore, is to determine CCF as a function of cloud cover. This can be done by using the recorded values of the total solar intensity on a horizontal surface, I_{rec}, and correlating the ratio I_{rec}/I_{TH} with the cloud cover records on an hourly basis.

DATA USED

An analysis of this type was made using the solar radiation and cloud cover observations for Ottawa, Ontario (45° 27'N, 75° 37'W) that are published by the Meteorological Branch of the Canadian Depart-

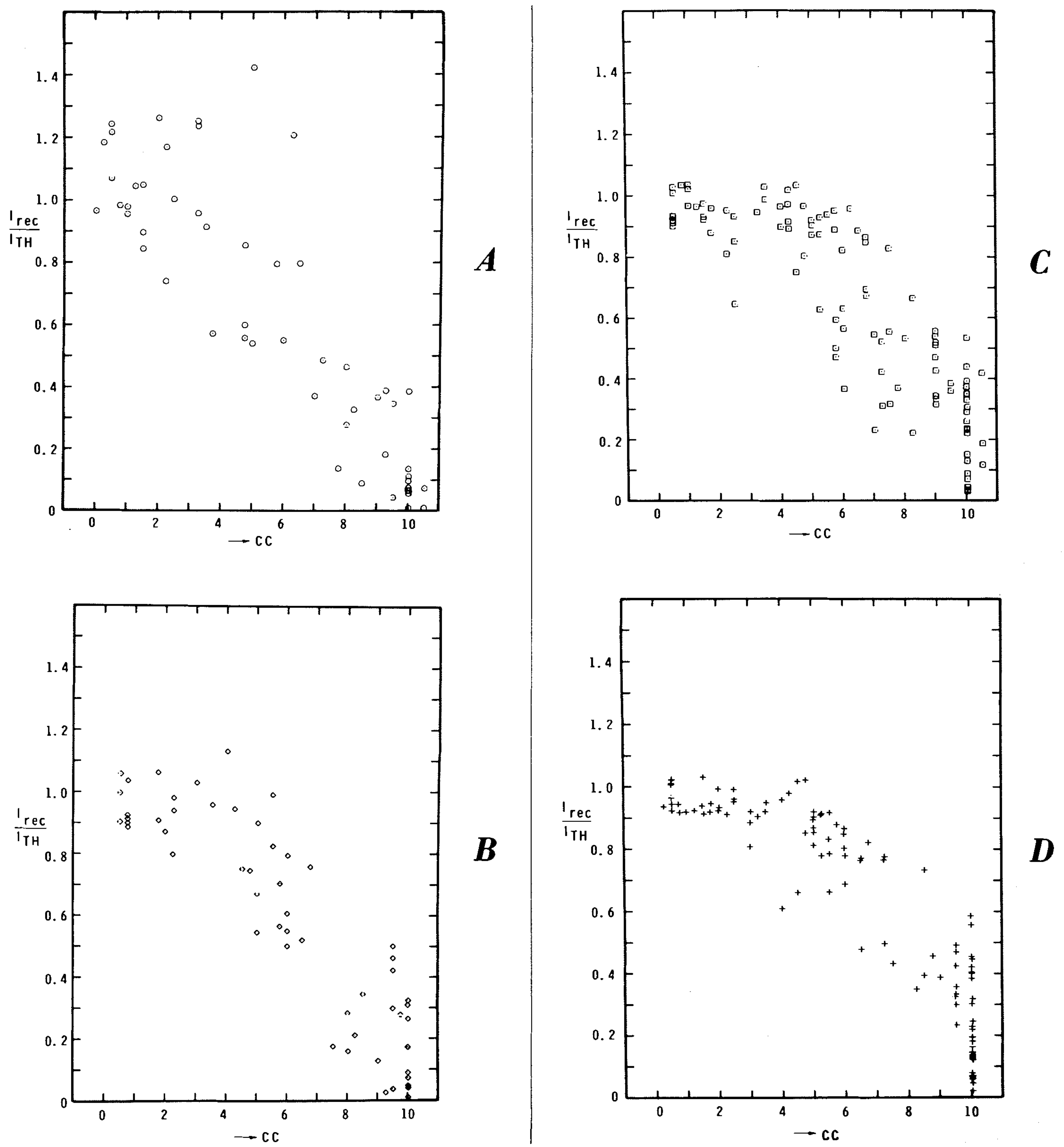
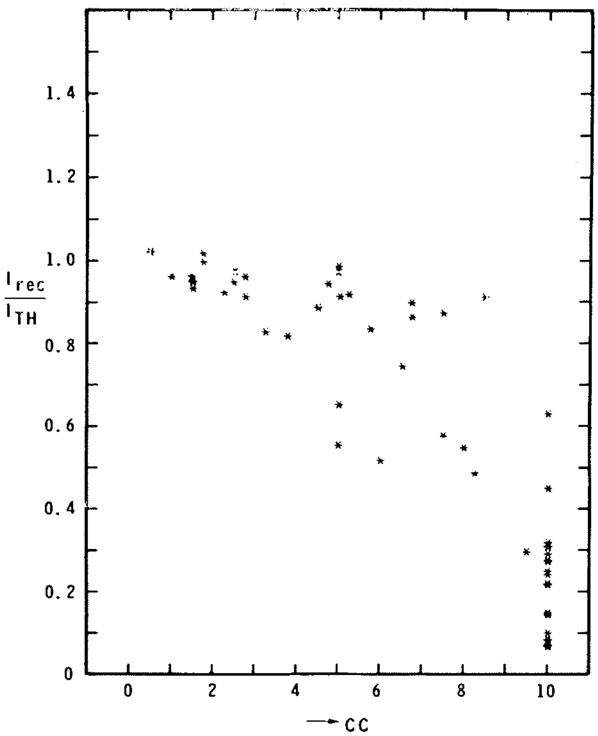


Fig. 1 Ratio of radiation incident on horizontal surface to amount calculated for cloudless day for Sin β: (a) 0.1 – 0.3, (b) 0.3 – 0.5, (c) 0.5 – 0.7, (d) 0.7 – 0.9, and (e) 0.9 – 1.0



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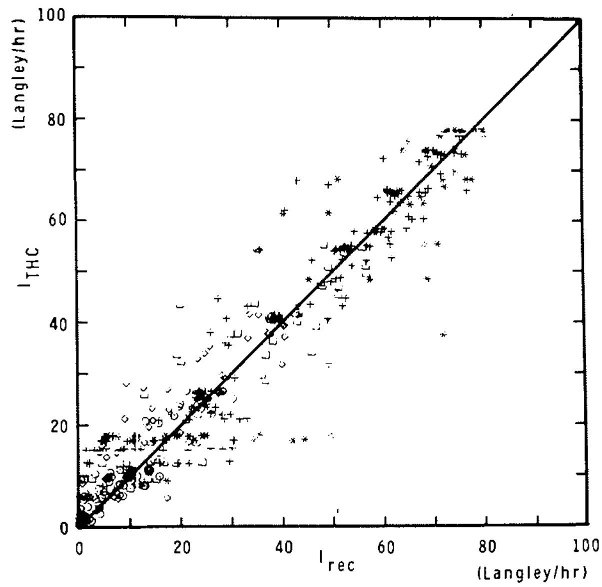

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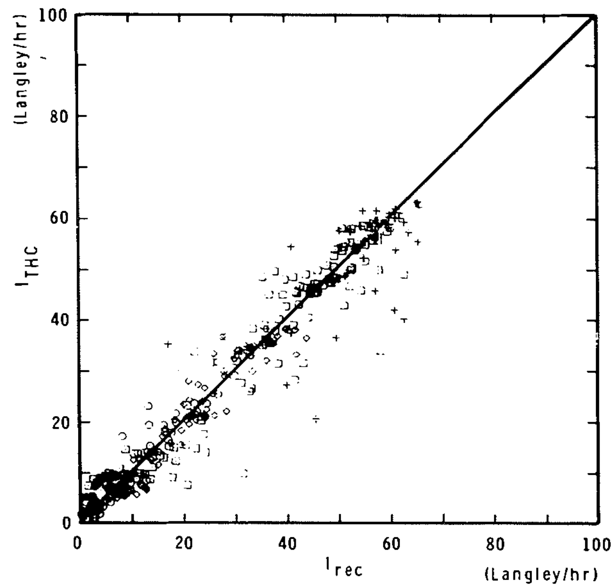
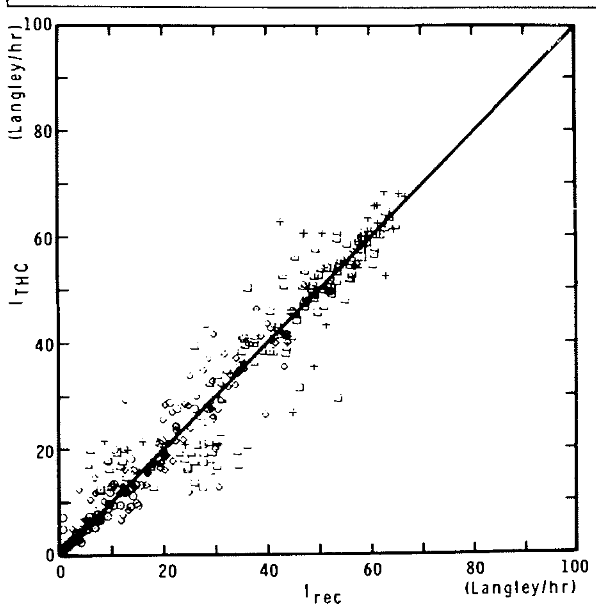


C

LEGEND OF SYMBOLS IN FIGURES 1 - 2

Symbol	Sin β
✳	0.9 - 1.0
+	0.7 - 0.9
⊡	0.5 - 0.7
◇	0.3 - 0.5
⊙	0.1 - 0.3

Fig. 2 Correlation between calculated radiation based on CCF and recorded radiation on horizontal surface for all daylight hours in (a) March 1967, (b) June 1967, (c) September 1967, and (d) December 1967



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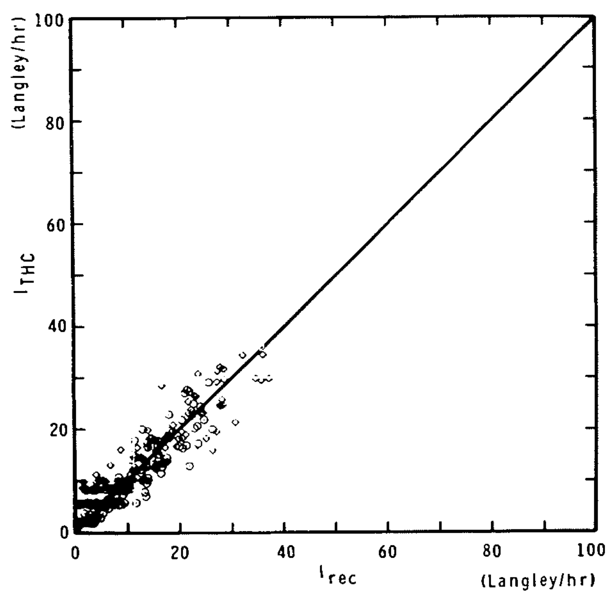

D

ment of Transport[2,3]. The radiation values are measured by a thermopile type of pyranometer coupled with an integrating type of recorder that gives the total solar radiation incident on a horizontal surface during a period of one hour ending on the hour in Apparent Solar Time. The cloud cover observations are made every hour (Standard Time) by experienced observers who estimate the amount of cloud on a scale of 0 to 10 and indicate the type of cloud in four different layers. These data were available on punched cards so the analysis could be made by computer without any data transcription. The analysis was made for the months of March, June, September and December in 1967, to see if there was a seasonal variation in the relationship between I_{rec}/I_{TH} and the cloud cover (CC).

The value of I_{TH} was calculated for every hour in apparent solar time (ie: for hour angles that are evenly divisible by 15 degs), but the value used as the denominator in each ratio was the average of the values computed for the beginning and end of the hour during which I_{rec} was measured. Similarly, the value of CC associated with each value of I_{rec}/I_{TH} was the average of the values at the beginning and end of the hour. No allowance was made for the fact that the cloud observations were made in Standard Time rather than in Apparent Solar Time.

The value of CC used for this analysis is defined as the recorded total amount of cloud minus half of the amounts of cirrus, cirrostratus and cirrocumulus. This discounting of the amounts for these three types of cloud makes the value of CC agree very closely with the opacity value for the cloud cover. The value of CC defined in this way was used instead of opacity, because opacity is not given in the records for stations in the United States.

RESULTS

The values of I_{rec}/I_{TH} were separated into different groups on the basis of the solar altitude angle, β. Fig. 1 (a-e) shows the results for June 1967 for $0.1 < \sin\beta < 0.3$, $0.3 < \sin\beta < 0.5$, $0.5 < \sin\beta < 0.7$, $0.7 < \sin\beta < 0.9$ and $0.9 < \sin\beta$, respectively. The general form of the relationship between I_{rec}/I_{TH} and CC is similar for the different values of solar altitude but the scatter of the points are substantially lower for the higher solar altitudes. This is to be expected as the total solar radiation incident on a horizontal surface is much less at the low altitude angles and consequently the cloud reflected component, which is quite variable depending on the position and type of the cloud, and is a higher proportion of the total for the low altitude angles. All of the points in Figs. 1 (c-e) (ie: $\sin\beta > 0.5$) were used to determine the coefficients P, Q and R in the expression

$$CCF = P + Q \cdot CC + R(CC)^2. \qquad (2)$$

Values of P, Q and R for the other months were obtained in the same way, and the values for all four months are given in Table I. The value of CCF given by Eq 2 and the data in Table I were used to calculate I_{THC}, the solar intensity that could be expected with the observed cloud conditions for all the daylight hours during each month. These computed values of I_{THC} vs the actual measured values of I_{rec} are plotted in Fig. 2 (a-d). These graphs show that all the points fall in a band centered on the 45 deg line. This indicates that the absolute error in the solar intensity estimated using the CCF based on the high solar altitude measurements is fairly constant regardless of the actual solar altitude.

Figure 1 (a-e) also shows that it is not uncommon for the value of I_{rec} to exceed the calculated I_{TH}. This indicates that the values of I_{TH} given by the formulas in the ASHRAE HANDBOOK OF FUNDAMENTALS are not overly conservative for design purposes. The frequency with which these values are exceeded suggests that they should provide a reasonable basis for computing the loads that the air-conditioning system needs to be able to handle.

TABLE I

CONSTANTS IN EQ 2 FOR OTTAWA

Month	sin β	P	Q	R
March	0.5 – 0.9	1.06	0.012	−0.0084
June	0.5 – 1.0	0.96	0.033	−0.0106
September	0.5 – 0.9	0.95	0.030	−0.0108
December	0.3 – 0.5	1.14	0.003	−0.0082

CLOUDLESS-SKY FACTOR

The formulas for calculating solar intensity that are given in the ASHRAE HANDBOOK OF FUNDAMENTALS are for average cloudless sky conditions. Some localities have a very clean atmosphere and consequently have higher than average solar intensities when the sky is cloudless; and other places with an "industrial" atmosphere have less than average solar intensities. These local peculiarities are taken into account by the Cloud Cover Factor. The value of CCF for a cloud cover of zero (ie: cloudless sky) can be considered the Cloudless-Sky Factor for the locality. The data analysis yields values of CCF for cloudy conditions also establishes the value of this factor for cloudless conditions. This Cloudless-Sky Factor is just the constant term, P, in the polynomial relating CCF to cloud cover, as used in Eq 2.

DIRECT AND DIFFUSE INTENSITIES

This study has only been concerned with the total solar radiation incident on a horizontal surface: there were no data on the direct or diffuse components separately. It is often necessary, however, to be able to estimate the direct and diffuse components separately. This can be done for the cloudless sky by using the data of Parmelee.[4] The proportions of direct and sky-diffuse solar radiation given by the formulas in the ASHRAE HANDBOOK OF FUNDAMENTALS are consistent with the information presented in Parmelee's paper. Thus, if P turns out to be 1, the proportion of direct and diffuse should be appropriate. When P is greater than 1, ie: the total solar radiation incident on a horizontal surface under a cloudless sky is greater than the values indicated by the formulas in the ASHRAE HANDBOOK OF FUNDAMENTALS, the intensity of the diffuse solar radiation from the sky is less than that indicated by the formulas; and conversely when P is less than 1, the diffuse component is larger than under the standard conditions. Parmelee showed that the diffuse and direct components for cloudless conditions are related by an expression of the form:

$$I_{dH} = X - Y \cdot I_{DH} \qquad (3)$$

where X and Y are functions of the solar altitude; I_{dH} and I_{DH} are diffuse and direct solar radiation on horizontal surfaces for cloudless sky conditions, respectively.

Thus,

$$I_{TH} = X + (1 - Y) I_{DH} \qquad (4)$$

If an * is added to indicate that P is other than unity, and no asterisk indicates P = 1, it follows that

$$I^*_{TH} = X + (1 - Y) I^*_{DH}$$
$$= P\{X + (1 - Y) I_{DH}\} \qquad (5)$$

so

$$I^*_{DH} = P \quad I_{DH} + \frac{(P - 1)X}{1 - Y} \qquad (6)$$

The increase of direct component due to P larger than unity is

$$I^*_{DH} - I_{DH} = (P - 1)\left\{I_{DH} + \frac{X}{1 - Y}\right\}$$
$$= \frac{P - 1}{1 - Y} I_{TH} \qquad (7)$$

Therefore

$$\frac{I^*_{DH}}{I_{TH}} = \frac{I_{DH}}{I_{TH}} + \frac{P - 1}{1 - Y} = K \qquad (8)$$

and as

$$\frac{I_{DH}}{I_{TH}} = \frac{\sin\beta}{C + \sin\beta} \qquad (9)$$

where C is given in Table 8, p. 476 of Ref 1.

$$K = \frac{\sin\beta}{C + \sin\beta} + \frac{P - 1}{1 - Y}. \qquad (10)$$

The function Y is expressible by a second order polynomial in $\sin\beta$ viz:

$$Y = 0.309 - 0.137 \sin\beta + 0.394 \sin^2\beta, \qquad (11)$$

thus K can be evaluated for any value of $\sin\beta$.

It seems reasonable to assume that the direct component with a partly cloudy sky should be proportional to the fraction of the sky that is clear, as explained in Ref 5. Thus for a partly cloudy sky

$$\frac{I_{DHC}}{I_{TH}} = K\left(1 - \frac{CC}{10}\right) \qquad (12)$$

and

$$\frac{I_{dHC}}{I_{TH}} = CCF - K\left(1 - \frac{CC}{10}\right) \qquad (13)$$

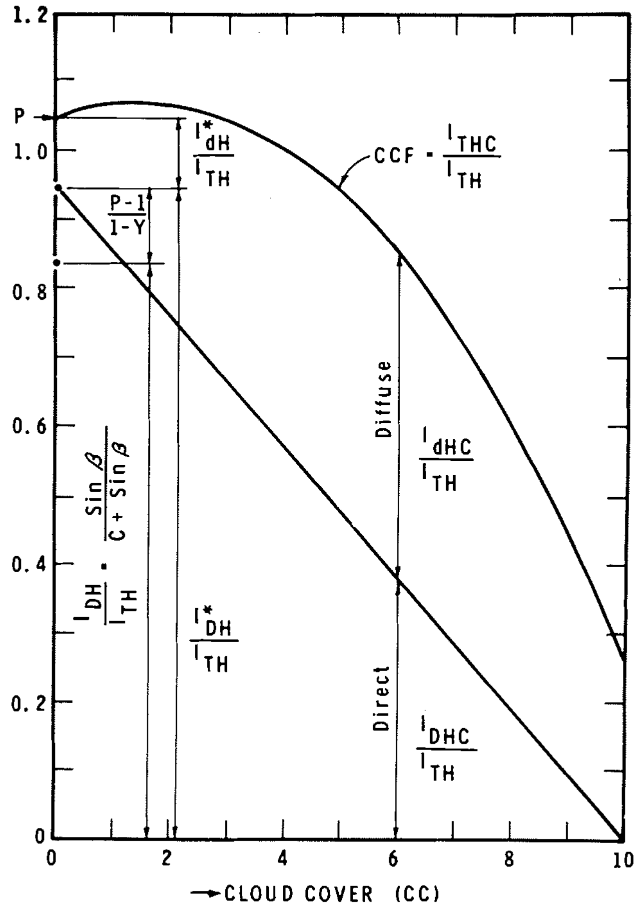

Fig. 3 Direct and diffuse components of Cloud Cover Factor (CCF)

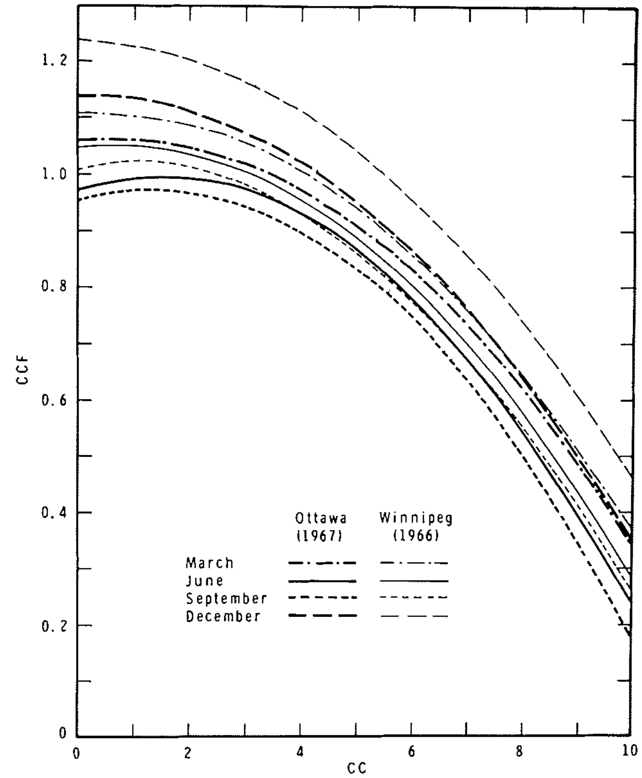

Fig. 4 Cloud Cover Factor for four months at Ottawa and Winnipeg

Fig. 3 shows the magnitude of these components for a location with a cloudless-sky factor that is greater than 1.

Once the direct and diffuse components of solar radiation on a horizontal surface are known for cloudy days, it is possible to estimate both the components on any inclined surface using the standard formulas as in Ref 1.

VARIATION OF CCF

The results given in Table I show that there is a small increase in P during December and March compared with the other months. This increase may be associated with the fact that the ground is covered by snow during most of December and March. The high albedo for a snow-covered surface means that a substantial part of the solar radiation falling on the snow surface is reflected back toward the sky where it is again scattered and reflected, and so contributes to a greater diffuse solar intensity than would occur otherwise. It is also reasonable to assume that there are fewer dust and smoke particles in the atmosphere during the winter than the summer. Allowance is made for this seasonal variation by the values of the A, B and C constants in the ASHRAE formulas, but it is possible that this seasonal effect is more pronounced at Ottawa. If the increase in P is due to ground reflection, the increase would be in the diffuse component, whereas if it is due to lower turbidity of the atmosphere, the direct component should be the one that is increased. Separate measurements of the diffuse and direct components are needed to indicate which one causes the higher P during the winter. Because of this uncertainty the Ottawa results should only be applied to areas that have a similar climate.

The geographical variation of the CCF vs CC relationship was checked by making a very limited study of some data for Winnipeg, Manitoba (49° 54' N, 97° 14' W). In this case, four 10-day periods were used rather than complete months. The results are summarized in Fig. 4 which shows that CCF is higher than at Ottawa but the relative seasonal variation is much the same as at Ottawa.

CONCLUSION

The results of an analysis of four months of solar radiation and cloud cover records for one location indicate that radiation intensities can be estimated when cloud cover records are available. It is also possible to estimate the proportion of the total solar radiation falling on a horizontal surface that is due to the direct solar beam and the proportion due to sky scattering and reflection from the clouds. The results also show that the solar intensity on a partly cloudy day can be higher than on a completely cloudless day; and that this maximum can be greater than the value indicated by the ASHRAE formulas. It would be very desirable to have a similar sort of analysis done for several places in different parts of North America.

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4. G. V. Parmelee, Irradiation of Vertical and Horizontal Surfaces by Diffuse Solar Radiation from Cloudless Skies, ASHVE TRANSACTIONS, Vol. 60, 1954.
5. N. Robinson, (ed.) Solar Radiation, Elsevier Publishing Co., Amsterdam, 1966, p. 125.

DISCUSSION

C. W. PENNINGTON (Dep't. of Mech. Engr., Univ. of Florida): It seems obvious that to calculate the heating and cooling loads on a building in order to estimate the energy requirements, the solar flux on the surfaces of the building must be known. The authors have suggested a method by which this solar flux can be measured on an hour by hour basis. While their method involves personal observation and judgement factors, the results agree well with measured values.

Rather than depend upon visual observation and judgement, it appears to me that the actual solar flux could and should be measured and recorded. We have been recording solar intensities on a horizontal surface for years and reporting daily and monthly totals of solar incidence to the weather bureau. Since the recording is continuous, hourly totals could be reported as well. The cost of equipment is not excessive. Our equipment at the University of Florida cost less than $2,000, and comparable equipment, although perhaps not as accurate, can be purchased for less than one-half that amount.

We would be pleased to make a study similar to that made for Ottawa for our area, northern Florida. If cloud cover observations on an hourly basis are available from the Weather Bureau, these could be used for comparisons of solar intensities already recorded. If such observations are not available, it would be necessary to observe and record solar intensities over the next year or two. These observations could be extended to include vertical surfaces and separation into diffuse and direct.

In either case, some financial sponsorship would be necessary to cover salary costs involved.

THE AUTHORS: It would certainly be of great use to have available measurements of solar radiation at many different locations for use in energy calculations. If this is undertaken these measurements should preferably be made in urban districts where the atmosphere is quite different from that at the current weather stations which are usually located at airports.

T. KUSUDA (National Bureau of Standards, Washington, D.C.): Drs. Kimura and Stephenson should be congratulated for their excellent work on this timely subject. As the chairman of the Subcommittee for Heating and Cooling Loads for the ASHRAE Task Group on Energy Requirements, I cannot emphasize enough the importance of the effect of radiation to the building energy requirement. Current data in the ASHRAE HANDBOOK OF FUNDAMENTALS are only for the cloudless days, and yet most of the days in the year are cloudy days where radiation data are incomplete. The method suggested by the paper for estimating the direct and diffuse radiation under cloudy skies should be an important first step for this most neglected area.

The Subcommittee for Heating and Cooling Load Calculations is proposing to ASHRAE initiation of research projects for similar studies based upon the solar data in the United States.

THE AUTHORS: We are extremely interested to hear of the Subcommittee's proposal concerning initiation of a research project in the United States similar to our study. It will be interesting to see how different the CCF curves will be from those we obtained in our studies.

H. B. NOTTAGE (Prof. Eng., UCLA): Things in environmental realities are inherently stochastic. The use of stochastic inputs for design analyses is an important practical need. What experiences have the authors had in a statistical treatment of the data? What practical significance may be inferred in regard to statistical aspects? If least squares fitting, for example, proves to be discouraging, what sort of approach might be considered? As the need for extensive data is emphasized, might other "secondary-importance" variables be introduced and measured?

THE AUTHORS: The least squares method was first used to calculate the coefficients of second order polynomials where all the points were equally weighted. The curve derived from this polynomial did not agree well with the data at higher solar intensity, probably as a result of fewer data points for higher solar intensity. Consequently higher order polynomials were calculated using the least squares method. The error at higher solar intensities, however, still remained approximately the same as with the second order polynomials. Weighting of the data points was considered. This would have involved subjective judgement, however, in selecting these weights. An attempt was then made to take account of medium height clouds, but the correlation did not improve significantly. We think that the correlation could be improved it more of the records concerning the type and height of clouds were taken into account. The cloud observation data as expressed by 1 to 10 scale do not seem sufficiently accurate to use as a basis for exact relationships. In addition, we believe that simplicity of method is one of the primary requirements; therefore results based on more extensive correlation procedures were not included in this presentation.