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Cosine response of pyranometers — Measurements at Pune

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सार — पाइरैनोमीटर की समग्र परिशुद्धता और उसके कार्य निष्पादन का पता लगानेके लिए इसके विभिन्न अभिलक्षणों में से सबसे महत्वपूर्ण अभिलक्षणों कोसाइन लॉ (नियम) का सही ढंग से पालन करना है। परन्तु इस कोसाइन प्रतिक्रिया को समझना और उसके अनुसार सुधार करना कठिन कार्य है। विभिन्न प्रकार के पाइरेनोमीटरों की जो कोसाइन प्रतिक्रियांए पुणे में उपलब्ध हैं, उनका पता केन्द्रीय विकिरण प्रयोगशाला की ऑप्टीकल प्रणाली से लगाया गया है। इन अध्ययनों के परिणामों को इसमें संक्षेप में प्रस्तुत किया गया है।

ABSTRACT. Among the various characteristics that determine the overall accuracy and performance of a pyranometer, the strict adherence to the cosine law is an important one. But this cosine response is difficult to realise and to correct for. The cosine response of various types of pyranometers available at Pune was determined on the optical set up in Central Radiation Laboratory. The results of these studies are presented briefly.

Key words — Pyranometer, Solar irradiance, Response, Cosine, Azimuth.

1. Introduction

Meteorological measurements of solar irradiance are carried out on long term basis, usually using thermoelectric pyranometers. The basic assumptions made are: (*i*) the pyranometers have nearly flat response over the entire spectrum; (*ii*) the temperature dependence of the output is nearly absent and (*iii*) the instrument strictly follows the Lambert's Cosine Law. In many cases this may not be the case and the quality of the data generated depends much on the repeatability of the measurements made with the pyranometers on a network scale.

Some of the more important parameters that influence the performance of a pyranometer are:

(1) the uniform responsivity over the entire spectrum, *viz*., 290- 4000 nm

(2) linear response with the changes in irradiances

(3) fast response time to changes in irradiances

(4) lowest temperature coefficient

(5) absence of zero depression due to IR fields

(6) long term stability of calibration

(7) low response to thermal shocks

(8) changes in the tilt, *i.e.*, non-horizontality of the sensor

(9) cosine response arising out of the changes in the angle of incidence of the irradiation

(10) azimuth response due to the apparent shifts in the sun's azimuthal position in the ecliptic.

The individual quantification of the above parameters will enable a good choice of a pyranometer for a specific application. A complete characterisation of an instrument is, therefore, desirable. However, it is too time consuming to have complete characterisation for each instrument. The cosine and azimuth responses are the most important ones which vary widely from instrument to instrument and they are to be preferably determined for each instrument.

2. Optical arrangement for cosine response determination

The Laboratory set up basically consists of two semicircular arcs mounted on steel balls fixed to a 2 m long optic bench (Kanade 1992). The arcs are graduated in degrees of angles and have provision for mounting a lamp holder. The lamp holder carries an achromatic lens at whose focal length a 200 W tungsten halogen lamp is mounted. This enables a well collimated and intense beam to illuminate the thermopile and its glass cover. The lamp holder can be fixed at any desired angle. The lamp requires a steady DC supply at 24V 8A. This is provided by converting a very stable AC

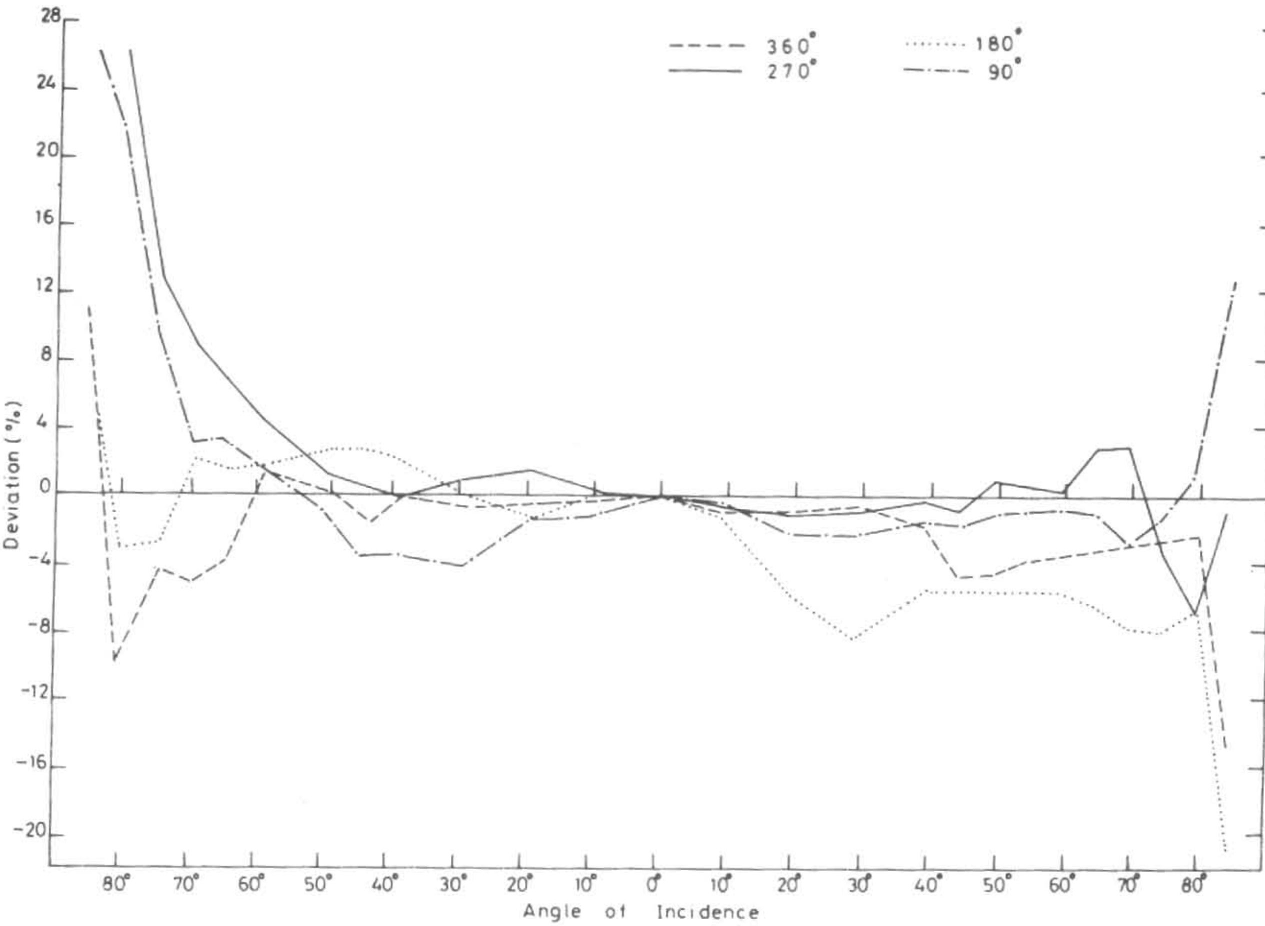

Fig.1. Deviation from cosine response for the MG instrument

supply by means of an HP power supply unit. The power cables are taken through conduits so that no hanging wire becomes a source of error.

The pyranometer is mounted on a separate pedestal and properly levelled. The output of the pyranometer is measured on a well calibrated HIL $4\frac{1}{2}$ digit millivoltmeter. The low output of the pyranometer is amplified by an amplifier unit which has a magnification of 50. All the units are mounted below the level of the table on which the optic bench is kept, to avoid any disturbance to the radiation field at the pyranometer. The entire area including the ceiling is made black to avoid all possible reflections. The temperature of the room is maintained at 25°C to avoid any error due to the temperature coefficient of the pyranometers.

The initial mounting of a pyranometer is done with the cables taken out from a direction away from the control units and perpendicular to the axis of the optic bench. This is designated as 360° orientation. The right side then becomes the 90° orientation. The measurement begins with the lamp at 0° elevation on the right side. Then the outputs are taken at 5°, 10°, 15°, 20°, 30°, 45°, 60°, 75° and 90° positions of lamp holder. Collins (1966) had reported that lamp output varies by atleast 7 per cent when its position changed through large angles. It was, therefore, decided to monitor the output at each position by using a calibrated Eppley thermopile always held normal to the irradiation. Only when the output of the lamp reached the same and steady irradiation, the output of the pyranometer was read. The measurements were carried out for all the different angles of elevation from 0° on right side to 0° on the left side through 90°. For each reading of the pyranometer, the power supply was checked using an accurate voltmeter and an ammeter and the stability of the lamp output by the Eppley thermopile at normal incidence. After a complete series of measurements for the 360° orientation, the series is repeated for 90°, 180° and 270° orientation, *i.e.*, the output cables were in the 90°, 180° and 270° directions from the first series. This was done to study the azimuthal effects.

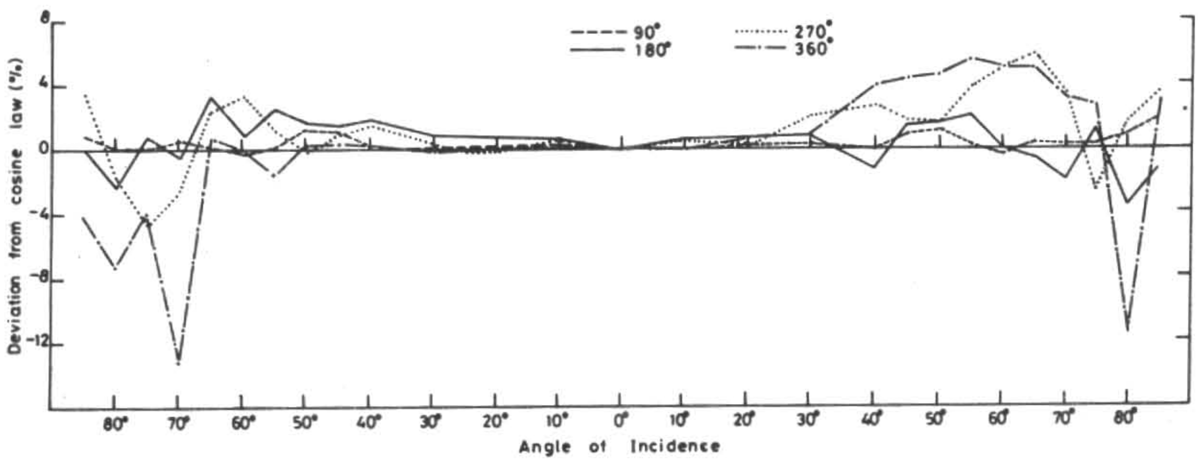

Fig.2. Deviation from cosine response for CM-11

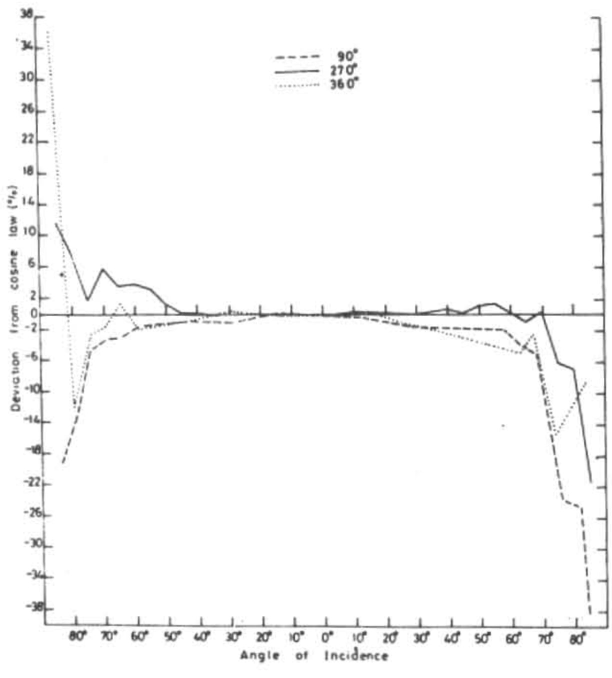

Fig.3. Deviation from cosine response for PSP

3. Instruments under test

Different types of pyranometers were tested. They are:

(*i*) Moll-Gorczynski (MG) pyranometer No.1154 of CM-5 type

(*ii*) CM-11 pyranometer No.871776

(*iii*) Eppley PSP pyranometer No.11919 F3

(*iv*) Star (Schenk) pyranometer No.509

(*v*) Yanichevski pyranometer No.9784 and

(*vi*) IMD (Indian) thermoelectric pyranometer No.85/85

The MG and IMD pyranometers were selected at random without any bias on their previous performance.

4. Results

4.1. *Performance of CM-5 pyranometer*

(1) The deviation from the cosine law is within 4 per cent for angles of incidence up to 70° and it is about 10 per cent between 80° and 90° and it was negative (Fig.1) when the orientation was 360°.

(2) There is a large and conspicuous change when the orientation became 180°. The error was within +3 per cent when the irradiation was from the right hand side and it became as high as –6 per cent when it was from the left side. In both cases the longer side of the thermopile was in the 180°-360° axis.

(3) The departure in the case of 90° and 270° is over a very narrow range, ± 2 per cent in general.

(4) The departure when the angle of incidence is greater than 80°, is always higher, +12 per cent when illuminated from the right side and more than –16 per cent from the opposite side for both 360° and 180° orientations. The 270° orientation has more than +25 per cent deviation when the lamp is on the right side as against the hardly –6 per cent for 80° angle of incidence when illuminated from the opposite side. The deviation is +25 per cent and +12 per cent respectively when the pyranometer is oriented towards 90° direction. Obviously the extreme edges of the thermopile are not exactly flat.

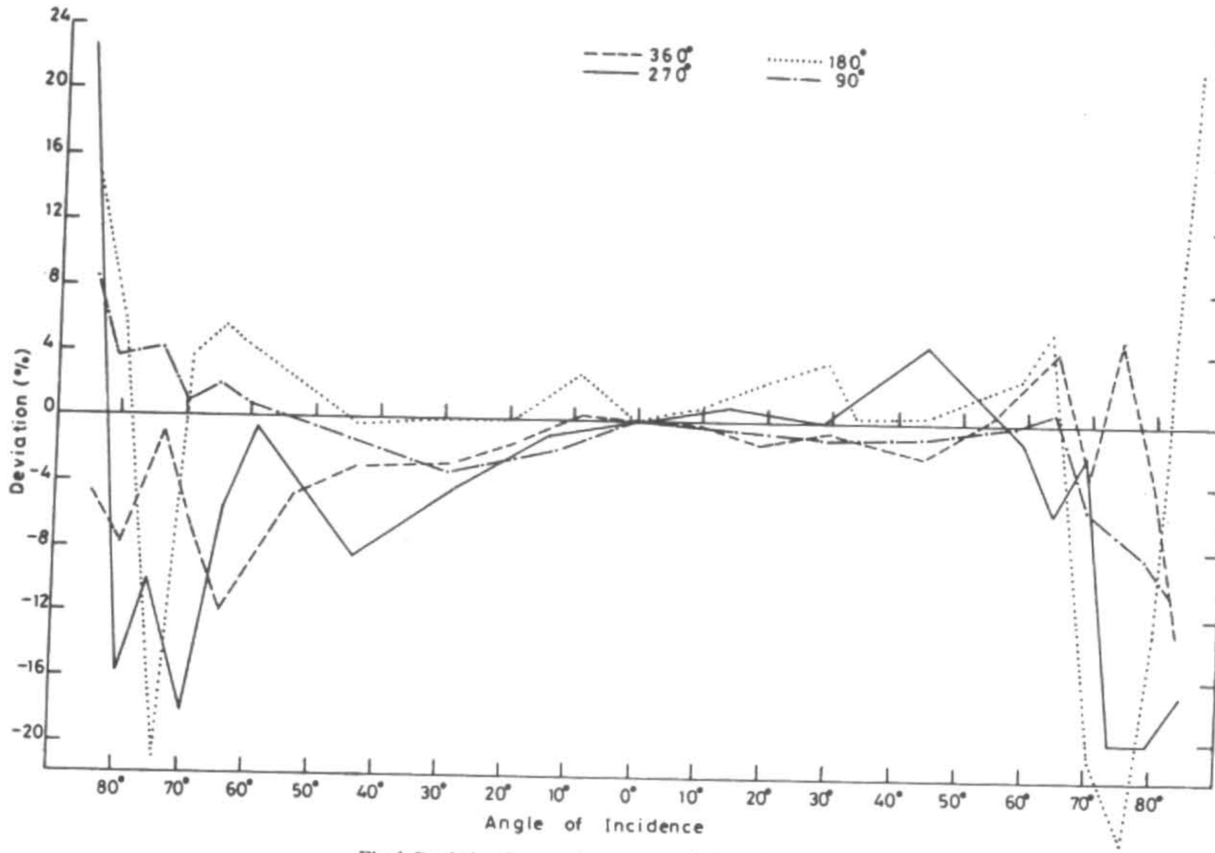

Fig.4. Deviation from cosine response for Dirmhirn pyranometer

(5) Both (Fröhlich 1984) and (Liedquist 1984) have reported much larger departures.

4.2. *CM-11*

(1) When the instrument was in 90° and 180° orientation, there is no appreciable deviation (Fig.2) from cosine response. The deviations were generally around 1 per cent.

(2) For the 270° orientation, a sharp –4 per cent deviation at 75° incidence is seen from the right side and a slightly higher and erratic error when illuminated from the left even for elevation angles of 50°.

(3) The errors in the case of 360° orientation, however, are very high, The error is more than – 4 per cent for angles greater than 75° when illuminated from the right side of the instrument. It became –13 per cent for 70°. The error was found to be repeatable when checked again and again as it is against the normal performance of a CM-11 instrument. The error again became –12 per cent when irradiated at an incidence angle of 80° from the left side.

4.3. *Eppley precision spectral pyranometer (PSP)*

PSP instruments are reputed to have the best performance, with a claimed average error of 1 per cent. The instrument under reference, however, shows larger deviations at angles larger than even 60°. Fig. 3, however, shows remarkable symmetry in the deviations. The instrument could not be checked in the 180° orientation as it developed some defects by then.

(1) With pyranometer facing 360° orientation, the deviations are more than 10 per cent even at an angle of elevation as high as 20°.

(2) The more or less symmetrical output, however, indicates a small unevenness of the surface from the edges to the centre of the sensor.

(3) The symmetry in the errors is more pronounced when the instrument is oriented towards 90° orientation, though the departures from the cosine response are larger.

(4) The 270° orientation shows a mirror image type of errors, though the magnitudes are smaller. The departures are mostly on the positive side except for low-angles of elevations from the left side.

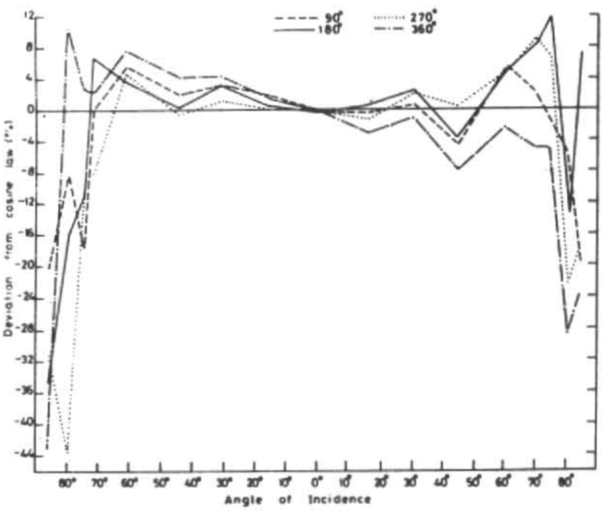

Fig.5. Deviation from cosine response for Yanichevski

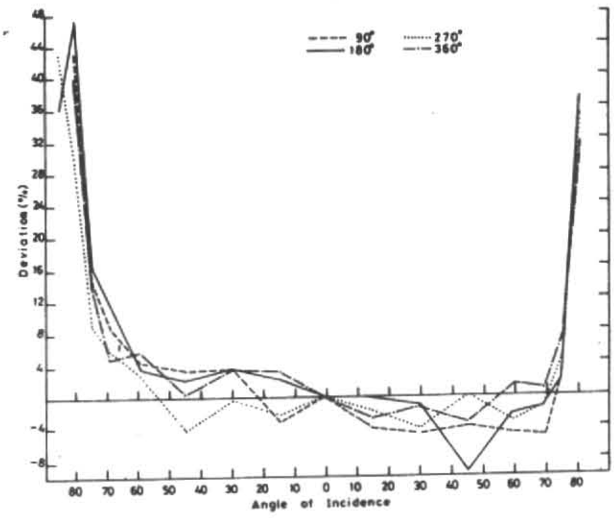

Fig.6. Deviation from cosine response for IMD

(5) PSP is one of the pyranometers which has been subject to tests by a large number of scientists. Nast (1983) and Jeffrey Mohr *et al.* (1979) obtained very little correction upto an 80° of angle of incidence. Fröhlich (1984) and Liedquist (1984), however, got very high corrections, even greater than 10 per cent.

4.4. *Schenk star pyranometer*

The star pyranometers are reputed to have no or little cosine error. A general conclusion that is drawn from a perusal of Fig.4 is that the specific star pyranometer has large deviations even at angles as low as 50°. There is no symmetry in the errors as seen in the case of PSP. The particular instrument also showed variations in the thickness of paints, both black and white, over different parts of the sensor.

(1) The deviations are of opposite type, as they should be, for the 360° and 180° orientations. The errors are larger when illuminated from the right side than those for irradiation from the left.

(2) Similar is the case for both 90° and 270° orientations, though the magnitudes of the deviations are widely different without any pattern. This perhaps is a clear indication of the unevenness of the surface.

The above performance only indicates that the particular instrument is far from the satisfactory standards and should not be in use anywhere.

4.5. *Yanichevski pyranometer*

The deviations for elevation angles greater than 20° are all positive when the irradiation is from the right side and of the order of 4-6 per cent. The fluctuations in the deviations are wide when the illumination is from the left side (Fig.5).

(2) The cosine error is larger for an angle of incidence of 70° or more.

(3) The errors for the 360° orientation are all positive when irradiated from the right and negative and larger when it is from the left.

(4) In the case of 180° orientation, the deviations are of opposite nature.

(5) Similar trends are seen in the case of 90° and 270° orientation.

4.6. *IMD pyranometer*

(1) The deviations from cosine response for both 360° and 180° orientations are of same type. They are larger than 4 per cent for elevations less than 30°. It is as high as 35 per cent for 85° of incident angle (Fig.6).

(2) In the 90° direction, positive departure is seen for the irradiation from the right side and negative in the opposite case. The deviations are nearly 4 per cent in both cases.

(3) The error is negative for most of the angles when the instrument is in 270° orientation and lies within 4 per cent.

(4) The increase in the departure towards the higher angles of incidence is gradual when the source irradiates from the right and it is sharp from the opposite direction of irradiation. It is obvious that the surface is not exactly horizontal.

(5) The large deviation in all cases at very low angles of incidence is always positive with this particular pyra-

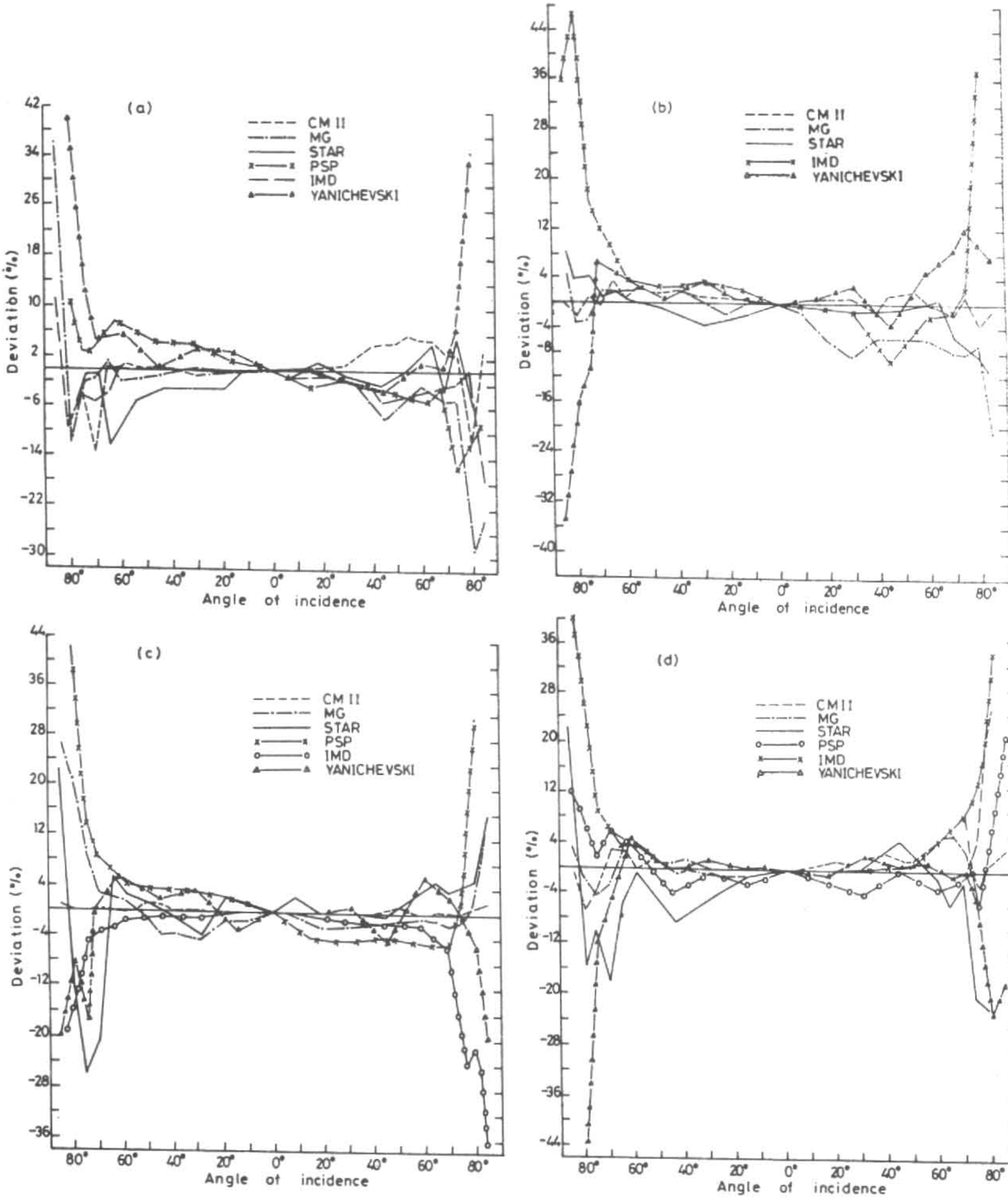

Fig.7. Comparative study of all the pyranometers

nometer. A later careful check indicated a slight sloping down, at the edges, of the aluminium foil to be the main reason.

4.7. *A comparative study*

Fig.7 gives the performance of each pyranometer in a given direction. In general it is seen that PSP has the

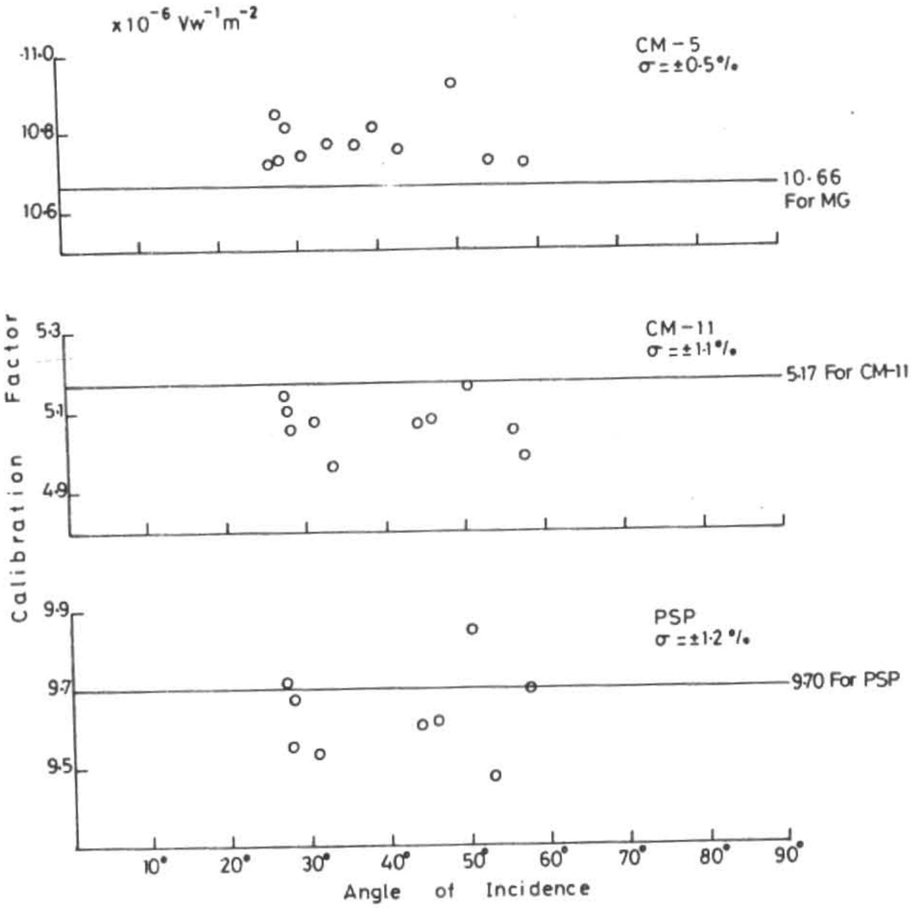

Fig.8. Variation in calibration factor with solar zenith angles

best performance over all different zenith distances and azimuthal orientations. The particular CM-5 included in the study also seems to be of better standard than reported by others elsewhere. In fact CM-5 appears to have lower deviations than PSP, Yanichevski, star and IMD pyranometers show large variations. The performance of CM-11 is exceptionally good only in the 180° orientation. Almost all instruments have very large percentage errors for angles of incidence greater than 70°. Fröhlich (1984) in a different study ascribed the differences in different orientations to some of the suspected effects like non- linearity and spectral response to have cross actions alongwith cosine response. Liedquist (1984) also found that the responsivity for azimuth changes to be very random and only the perio-dicity of response with azimuth angle is consistent within each type of pyranometer. Flowers (1984) obtained a good scatter for three different types of instruments, *viz.*, PSP, Eppley Black and white and CM-6 pyranometers. Azimuth response also showed large variations, particularly for the star pyranometer. Thus the result obtained at Pune is not exceptional and not improbable either.

5. Conclusion

The directional response is a unique property of a pyranometer and its variation has a significant effect on the output of the instrument. The salient features of the studies made with different types of pyranometers available at Pune are summarised below:

(*i*) Almost all instruments have good cosine response up to angles of incidence of 70°. In general the errors are within 2-4 per cent.

(*ii*) Beyond 70° of angle of incidence, all instruments have wide and random deviations from the cosine law, suggesting certain inhomogeneties in the sensor surfaces.

(*iii*) PSP instrument has the best cosine and azimuth response. Although variations are larger than 5 per cent at 80° and above, they exhibit symmetry for different azimuth orientations.

(*iv*) CM-11 instrument though showing larger deviations, has consistency over a wide range of angles of incidence and for different azimuth orientations.

(*v*) The star pyranometer reveals the effect of inhomogeneity in its surface - both black and white segments. The deviations do not follow any trend and are erratic for different angles of incidence and orientation. Even for a given position, the changes in the deviation are dissimilar when the irradiation is from opposite direction.

(*vi*) The IMD pyranometer shows a peculiar characteristics, while the sensor is flat almost throughout the surface, the aluminium foil attached to the thermopile slopes downward towards the edges. The result is that there is a sudden increase in the output of the pyranometer at larger angles of incidence. This is a symmetrical error for all orientations. Later instruments do not have this apparent error due to extra care taken in fixing the foil.

(*vii*) The CM-5 pyranometer at Pune has better cosine response characteristics than those reported elsewhere. Sinçe the sensor has rectangular shape, the deviation is found to be more on the transverse position than along the longitudinal direction.

(*viii*) The indoor characterisation carried out should be checked outdoor under working conditions. The few routine calibration data obtained outdoors do indicate the low dispersion of the factors with solar zenith angle (Fig.8). These were made without any conscious exercise to check the cosine response. More data are, however, needed to yield better results.

(*ix*) The cosine response of a pyranometer is highly individualistic. A reputed pyranometer like PSP and CM-11 may show larger deviations because the particular instrument's surface is so. Similarly, an instrument like that from IMD may have excellent performance in specific instances. Thus it is essential that each pyranometer is individually characterised for the cosine law and for the tilt effect if it is to be used in other orientations than in the conventional horizontal position. Instruments with large deviations should not be used at all.

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