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Cosine response of an Indian pyranometer

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सार — पाइरैनोमीटर का कार्य निष्पादन-विभिन्न अभिलक्षणों, जैसे, स्पेकट्रमी प्रतिक्रिया, निष्पादन की रैखिकीय, तापमान सहसंबंध और दिशात्मक प्रतिक्रिया पर निर्भर करता है । कोसाइन नियम से विचलन को सुधार पाना ही नहीं बल्कि व्यक्तिगत रूप से इसका पता लगा पाना भी एक अत्यंत कठिन कार्य है । केन्द्रीय विकिरण प्रयोगशाला द्वारा पुणे में कोसाइन से विचलन का पता लगाने का कार्य किया गया है । देशी ताप विद्युत पाइरैनोमीटर की इस तरह की माप के परिणामों को तथा उनसे संबंधित विचारों को इस शोधपत्र में प्रस्तुत किया गया है ।

ABSTRACT. The performance of a pyranometer depends on various characteristics like spectral response, linearity of output, temperature coefficient and directional response. The departure from the cosine law is one of the most difficult to correct for and even to determine individually. The Central Radiation Laboratory has carried out the determination of cosine error at Pune. The results of such a measurement on an Indian made thermoelectric pyranometer are presented and discussed.

Key words — Pyranometer, Cosine response, Irradiance, Thermopile, Angle of incidence

1. Introduction

Pyranometers are thermopile radiometer detectors which measure the incident solar irradiance from the sun and the celestial hemisphere subtending a solid angle of 2π steradians at the sensor. The hectic industrialisation and urbanisation activities in the name of development are gradually affecting the delicate radiation balance of the atmosphere - earth system. Any change in this solar irradiance in a sustained and larger degree will disturb the delicate balance in a disastrous way. The variations that may initially be felt will be small and the measurements to monitor this incoming irradiance are of great importance. Hence these have to be of very high accuracy. Thus the pyranometers used for the purpose must be capable of yielding high quality and reproducible data. This would then necessitate the identification of the various sources of errors which ultimately result in the uncertainties in the measurements. With the demand for information on the availability of solar irradiance for applications, more and more people will be operating small networks. The information gained can be of high accuracy and general value only if certain minimum precautions are taken during the instrument's initial calibrations. These calibrations have two components: (1) the testing of possible sources of errors with optical arrangement in a laboratory and (2) the meticulous series of calibrations done outdoors to establish the overall calibration factor under natural conditions.

The determination of various corrections to the overall final factor is referred to as the characterisation. The various sources of errors are identified and each one of them is experimentally determined. Some of the important characteristics are: (1) uniform spectral responsivity, (2) linearity of output with changes in irradiances, (3) the response time, (4) the temperature coefficient, (5) the zero offset, (6) stability of performance, *i.e.*, the reproducibility of the calibrations and (7) the directional response. Of these it is the directional response which is difficult to control and corrections to errors due to deviations are difficult to apply. A specific aspect of this directional response, *viz.*, the departures from the cosine response is being presented here for one of the pyranometers being made by India Meteorological Department (IMD) at Pune.

Kanade (1992) has made an exhaustive study of the cosine law and the performance standards of the different types of pyranometers.

2. Materials and method

2.1. *Directional response*

The basic Lambert's cosine law stipulates that the radiation absorbed by a surface on which it is incident is proportional to the cosine of the angle of incident radiation. The variations in the angle of incidence can be due to — (1) the change in the direction of the beam from the normal; (2) the changes in the azimuthal direction from which the radiation is received and (3) the tilted position of the receiver with respect to the horizontal. In practice however, the strict adherence to this cosine response is not realised.

Robinson (1966) reasons that the deviation occurs due to — (1) different absorption properties in the various parts of the receiver with the angle of incidence; (2) the unevenness in the receiving surface and in the optics of hemispherical glass domes; (3) the incorrect levelling of the receiving surface and (4) the variations in the temperature of the receiver with the angle of incidence. The first two sources of errors are due to the surface condition and cannot be corrected. Fröhlich (1984) stresses the fact that the behaviour of the pyranometers is much dependent on the azimuthal angle of irradiation. He points out that the behaviour depends on (1) the variability due to the tilt of the sensor surface and (2) the variability which increases with decreasing angle of elevation of the sun. The effect due to tilt is inherent in the thermopile sensor and is difficult to correct for. The second due to missalignment of the normal on the surface of the thermopile and the axis of the instrument can be corrected by realignment. The convective losses by the surface due to its hemispherical glass cover is disturbed due to the tilting angle of the sensor surface from its horizontal. Dehne adds to the sources of errors: (a) the infrared irradiance on the receiver from the sky and the ground is different at different angles and (b) the warming by direct irradiation of the pyranometer body depends on the orientation of the pyranometer with respect to the direction of irradiation.

What is known as the cosine response or more explicitly as the cosine error is the deviation from the Lambert's Cosine Law. When the angle of incidence is changed in the horizontal plane but within the same vertical plane. In other words, it is due to the non adherence of the output of the pyranometer to the cosine law when the elevation of the source of irradiance from the horizontal changes. Fröhlich states that it is the most difficult effect to correct for. It is this effect which affects the performance of a pyranometer the most. It is proposed to restrict the study here to the performance of the IMD pyranometer to the laboratory tests.

2.2. *IMD Pyranometer*

The pyranometer thermopile is wire wound copper-constantan thermopile. Constantan wire of 36 SWG is wound in the marked grooves on a circular acrylic former. Half of these turns are suitably electroplated with copper so that copper-constantan junctions form at the centre of the flat surfaces. A thin alluminium foil is fixed to each side using an epoxy cementing glue which in thin layers ensures good thermal contact and yet provides good electrical insulation. The former is then mounted on a thick brass mount which in turn is housed in a massive brass body to provide a very good heat sink. The top surface of the former is then painted black using black lacquer having uniform absorption of better than 98 per cent. The active surface is then enclosed within two concentric infrasil hemispherical glass domes of 30 and 50 mm diameters. Because of the circular seonsor, the azimuthal response is nearly uniform and the departure from cosine law may be kept to the minimum if mounted very carefully. A circular white painted metallic guard plate protects the body of the pyranometer from direct solar heating.

2.3. *Optical setup for determining cosine error*

Kanade (1992) made a detailed comparative study of the various methods of optical arrangements to subject a pyranometer to various angles of irradiation. The laboratory optical arrangement used at Central Radiation Laboratory, Pune consists of two arcs mounted on steel balls which are fixed to an optic bench. Sliding over the arcs is a collimating achromatic lens, housed in lamp holder with proper ventillation (Fig. 1). The lamp holder slides over the arcs and can be fixed at the desired angle of elevations marked on the arcs themselves (Fig. 2).

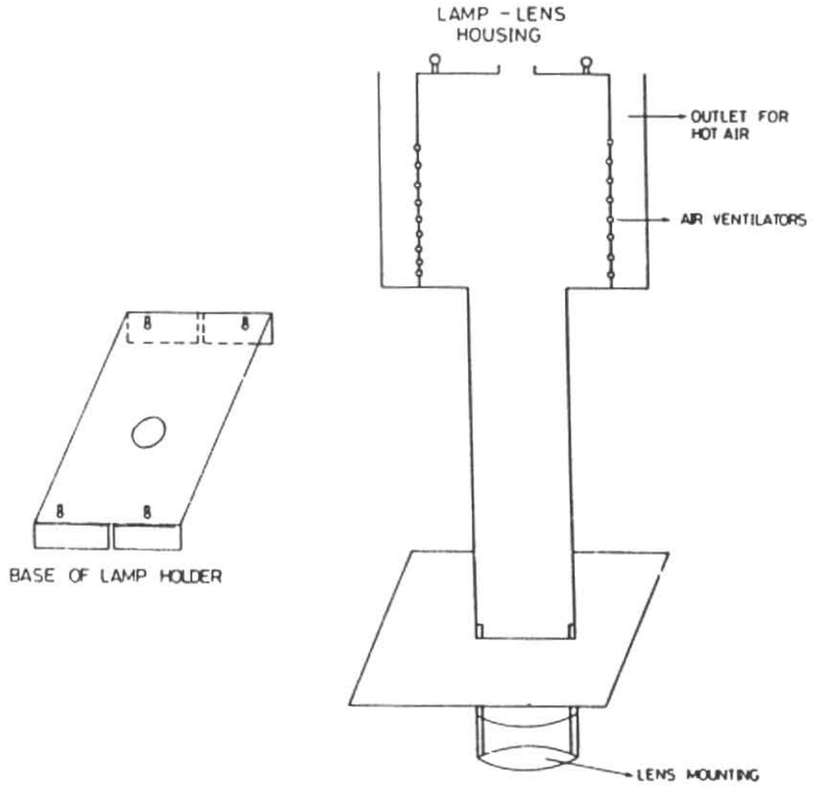

Fig. 1. Lamp housing

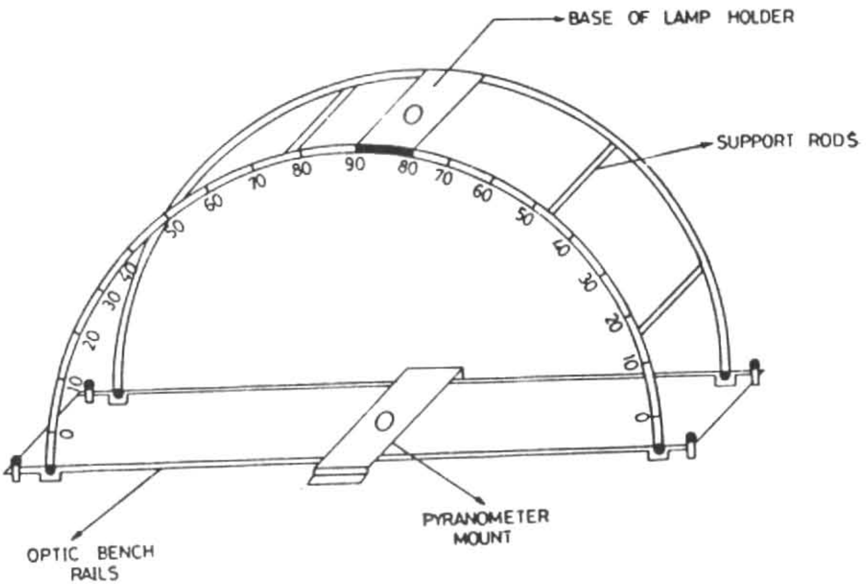

Fig. 2. Optical arrangement for cosine response determination

To prevent the power cable hanging loose, it is routed through a hollow pipe held by two stands resting on either side of the optic bench. The pyranometer is mounted horizontally on a suitable platform at the centre of the optic bench. All parts are painted matt black to reduce reflections. The optic bench has provisions to ensure exact levelling. The lamp housing (Fig. 1) has a lid to prevent the

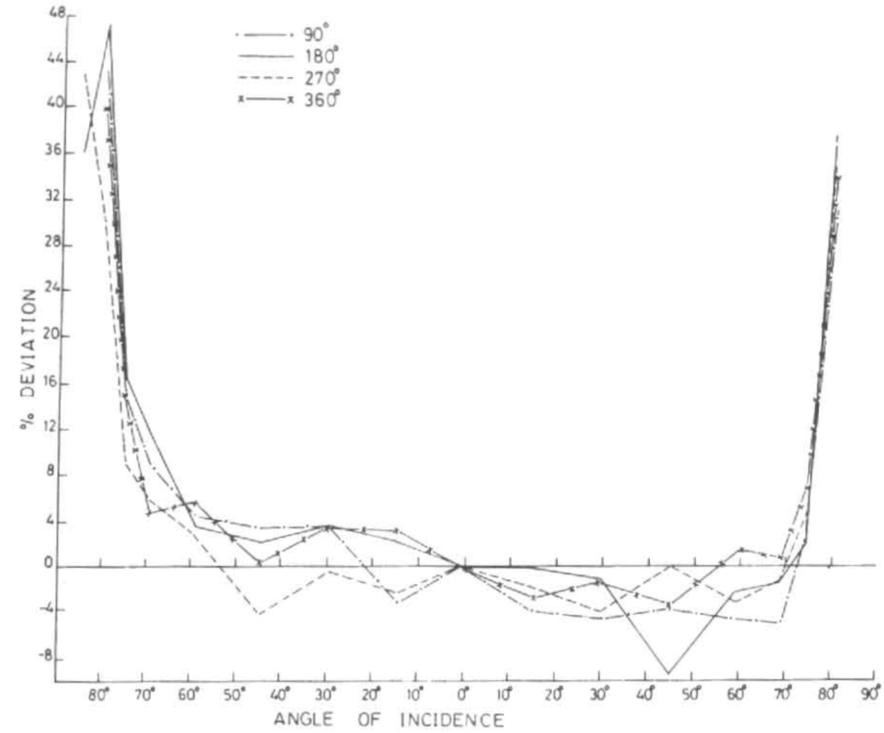

Fig. 3. Deviation of cosine response for IMD pyranometer

illumination in the backward direction and its possible reflection on to the pyranometer. The achromatic lens which has the lamp at its focal point provides a collimated beam at the pyranometer. An incandescent 200W tungsten halogen lamp is used as the radiation source.

The lamp operates on a power supply unit which can provide a dc voltage of 0-50V and dc current from 1 to 20A. The supply used is a 24V dc at 8A. The input power supply is routed through a voltage stabiliser. The output of the pyranometer is read out on a well calibrated HIL $4^1/_2$ digit millivoltmeter of high accuracy. Since the pyranometer output is quite low with this 200W lamp, a linear amplifier unit having a magnification of 50, is used. All the assemblies are mounted at a much lower level than that of the optic bench which itself is kept on a table having black top. To eliminate chance drifts due to temperature variations, the measurements are carried out under controlled temperature conditions. The entire place of measurement is made completely dark, including ceiling, to eliminate the chances for any reflections.

2.4. *Measurement schedule*

To ensure the stability of the irradiance from the 200W halogen lamp, a stabilised ac power supply is converted into a dc supply. The halogen lamp's requirement of 24V, 8A dc supply is monitored constantly using well calibrated and accurate dc voltmeter and dc ammeter. The output of the pyranometer is read on an HIL $4^1/_2$ digit millivoltmeter, after magnifying it with an amplifier unit designed for the purpose. The different outputs of the pyranometer for different angles of incidence 0°, 15°, 30°, 45°, 60°, 70°, 75°, 80° and 85° are measured by adjusting the lamp at different desired positions. To obviate the variations in the outputs of lamps possible because of the changes in the orientations of the lamp [Collins (1966) had reported 7 per cent variation when the source is turned through 180°], an Eppley calibrated thermopile sensor is held normal to the incident beam and the output is measured. The output is then adjusted to its normal value (within 1 per cent). Sufficient time is allowed for the lamp to stabilize its output after each shift. The voltage and the current of the lamp is checked for each reading. The person who is reading the output is also made to be at a lower level, lower

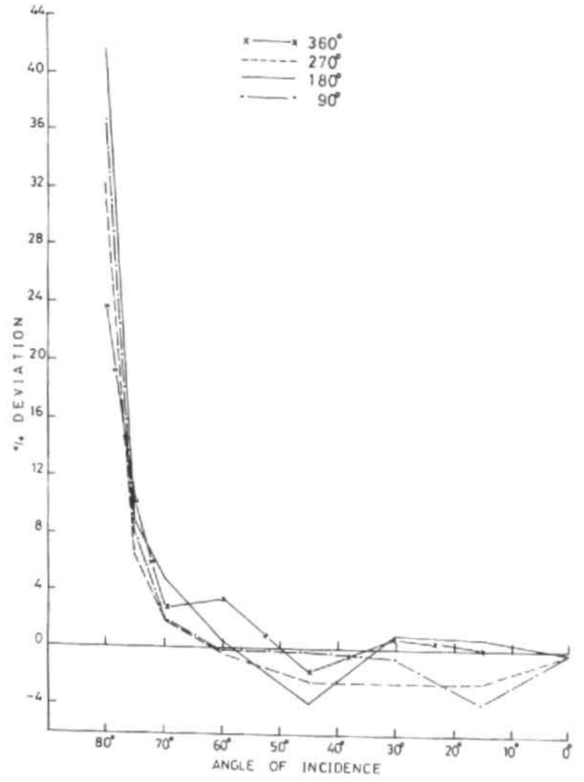

Fig. 4. Average of deviations of two directional beams for IMD pyranometer

than the table itself. With darkened surroundings, many sources of error have been reduced to minimum so that the repeatability could be achieved.

The leads of the pyranometer which is mounted on its mounting and properly levelled, is taken out in a direction perpendicular to the axis of optic bench. The position of the lamp is adjusted from 0° to 90° zenith on one side and then repeated on the other side. In each case the lamp output is allowed to stabilize and checked by the Eppley thermopile held at normal incidence. The irradiance is maintained at appropriate level by adjusting the power supply, where necessary. After a particular set of readings, the orientation of the pyranometer is changed through 90° and the whole series of measurements is repeated. The measurements are made for the four cardinal directions 360°, 90°, 180° and 270°. The existing facility does not permit the simulation of the sun's apparent path in the ecliptic.

3. Results and discussion

The IMD thermo-electric pyranometer is a wire—wound circular thermopile offering a symmetrical surface to the incident irradiation. (Fig. 3) shows the percentage deviation from the cosine law for various angles of incidence. A study of the curves for different orientation shows that the particular instrument under study is not having exact symmetry in its geometry. The instrument under study was taken at random without any specific consideration. The surface near the edges seems to have a downward slope, as can be inferred from the sharp increases seen at large angles of incidence. Some of the striking points that can be inferred are:

(*i*) The departure from cosine response are normally within ± 4 per cent when angle of incidence is less than 70°.

(*ii*) The error sharply increases from 70° onwards, it is more than 35 per cent for 85° of angle of incidence. For a PSP pyranometer which was tested similarly, the error is of comparable value; it is 38 per cent.

(*iii*) The departure for both 360° and 180° orientations of the pyranometer are somewhat of same type. They are less than 4 per cent for lower angles of incidence.

(*iv*) At 90° orientation, the pyranometer shows a positive error when it is irradiated from the relative direction of 90° orientation. The error becomes negative when the lamp irradiates from the opposite side, *i.e.*, 270° orientation. This shows that the sensor surface is not exactly horizontal but tilted slightly to the 90° orientation. In both cases the magnitude of the error is 4 per cent.

(*v*) When the pyranometer is turned to 270° orientation (*i.e.* the connecting leads are taken out along the 270° direction of the original set up), the errors are negative in most cases and the magnitude is within 4 per cent.

(*vi*) The increase towards the higher angles of incidence are gradual when the source irradiates from the right side and is very sharp when it is done from the opposite side (*i.e.* left side). This is obviously due to the non-horizontal sensor surface.

(*vii*) Fig. 4 gives the mean of the errors obtained from the two directional positions (*i.e.* left and right sides) of the lamp. The instrument appears to have a narrow deviation bandwidth as compared to many other pyranometers (The results are being compiled and will be presented separately), except when the angle of incidence is higher than 70°. The 180° orientation gives a steady 1 per cent deviation as compared to the more than 2 per cent error when the pyranometer is oriented in the 360° direction.

(*viii*) At higher angles of incidence, the errors are larger and there is no specific trend.

4. Conclusions

In conclusion, the results of measurements show that the sensor is nearly flat except at the edges where the aluminium foil attached to the thermopile has a downward slope.

This is perhaps due to the pressure applied to make the thermal contact between the foil and the thermo-elements uniform throughout. The result is that there is a sudden increase in the output at larger angles of incidence. This performance is seen to repeat for any directional orientation. This study has enabled the laboratory to take extra precautions so that the edges remain horizontal in the sensors prepared after this study.

One must bear in mind that the cosine response characteristic is individualistic. An instrument belonging to the same batch of manufacture may have different cosine response from the other instrument of the same batch. It is, therefore, essential that each pyranometer is individually characterised for cosine response before it is put into use. Pyranometers which are found to have large deviations should not be used at all. The sensor of such an instrument should be prepared again.

References

Collins, B.G., 1966, "Determination of the cosine response of the pyranometers", *J. Sci. Inst.*, **43**, pp. 837-838

Dehne, K., "Results of indoor test of solarimeter specifications (CM-6 & CM-10) - Private Communication

Fröhlich, C., 1984, "The need for characterisation of pyranometers", Proc. Symp. on Recent Advances in Pyranometry, Nörrkoping, Sweden, pp. 164-170.

Kanade, V.V., 1992, "Laboratory determination of Cosine Response of pyranometers", M. Sc. Thesis, University of Poona.

Robinson, N., 1966, "Solar Radiation", Elsevier Publishing Co.