Hukseflux Thermal Sensors

What is a pyranometer?

A quick introduction to pyranometer basics.

This article aims to give a reader with a basic level technical background an introduction to pyranometers and the measurement of global irradiances.

Introduction

Simply said a pyranometer is a device that measures solar irradiance from a hemispherical field of view incident on a flat surface. The SI units of irradiance are watts per square metre (W/m^2).* Traditionally pyranometers were mainly used for climatological research and weather monitoring purposes, however recent worldwide interest in solar energy has also lead to an increased interest in pyranometers.

In this article we will explore the basic aspects of pyranometers: what does it measure; what is it useful for; and how does it work?

Pyranometer: a solar irradiance sensor

Pyranometers measure global irradiances: the amount of solar energy per unit area per unit time incident on a surface of specific orientation emanating from a hemispherical field of view ($2\pi\,\mathrm{sr}$), denoted $E_{g\downarrow}$. The global irradiance includes direct sunlight and diffuse sunlight (and in some cases specular reflections of sunlight) as illustrated in Figure 1. The contribution from direct sunlight is given by $\mathrm{E}\cdot\cos(\theta)$ where θ is the angle between the surface normal and the position of the sun in the sky and E is the maximum amount of direct sunlight. The global irradiance is then:

$$\mathrm{E}_{g\downarrow} = \mathrm{E}\cdot\cos(\theta) + \mathrm{E}_d$$

where E_d accounts for the diffuse sunlight.

In most cases the surface is horizontal such that the hemispherical field of view corresponds to the sky dome. In that case the measured quantity is the so called global horizontal irradiance (GHI) denoted $\mathrm{E}_{g\downarrow h}$ (see Figure 2 left). In some cases the surface is tilted, for example in photovoltaic applications where the surface often corresponds to the plane of array (POA) of solar panels (see e.g. Figure 2 right). In this case the measured quantity is the global tilted irradiance (GTI) denoted $\mathrm{E}_{g\downarrow t}$.

* Occasionally the irradiance is expressed in different units such as the British thermal unit per hour per square feet (1 Btu/(hr·ft^2) = 3.155 W/m^2) or ergs per square centimetre per second (1 erg/(cm^2·s) = 0.001 W/m^2).

A special case is the case were the surface is horizontal, but with the pyranometer facing downwards instead of towards the sky. In this case the measured quantity is the diffuse reflection from the surface of the earth, denoted $\mathrm{E}_{r\uparrow}$.

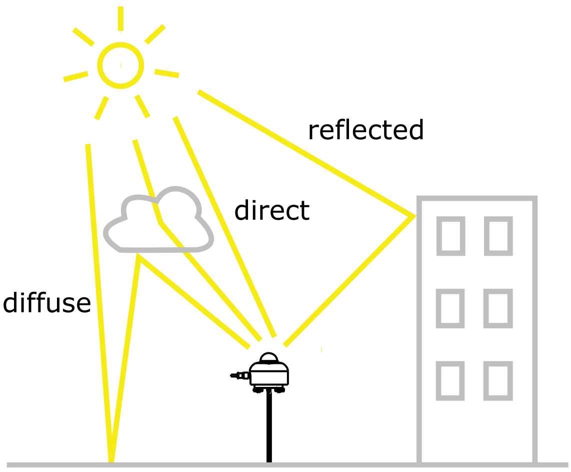

Figure 1 *The global irradiance includes direct sunlight and diffuse sunlight and specular reflections of sunlight.*

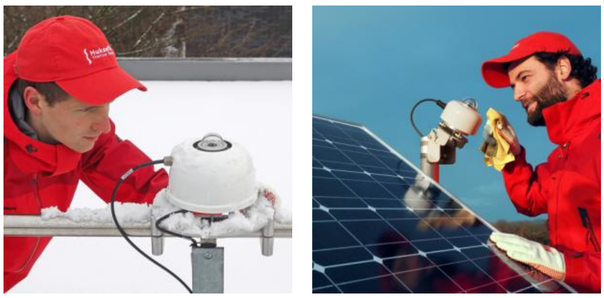

Figure 2 *Left: a horizontally aligned pyranometer measuring the global horizontal irradiance (GHI) and right: a tilted pyranometer measuring a global tilted irradiance (GTI).*

The global irradiance may vary greatly depending on the height of the sun in the sky (and thus location on the earth, time of day and time of year) and on meteorological and environmental factors such as clouds, aerosols, smog, fog, precipitation and others. Typical values for the global horizontal irradiance are in the range from 0 to 1400 W/m^2. In some cases it can be larger for example due to reflections from buildings or snow or in a more exotic example at the centre of a solar concentrator.

What are pyranometers used for?

The sun is earth's main source of extraterrestrial energy. This has important implications in two areas: weather and climate on the one hand and energy production by harvesting solar energy on the other hand.

Solar radiation is one of the driving forces behind the earth's weather patterns and thus an important factor in weather and climate studies. In such studies pyranometers are mostly used to measure the GHI to determine the irradiance incident on the surface of the earth. The GHI that one would measure just outside earth's atmosphere is fairly predictable, but at the surface of the earth the irradiance depends strongly on factors such as cloud coverage, aerosol concentration, fog and smog. Another interesting measurement is that of the net irradiance $E_* = E_{g\downarrow} - E_{r\uparrow}$ or the albedo $A = E_{r\uparrow}/E_{g\downarrow}$. In this case two horizontally aligned pyranometers are used: one facing towards the ground and one facing towards the sky.

In the solar energy industry pyranometers are used to monitor the performance of photovoltaic (PV) power plants. By comparing the actual power output from the PV power plant to the expected output based on a pyranometer reading the efficiency of the PV power plant can be determined. Drops in efficiency may indicate that maintenance of the PV plant is required. Pyranometers can also be used to determine the suitability of potential sites for PV power plants. In this case pyranometers are used to determine the expected output of a PV installation.

Other areas of application also exist such as building automation or agriculture.[1]

How does a pyranometer work?

Pyranometers are irradiance sensors that are based on the Seebeck- or thermoelectric effect. The main components of a pyranometer are one or two domes, a black absorber, a thermopile, the pyranometer body and in some cases additional electronics.

The dome on a pyranometer acts as a filter that transmits solar radiation with wavelengths from roughly 300 nm to about 3 µm (this contains the near-infrared, visible, UV-A and part of the UV-B radiation, see Figure 3), but blocks thermal radiation with wavelengths longer than 3 µm. Occasionally a second dome is used to improve the pyranometer performance.[2] Pyranometer domes are typically made from Schott N-BK7 glass or Schott WG295 glass, but in some cases sapphire or fused silica (Spectrosil or Infrasil) domes are used. The transmission τ of solar radiation through a dome is ideally close to 100%, but is in practice closer to 92%. The dome also serves to protect the black absorber and the thermopile from the elements (rain, snow, etc.).

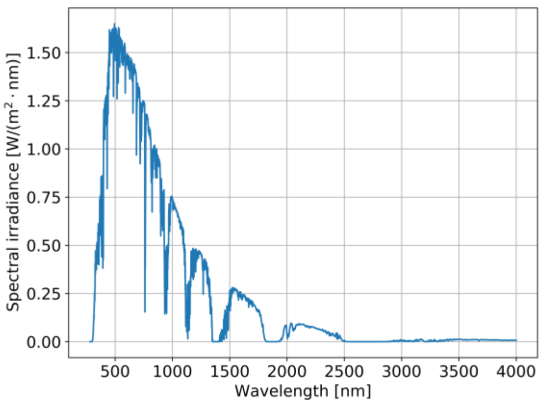

Figure 3 *The spectral distribution of a global tilted irradiance (GTI). Data from the ASTM G173-03 Reference Spectra.*

The filtered radiation is absorbed by the black surface on the pyranometer and converted into heat. If the transmission through the dome(s) is τ, the area of the black surface is A and the absorption coefficient of the black surface is α then the heat absorption can be calculated as follows:

$$P_{absorption} = \alpha \cdot \tau \cdot A \cdot E_{g\downarrow}$$

This creates a temperature gradient from the black surface through the thermopile to the pyranometer body which acts as a heatsink. The temperature difference is given by:

$$\Delta T = R_{thermal} \cdot P_{absorption}$$

Where $R_{thermal}$ is the thermal resistance of the thermopile sensor. This thermal resistance depends on the specific composition and geometry of the thermopile sensor. A thermopile consists of a number of thermocouples connected in series. Each thermocouple will generate a voltage proportional to the temperature difference between the black surface and the body:

$$u = \varsigma \cdot \Delta T$$

Where ς is the Seebeck coefficient. For example, the Seebeck coefficient of a copper-constantan thermocouple is 41 µV/K.

The voltage U accros the thermopile leads is simply the sum of the voltages u_i from the individual thermocouples. If the thermopile consists of N identical thermocouples the voltage across the thermopile leads is:

$$U = \sum_{i=0}^{N} u_i = N \cdot \varsigma \cdot \Delta T$$

Putting thermocouples in series allows one to detect very small temperature differences. The overall sensitivity of the pyranometer is:

$$S \equiv \frac{U}{E} = \alpha \cdot \tau \cdot N \cdot \varsigma \cdot R_{thermal}$$

And the measured global irradiance is then:

$$E_{g\downarrow} = \frac{U}{S}$$

In practice the sensitivity is determined by calibration against a reference pyranometer rather than by calculation from the separate coefficients.

The output signal from the pyranometer can either be the output voltage from the thermopile or the pyranometer can include electronics that convert the signal from the thermopile to a more convenient output signal. Typical outputs include amplified voltage outputs, 4 -20 mA electric current outputs and digital output signals like Modbus RTU over RS-485.

The irradiance of a surface by a beam of light depends on the angle of incidence of that beam of light: the irradiance is maximum if the beam is orthogonal to that surface and zero if the beam is parallel to that surface. More generally the irradiance changes as:

$$E_{g\downarrow} = E \cdot \cos(\theta)$$

where E is the maximum irradiance (at normal incidence) and θ is the angle of incidence between the surface normal and the incident beam as illustrated in Figure 4. Therefore the directional response of a pyranometer is this so called cosine- or Lambertian response. This response is shown in Figure 5. To get as close as possible to the Lambertian directional response pyranometers use hemispherical domes. If e.g. glass plates were used, the transmission would vary with the angle of incidence according to Fresnel's laws of optical transmission and reflection.

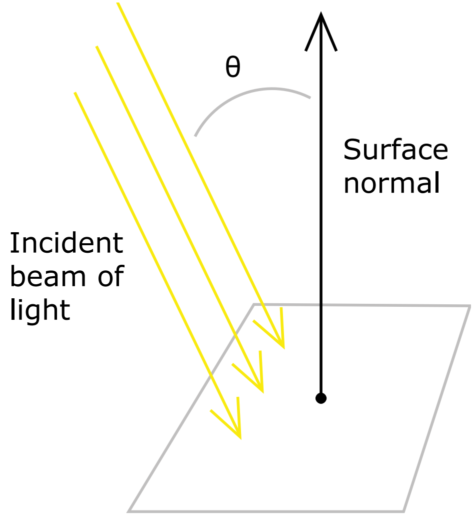

Figure 4 *Illustration of the angle of incidence θ of a beam of light incident on a surface.*

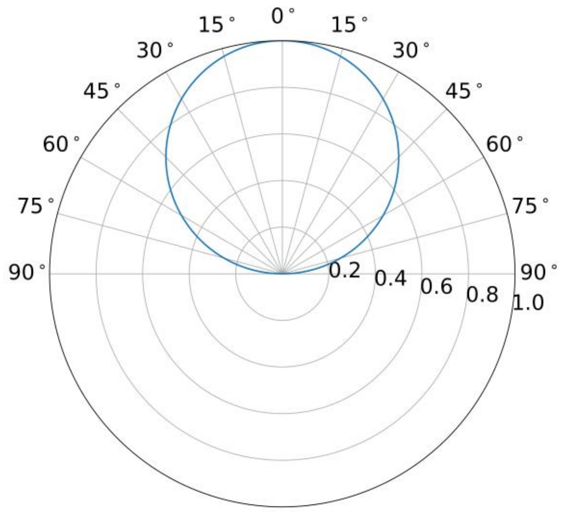

Figure 5 *A polar plot of the Lambertian or cosine directional response (distance to origin corresponds to $E_{g\downarrow}/E = \cos(\theta)$) of a pyranometer as a function of the angle of incidence. The directional response is 1 for an angle of incidence of 0° and 0 for an angle of incidence of 90°. Pyranometers are not sensitive to light coming from the bottom.*

Depending on the pyranometer specifications such as the response time, thermal offsets, non-stability, non-linearity, directional response, spectral response, temperature response and tilt response; and on the calibration method, a pyranometer may be classified either as a secondary standard, first class or second class pyranometer in accordance with the ISO 9060 standard.[3]

A more in-depth discussion on how pyranometers work can be found in the book by *Vignola et al.*[4]

Pyranometers in the field

Performing reliable pyranometer measurements in the field adds many practical aspects such as the pyranometer alignment, limitations on data availability due to precipitation and pyranometer maintenance and calibration.

When installing pyranometers special care should be taken of the pyranometer alignment. To measure the GHI, the pyranometer must be aligned horizontally. To this end most pyranometers come equipped with a bubble level and adjustable levelling feet or ball levelling mechanisms to align the pyranometer. In some cases the pyranometer has to be aligned in a POA to measure a GTI. Special mounting brackets exist specifically for this purpose. Some pyranometers even come with build-in tilt sensors to verify that the pyranometer remains aligned over time.

When taking measurements one should make sure the pyranometers has a clear hemispherical view of its surrounding. Snow, frost, rain, dew or dust collecting on the dome can absorb, scatter or focus radiation leading to erroneous measurements (see Figure 6). Some pyranometers come equipped with heaters and fans to deal with snow, frost and dew and thereby increase the data availability.[5] To avoid dust from collecting on the dome frequent cleaning of the dome is recommended.

Figure 6 *Dew (top left), frost (top right), snow (bottom left) and rain (bottom right) can affect pyranometer readings.*

For more information on how to measure solar radiation we recommend reading references [6-8].

Literature

1. Hukseflux Application Notes: Why measure solar radiation in building automation?
2. Hukseflux Application Notes: Why the second dome?
3. ISO (1990) ISO 9060:1990: Solar energy – Specification and classification of instruments for measuring hemispherical solar and direct solar radiation.
4. Frank Vignola, Joseph Michalsky, Thomas Stoffel; *Solar and infrared radiation Measurements*; CRC Press
5. Hukseflux Application Notes: SR30: Solar measurement in cold climates
6. WMO (2012) WMO-No.8 WMO Guide to Meteorological Instruments and Methods of Observations, Chapter 7
7. M. Sengupta, A. Habte, S. Kurtz, A. Dobos, S. Wilbert, E. Lorenz, S. Wilcox, P. Blanc and R. Perez (2015) Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications.
8. McArthur L.J.B. (2005) WMO/TD-No. 1274 Baseline Surface Radiation Network (BSRN). Operations Manual. Version 2.1

Standards

Products are manufactured under ISO 9001 quality management system. If applicable, the sensors comply with industrial standards such as ITS90, ANSI, DIN, and BS. Sensors for hazardous areas can be manufactured according to safety standards like EExi, ATEX / Cenelec and NAMUR.

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Hukseflux has support available around the globe, with local representatives in:

- EU (Amsterdam region)
- USA (New York region)
- India (New Delhi region)
- China (Shanghai region)
- Japan (Tokyo region)

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Hukseflux Thermal Sensors offers measurement solutions for the most challenging applications. Hukseflux sensors, systems and services are offered worldwide via our office in Delft, the Netherlands and local distributors.

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