A shadow ring for measuring diffuse solar radiation on a vertical surface

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Abstract

A shadow ring is constructed to use with the pyranometer for measuring the diffuse solar radiation incident on a vertical surface. The shadow ring is used to block the component of the beam solar radiation from the measured global solar radiation by providing the shadow from the ring imposed on the sensor of the pyranometer. The pyranometer is mounted in a vertical plane to measure the solar radiation incident on the vertical surface. The shadow ring is designed to account for the seasonal variation of the sun path by moving the pyranometer horizontally instead of moving the shadow ring. The shadow ring is specially designed to use for Bangkok location. The ring diameter is chosen to be 480 mm and the ring width is chosen to be 60 mm. The correction factor is also derived to account for the amount of the diffuse solar radiation blocked by the shadow ring. The constructed shadow ring is tested to verify its accuracy. It is found that the shadow ring is performed quite accurate and satisfactory.

Keywords: shadow ring, diffuse solar radiation, horizontally moveable sensor, vertical surface.

1. Introduction

Countries, that located in the zone near the equator, have the better opportunity compared to countries in the other part of the world in harvesting solar radiation to use as the auxiliary energy. But in a certain application, such as building application, having high solar radiation also has certain disadvantages when considering in term of solar cooling load, especially building with large amount of glass windows installed as building envelope. Large air conditioning system is usually required for removing this high solar cooling load. Thoroughly understanding of the thermal performance of glass window in term of heat transmission and thermal comfort is needed for designing an energy efficient building which has lower solar heat gain through the glass window. In order to use a mathematical model to predict the solar heat gain through the glass window, the data of local solar radiation incident on the glass window (vertical surface) must be known. The components of the solar radiation which are required as the input to the mathematical model are usually the direct (beam) solar radiation and diffuse solar radiation. One way to measure the local solar radiation in both components is to use the pyranometer and pyrheliometer. The pyranometer is used for measuring the global solar radiation. The pyrheliometer is used to measure the direct normal solar radiation. Some means of equipment (i.e. sun tracking device to track the sun position) is required to move the pyrheliometer to follow the sun path and to point the pyrheliometer directly to the sun (the sensor has to align with the beam of the solar radiation). The direct solar radiation can be calculated from the measured direct normal solar radiation. The diffuse solar radiation can be evaluated from the difference of the measured global solar radiation and the direct solar radiation. The pyrheliometer and the sun tracking device are quite expensive. The other method that is quite popular for measuring the diffuse solar radiation is to install the shadow ring to the pyranometer. The shadow ring is composed of a ring or band arranged to provide the shadow over the sensor of the pyranometer. The shadow ring will block the solar radiation in the part of direct normal component and measure the solar radiation in the component of the diffuse radiation. Measuring the diffuse solar radiation by using the shadow ring is quite popular because it is simple to operate and provides a direct estimated value of the diffuse solar radiation and it is not required the special equipment to track the sun position. The study of measuring the diffuse solar radiation using the shadow ring has been performed by Robinson and Stoch [1], Drummond [2], LeBaron et al. [3], and Battles et al. [4]. Oliverira et al. [5] presented a new shadow-ring device for measuring diffuse solar radiation at the surface. The development is primarily based on measuring the diffuse solar radiation incident on the horizontal surface. In this study, the shadow ring is constructed to use with the pyranometer for measuring the diffuse solar radiation incident on a vertical surface. The shadow ring is designed to account for the seasonal variation of the sun path. The correction factor due to the blocking effect is also derived to account for the amount of the diffuse solar radiation blocked by the shadow ring.

2. Shadow ring

Shadow ring used for measuring the diffuse solar radiation available worldwide are based on the types proposed by Robinson (Robinson and Stach [1]) and Drummond (Drummond [2]). The Robinson's shadow ring is composed of a set of rings of a certain width and they are used to cover the different celestial sphere sections. Fig. 1 shows the schematic representation of the Robinson's shadow ring and the shadow cast by the ring. The related parameters shown in Fig. 1 are: ϕ = local latitude, δ = declination angle, b = ring width, R = radius of the ring, sh = shadow width of the ring cast on the detector, N = north direction and S = south direction.

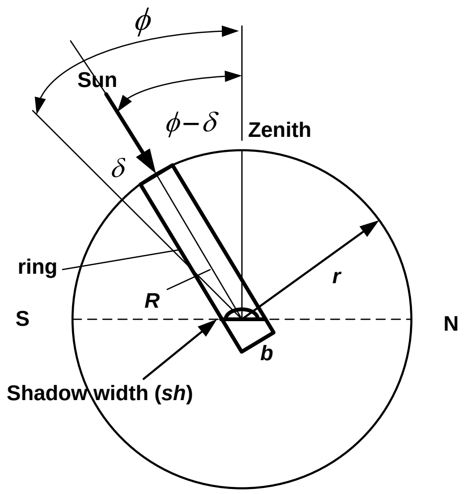

Fig. 1 Schematic representation of the Robinson's shadow ring and its shadow cast on the pyranometer.

The Drummond's shadow ring uses one single ring to cast a shadow on the sensor of the pyranometer. To compensate of the annual variation of the solar declination, the Drummond's shadow ring is displaced along the earth's axis direction. Fig. 2 shows the schematic representation of the Drummond's shadow ring and the shadow cast by the ring. Fig. 3 shows the Kipp & Zonen shadow ring (model CM 121B/C) which operates under the concept of the Drummond's shadow ring.

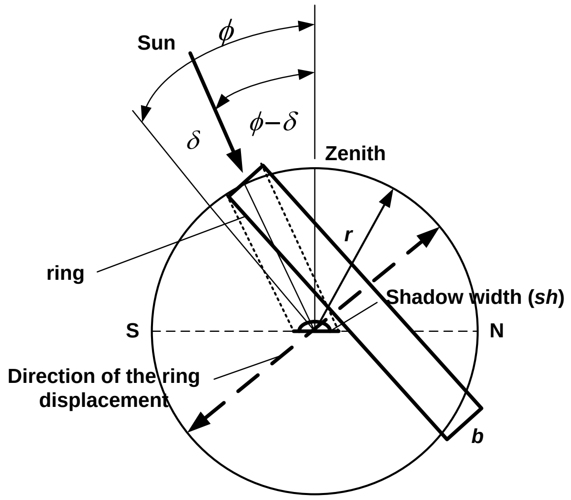

Fig. 2 Schematic representation of the Drummond's shadow ring and its shadow cast on the pyranometer.

Fig. 3 Kipp & Zonen shadow ring CM 121B/C [8].

The third type of the shadow ring is called movable detector device developed in the Laboratory of Solar Radiation at the State University of São Paulo in Botucatu, Brazil. (Melo [6], Escobedo et al. [7] and Oliveira et al. [5]). In this type of the shadow ring, the ring is fixed and the sensor of the pyranometer is displaced horizontally in the north-south direction. The ring is sloped at an angle equal to the local latitude. Fig 4 shows the schematic representation of the shadow ring of the movable detector type and the shadow cast by the ring.

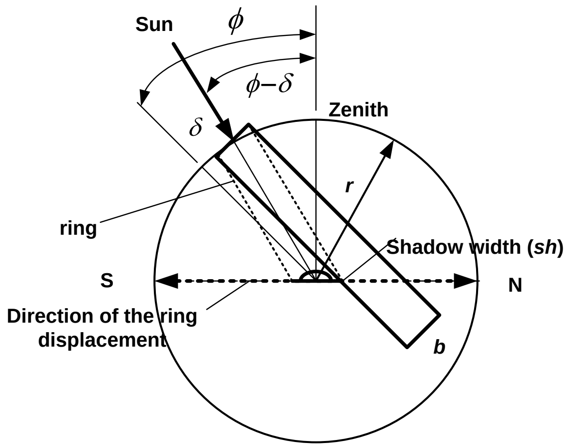

Fig. 4 Schematic representation of the movable detector shadow ring and its shadow cast on the pyranometer.

The three types of the shadow ring described above are all developed for measuring the diffuse solar radiation incident on the horizontal surface. In this study, the shadow ring of the movable detector type is developed specially to use with the pyranometer to measure the diffuse solar radiation incident on the vertical surface.

3. Theory

The operation of the shadow ring is to block the direct solar radiation to reach the sensor of the pyranometer by providing the shadow cast on the sensor of the pyranometer. The shadow ring must have the geometry of the ring and its alignment to be able to perform that task. In order to design the proper shadow ring, the sun path which dependent on the local position and time during the year has to be analyzed. In this study, the isotropic sky condition is assumed. Fig. 5 shows the three dimensional view of the earth, the sun's rays, local latitude ϕ, declination angle δ and solar hour angle ω related to point P (point on earth's surface) during the typical summer day.

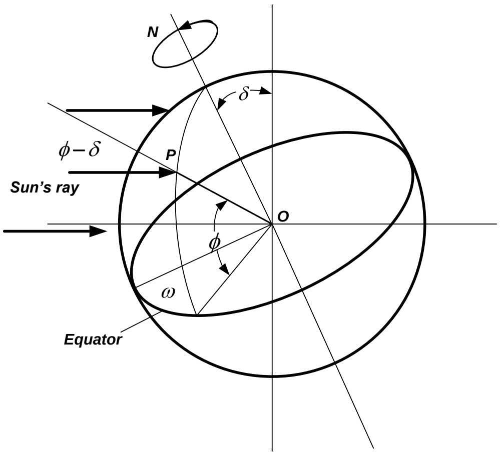

Fig. 5 The view of the earth, the sun's rays, local latitude ϕ, declination angle δ and solar hour angle ω related to point P during the typical summer day.

Fig. 6 shows the sun path with related parameters on the celestial sphere during the day time on the detector (sensor of the pyranometer) installed on the vertical surface.

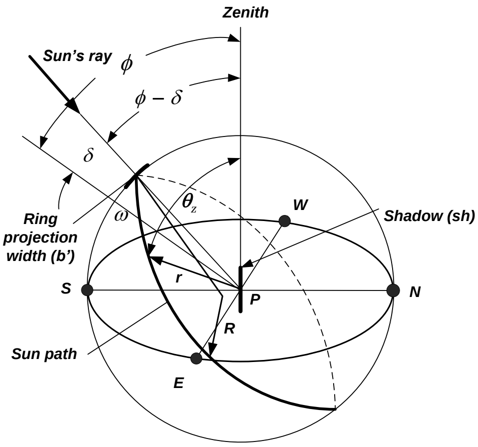

Fig. 6 The sun path imposed on the celestial sphere.

The related parameters shown in Fig. 6 are: *b'* is the ring projection on the celestial sphere, *R* is the radius of the circle formed by sun path, θ_z is the solar zenithal angle, *r* is the radius of the celestial sphere and *sh* is the shadow of the ring cast on the detector installed at the center of the celestial sphere in the vertical plane. The relationship between the solar zenithal angle and the other related angles can be expressed as

$$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \quad (1)$$

For the isotropic diffuse solar radiation, the total diffuse irradiance from the sky incident on the horizontal surface can be written as $E_d = \pi I_d$, where I_d is the diffuse component of the solar radiation from the sky. For the vertical surface, the diffuse solar radiation incident on the surface consists of the solar radiation from the sky and the solar radiation reflected from the ground. The total diffuse solar radiation incident on the vertical surface can be written as

$$E_{dv} = \frac{\pi}{2} I_d + \frac{\pi}{2}\rho_g I_d \quad (2)$$

where E_{dv} is the total diffuse solar radiation incident on the vertical surface and ρ_g is the ground reflectivity. Under the assumption of isotropic diffuse solar radiation, one can combine the direct solar radiation as a part of uniform diffuse solar radiation incident on the surface. Eq. 2 can be rewritten as

$$E_{dv} = \frac{\pi}{2} I_d (1+\rho_g) \quad (3)$$

Therefore, the amount of the diffuse solar radiation blocked by a ring of width *b* (which mostly comes from the sky diffuse solar radiation) can be expressed as

$$E_{bv} = \int I_d \cos\theta_z d\Omega \quad (4)$$

where Ω is the solid angle of the area ring element which can be expressed as

$$d\Omega = dS / r^2 \quad (5)$$

where dS is area ring element which can be expressed as

$$dS = b'Rd\omega \quad (6)$$

The correction factor accounted for the blocked part of the diffuse solar radiation of the ring can be written as

$$F_c = \left(1 - \frac{E_{bv}}{E_{dv}}\right)^{-1} \quad (7)$$

Fig. 7 shows the schematic representation of the developed shadow ring with the installed pyranometer.

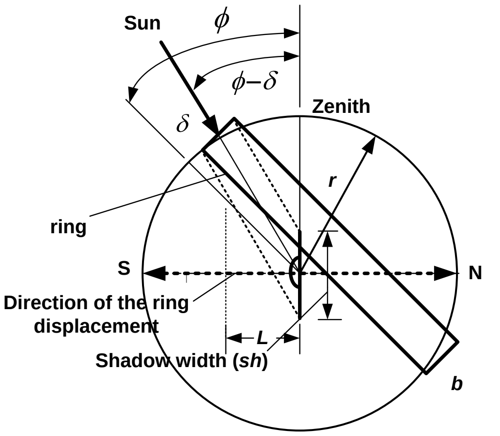

Fig. 7 Schematic representation of the movable detector shadow ring and its shadow cast on the pyranometer installed in the vertical plane.

By relating the parameters described in Fig. 6 to the shadow ring of the movable detector type with the pyranometer installed in the vertical plane as shown in Fig. 7, the parameters relating to the developed shadow ring can be obtained. The radius of the celestial sphere is equal to

$$r = R\left[\frac{\cos\phi}{\cos(\phi-\delta)}\right] \quad (8)$$

The ring projection on the celestial sphere can be written as

$$b' = b\cos\delta \quad (9)$$

The solid angle of the area ring element can be written as

$$d\Omega = \frac{b}{R}\cos\delta\left[\frac{\cos(\phi-\delta)}{\cos\phi}\right]^2 d\omega \quad (10)$$

The shadow of the ring cast on the detector installed at the center of the celestial sphere can be written as

$$sh = \frac{b\cos\delta}{\cos(\phi-\delta)} \quad (11)$$

The correction factor in Eq. 7 can be rewritten as

$$F_c = \left(1 - \left(\frac{4b}{\pi R(1+\rho_g)}\right)\cos\delta \left[\frac{\cos(\phi-\delta)}{\cos\phi}\right]^2 \omega_p \sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega_p\right)^{-1} \quad (12)$$

where ω_p is the hour angle at the sunset.

The distance (L) measured along the line of the sensor displacement from the line projected from the center of the ring width to the sensor of the pyranometer can be written as

$$L = \sqrt{r^2 - (R\sin(\pi/2-\phi))^2} \quad (13)$$

4. Development of the shadow ring

The shadow ring to be constructed is intended to use for measuring the diffuse solar radiation incident on the vertical surface. The location chosen for installing the shadow ring is on the fourth floor of Hans Buntli building, Department of Mechanical Engineering, Chulalongkorn University. The location of the building is assigned to be at Bangkok in which the latitude is at 13.73 degree north and the longitude is at 100.57 degree east. The time zone is at UTC (Coordinated Universal Time) +7.

The local latitude (ϕ) is chosen to be 13.73 degree. The ring diameter (2R) is chosen to be 480 mm. Since the width of the sensor of the pyranometer (Kipp & Zonen, model CMP 6) is 50 mm, in order to have the shadow ring performed throughout a day without adjusting the position of the pyranometer, the ring width (b) is chosen to be 60 mm. The variation of the shadow width of the ring cast on the sensor of the pyranometer with time throughout the year is shown in Fig. 8. The shadow width is always greater than the width of the pyranometer's sensor. The distance (*L*) for the sensor displacement in Eq. 13, which is varied throughout the year, is shown in Fig. 9. The distance (*L*) is in the range of 0 to 0.177 m.

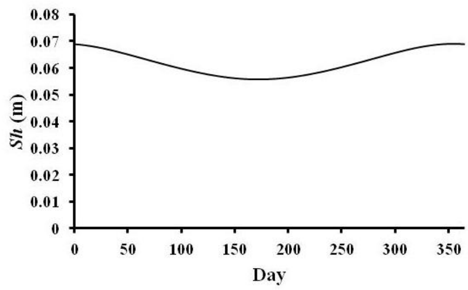

Fig. 8 The variation of the shadow width cast on the pyranometer's sensor throughout the year.

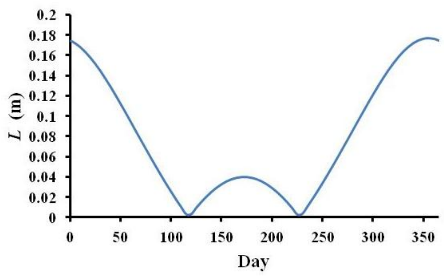

Fig. 9 The variation of the displacement of the pyranometer's sensor throughout the year.

The correction factor accounted for the blocked part of the diffuse solar radiation of the constructed shadow ring is evaluated from the expression in Eq. 12. The values of the correction factor with different value of ground reflectivity are shown in Fig. 10.

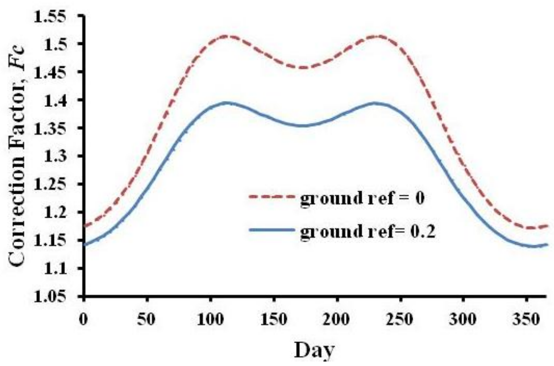

Fig. 10 The variation of the correction factor throughout the year.

Figs. 11 – 17 show the developed shadow ring and its components. Fig. 11 shows the shadow ring made of sheet metal with radius of 240 mm, width of 60 mm and thickness of 2 mm. The ring is painted black to reduce the reflected radiation from underside of the ring to reach the pyranometer's sensor.

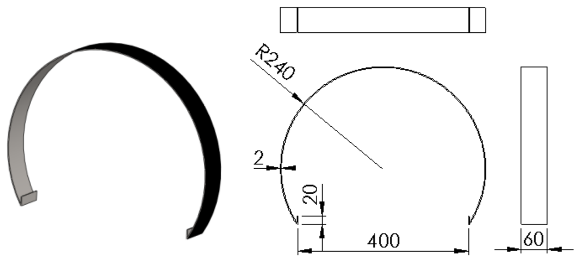

Fig. 11 The shadow ring and its related dimensions.

The shadow ring is designed to install on the metal stand (as shown in Fig. 15, 16 and 17). Fig. 12 shows the installation base plate for installing the pyranometer in the vertical plane. Fig. 13 shows the slider for installing the installation base plate. The slider is used for displacing the pyranometer in the north and south direction to receive the shadow cast by the ring. Fig. 14 shows the dimension of the Kipp & Zonen pyranometer model CMP 6 to be used with the shadow ring.

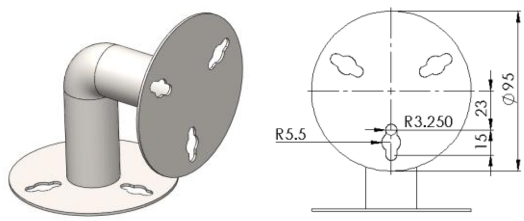

Fig. 12 The installation base plate.

Fig. 13 The slider used to move the pyranometer.

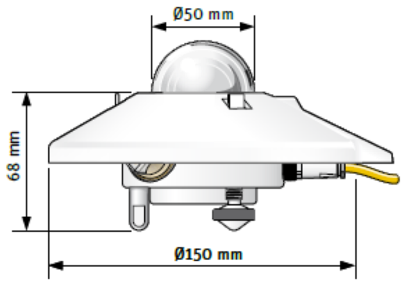

Fig. 14 Kipp & Zonen pyranometer model CMP 6.[9]

Fig. 15 shows the stand built from metal for installing the shadow ring and the pyranometers. Figs. 16 and 17 show two pyranometers installed with the shadow ring for measuring the diffuse solar radiation and global solar radiation.

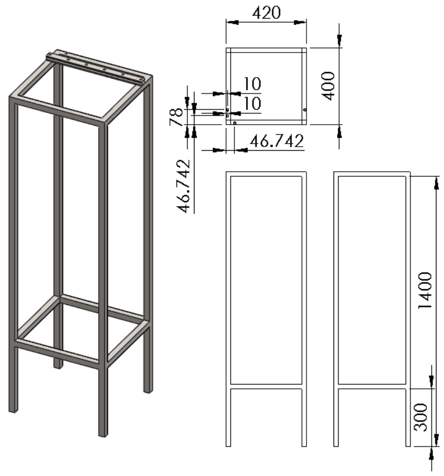

Fig. 15 The stand designed and built to install the shadow ring and the pyranometers.

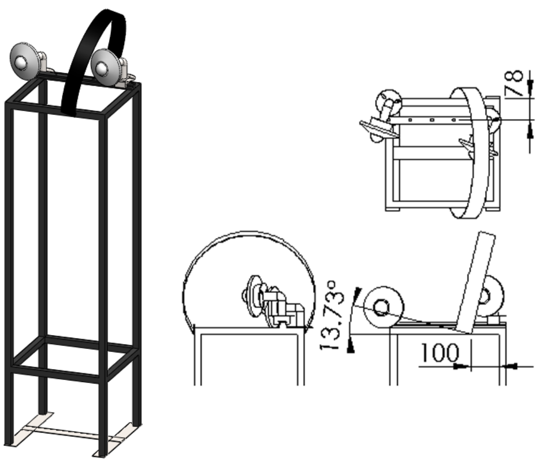

Fig. 16 Shadow ring installation with the pyranometers.

Fig. 17 Pyranometers with shadow ring installed on the stand.

In Fig. 16, one can see that the displacement of pyranometer is in the north and south direction. The ring has to be installed with an inclined angle equal to the local latitude (13.73 degree). The slider had to be installed offset from the center of the stand so that the sensor of the pyranometer is in the middle of the ring shadow.

5. Verification

The performance of the shadow ring is verified by comparing the measured diffuse solar radiation with the referenced value. The pyranometer equipped with the shadow ring is installed on the balcony of the 4th floor of Hans Buntli Building, Department of Mechanical Engineering, Chulalongkorn University. The pyranometer is installed in the vertical plane facing west direction. Another pyranometer is installed nearby on the test stand to measure the global solar radiation. Since both pyranometers are facing west direction, therefore both pyranometers measure the diffuse solar radiation in the morning. The pyranometer without the shadow ring will measure the global solar radiation which consisted of direct solar radiation and diffuse solar radiation in the afternoon. The data measured from the pyranometer with the shadow ring is corrected by multiplying the correction factor for the blockage effect from the ring. Since the value of the correction factor is dependent on the value of the ground reflectivity. In this study, the pyranometer with the shadow ring is installed 1700 mm above the balcony floor with very limited space of the ground existing in front of the pyranometer. The reflected part of the solar radiation would come from the nearby building and the metal bar around the balcony. The value of the reflectivity is chosen to be 0.2 for this study. The corrected data is then compared with the measured global solar radiation (the measured global solar radiation in the morning is referred as the referenced value for the diffuse solar radiation). Figs. 18 - 21 show the comparison of the corrected diffuse solar radiation with the measured global solar radiation on four consecutive days. The agreement between the diffuse solar radiation and the global solar radiation in the morning is quite good. The agreement between the diffuse solar radiation and global solar radiation on December 10th, 2012 (Fig. 21) is extended from the morning up to the time of 15.30. The explanation is that it was rained in the afternoon on that day.

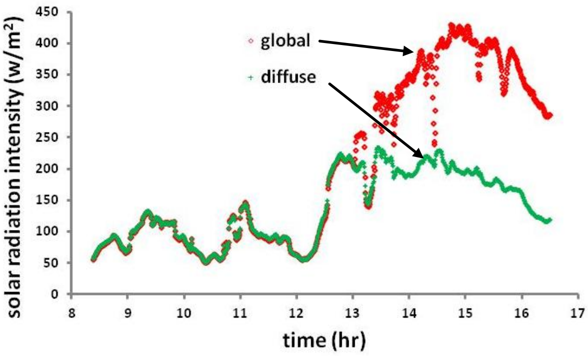

Fig. 18 The measured diffuse solar radiation and global solar radiation on December 7th, 2012.

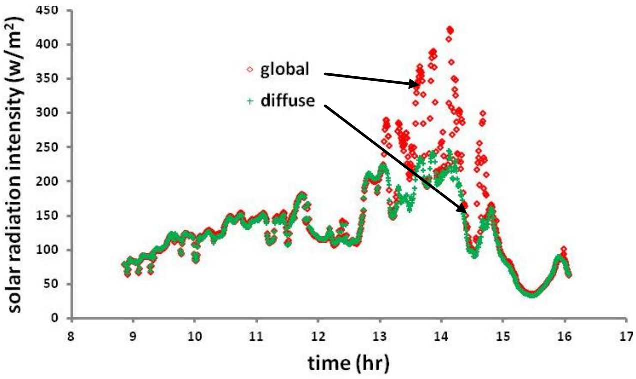

Fig. 19 The measured diffuse solar radiation and global solar radiation on December 8th, 2012.

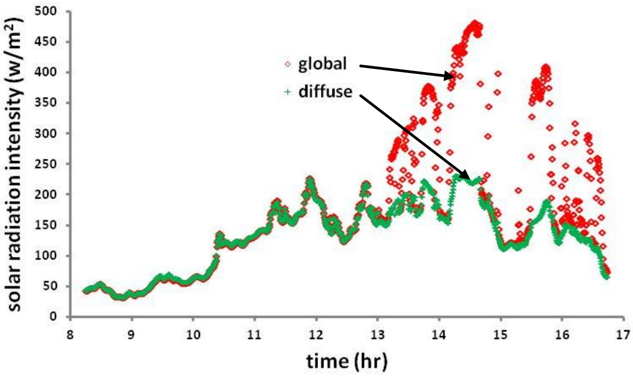

Fig. 20 The measured diffuse solar radiation and global solar radiation on December 9th, 2013.

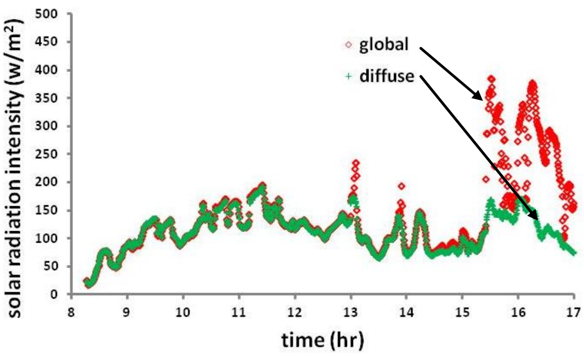

Fig. 21 The measured diffuse solar radiation and global solar radiation on December 10th, 2012.

The difference between the corrected diffuse solar radiation and the measured global solar radiation (in the morning) is found to be in the range around 0 to 2.8 % on December 7th, 0 to 3 % on December 8th, 0 to 4.5 % on December 9th and 0 to 2.6 % on December 10th.

It is also found from the test that the shadow ring can be performed throughout a day without adjusting the position of the pyranometer.

6. Conclusion

A shadow ring is constructed to use with the pyranometer for measuring the diffuse solar radiation incident on a vertical surface. The shadow ring is designed to account for the seasonal variation of the sun path by displacing the pyranometer horizontally instead of displacing the shadow ring (the method used in the typical shadow ring). The shadow ring is specially designed to use for Bangkok location. The correction factor is also derived to account for the amount of the diffuse solar radiation blocked by the shadow ring. The constructed shadow ring is tested to verify its accuracy. It is found that the shadow ring is performed quite accurate and satisfactory. It is also found from the study that the shadow ring is easy to use.

7. References

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