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Estimation of Solar Radiation in Ouagadougou: Contribution to the Thermal Study of Buildings

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ABSTRACT

In this work, we simulate the global solar radiation received by a horizontal surface and vertical surfaces of different orientations on the ground from theoretical models considering the diffusion and absorption of solar radiation through the atmospheric layer. We have to generate results of the global radiation by the model of Liu and Jordan for thermal systems optimization, particularly in the field of the building in the city of Ouagadougou. This work shows that the solar radiation on a surface, in addition to the seasonal variability, also varies according to the orientation and the inclination of the sun. Thus, in the case of buildings, for example, exposing the large surfaces of the building according to the southern orientation will be avoided in favor of the northern orientation. It is also necessary to consider the scenario of use of the building to situate it in space and time in order to minimize the thermal contributions.

1. Introduction

Solar energy is the most important basic resource for all renewable energy potentials. The phenomenon of climate change and greenhouse gas emissions places the use of renewable energies and energy efficiency at the heart of the news [1]. Thus, taking solar radiation into account in the design of buildings is very common nowadays [2], [3].

The earth receives on average a power of 1.4kW/m2 from the sun [4] for a surface normal to the earth-sun direction. This solar flux is attenuated when crossing the atmosphere by absorption or diffusion, depending on the meteorological conditions and the geographical coordinates of the place. A good knowledge of the amount of solar energy available at a specific place at each moment of the day and the year is necessary for a better design of thermal systems [5],[6],[7]. The estimation of solar radiation is essential for the construction of buildings in the perspective of better thermal insulation adapted to the geographical location and also for the passive air conditioning of buildings in hot tropical areas [8].

As part of our study on the dynamic simulation of the building, it is necessary to estimate the solar radiation arriving on any surface according to its orientation and its inclination at any time. But before being able to estimate the radiation on an inclined surface at ground level, it is necessary to present a general overview of the celestial coordinates as well as some statistical models for estimating solar radiation.

2. Methodology

We will present a brief description of the geometric parameters implemented in the context of the mathematical modeling of global solar radiation before describing the different static models used.

2.1. Modeling of geometric parameters

2.1.1. Geographical coordinates

The longitude of a place λ corresponds to the angle made by the meridian plane passing through this place with a meridian plane taken as origin. The meridian (origin 0°) was chosen as the plane passing through the Greenwich observatory. We agree to assign the sign (+) to the meridians located to the east of this meridian, and the sign (-) to the meridians located to the west [9], [10].

The latitude of a place ϕ corresponds to the angle with the equatorial plane, that makes the radius joining the center of the earth to this place. The terrestrial equator is therefore characterized by a latitude equal to 0°, the north pole by latitude +90° and the south pole by latitude -90°. This sign convention assigns the sign (+) to all locations in the northern hemisphere and the sign (–) to all locations in the southern hemisphere.

2.1.2. Time coordinates

The Solar declination is the angle formed by the direction of the sun and the earth's equatorial plane. It varies throughout the year, between two extreme values: (-23°27' and +23°27' approximately) and it vanishes at the spring and autumn equinoxes. The value of the solar declination can be obtained by Cooper's equation [11].

$$\delta = 23{,}45 \sin\left(360\,\frac{284+n}{365}\right) \qquad (1)$$

n: number of the day in the year.

This angle is zero at the equinoxes (March 21 and September 21), maximum at the summer solstice (June 21) and minimum at the winter solstice (December 21).

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The hour angle of the sun is the angle formed by the meridian plane of the place and that which passes through the direction of the sun if we take as origin the meridian of Greenwich. It measures the course of the sun in the sky. The hour angle is between 0° and 360° The value of the hour angle is zero at solar noon, negative in the morning, positive in the afternoon and increases by 15° per hour. It measures the course of the sun in the sky [12] and its expression is obtained by the equation:

$$\omega = 15.(TSV - 12) \quad (2)$$

TSV: True Solar Time. True solar time is equal to legal time corrected by an offset due to the difference between the longitude of the location and the reference longitude.

$$TSV = TL - DE + \left(\frac{E_t + 4\lambda}{60}\right) \quad (3)$$

$$E_t = 9.87\sin(2N') - 7.35\cos(N') - 1.5N' \quad (4)$$

$$N' = \frac{360}{365}(N - 81) \quad (5)$$

DE: time difference with respect to the Greenwich meridian;
TL: legal time (given by a watch;
E_t: Correction of the equation of time
λ: Longitude of the place

2.1.3. Horizontal coordinates

The angular height of the sun h is the angle formed by the horizontal plane at the place of observation and the direction of the sun. This height during the day can vary from 0 (sun at the horizon) to 90 (sun at the zenith).

$$\sin(h) = \cos(\delta)\cos(\phi)\cos(h) + \sin(\phi)\sin(\delta) \quad (6)$$

The azimuth α is the angle that the direction of the projection of the sun on the horizontal plane makes with the South direction, this angle being oriented positively towards the West. Knowing the azimuth of the sun is essential for calculating the angle of incidence of the rays on a non-horizontal surface.

$$\sin(\alpha) = \frac{\cos(\delta)\sin(\omega)}{\cos(h)} \quad (7)$$

2.2. Statistical model of global radiation

The first studies linking global radiation to diffuse are those of Liu and Jordan, which use daily values [12]. In recent years, several regressions have been proposed between the diffuse fraction of global radiation and the clarity index [12] [13] based on hourly, daily, and monthly averaged data. The models of Atawer and Ball, the model of Davies and Hay, the model of Bird and Hulstrom, the model of Lacis and Hansen [14] also make it possible to simulate more or less the solar radiation arriving at the ground. Perrin de Brichambaut's solar irradiation estimation model is only valid for a sky [15]. The second and third generation models concern, among others, the Time-Coulson model, the Klucher Perez model [11] [16] and will not be discussed here.

2.2.1. Estimation of solar radiation on a surface

The global radiation on a surface with an arbitrary orientation and an inclination β with respect to the horizontal is the sum of three components of solar radiation. The first component is the direct radiation I_b (β), the second component is the diffuse radiation Id (β) from the sky and the third component is the reflected radiation I_r (β).

Empirical models allow the estimation of the global illumination received on an inclined plane from the illuminations measured on a horizontal plane [17] [18]. These models are based on the different contributions of the sky to the diffuse radiation, namely the anisotropy and isotropy of the sky and the estimated albedo value for the reflected radiation from the ground.

- *Direct radiation*

An inclined plane is characterized by its inclination β with respect to the horizontal, and its orientation or azimuth γ with respect to the south. The angle of incidence ( ) is the angle formed between the normal of the plane and the rays of the sun. We speak of normal incidence when = 0. The angle of incidence is written as a function of the position of the sun (the height h and the azimuth α), the inclination β of the receiving plane and its azimuth γ by the relation:

$$\cos(\theta_i) = \cos(90 - h)\cos(\beta) + \sin(\beta)\sin(90 - h)\cos(\alpha - \gamma) \quad (8)$$

The illuination due to direct radiation on a plane of inclination and any orientation is given by the relation:

$$I_b(\beta) = I_b \times R_b \quad (9)$$

Avec R_b :

$$R_b = \max\left[0, \frac{\cos(\theta_i)}{\sin(h)}\right] \quad (10)$$

$$I_b(\beta) = I_{bn}\cos(\theta_i) \quad (11)$$

I_{bn} is the radiation on a normal plane and θ_i the angle of incidence on the considered plane (Angle between the normal to the surface and the ray of the sun)

- *Diffuse radiation from the sky*

The models for estimating the diffuse radiation of the sky can be classified into two categories, namely the first-generation models and the second-generation model. For first-generation models, the isotropic model of Liu and Jordan [19] is the most widespread.

The isotropic model of Liu and Jordan is the simplest of all the models, it is a model which assumes that the sky is isotropic. In this model, the intensity of diffuse radiation from the sky is assumed to be uniform over the entire celestial vault. The diffuse radiation of the sky on an inclined plane with an inclination β can be estimated by the following expression:

$$I_d = \frac{1}{2} I_d (1 + \cos\beta) \quad (12)$$

where I_d is the diffuse radiation on a horizontal plane

The circumsolar model assumes that all radiation originates from the solar disk. This is a model that assumes the sky is cloudless. It has been shown that:

$$I_d(\beta) = R_b \times I_d \quad (13)$$

$$R_b = \frac{\sin\delta.\sin(\varphi - \beta) + \cos\delta.\cos(\varphi - \beta).\cos\omega}{\sin\delta.\sin\varphi + \cos\delta.\cos\varphi.\cos\omega} \quad (14)$$

R_b is the ratio of the daily direct radiation on an inclined plane to the horizontal plane.

φ is the latitude and inclination of the surface horizontally. δ is the declination and the hour angle ω.

2.2.2. Radiation received by a vertical surface

The solar radiation arriving by short wavelength on the vertical walls of the building can be evaluated as follows:

$$I = I_d R_b + \frac{1}{2}\rho_y I_h + \frac{1}{2} D_h \quad (15)$$

Where I_d, D_h and I_h respectively represent direct, diffuse and global radiation on a horizontal plane. ρ_y is the albedo taken equal to 0.2

The geometric factor R_b is the ratio between the direct radiation on an inclined surface and a horizontal surface and is calculated by:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (16)$$

With θ and θ_z, the incident and zenith angles respectively. For vertical wall surfaces, these angles are defined by [20]:

$$\theta = \sin\delta\sin\emptyset\cos\beta - \sin\delta\cos\emptyset\sin\beta\cos\gamma + \cos\delta\cos\emptyset\cos\beta\cos\omega + \cos\delta\sin\emptyset\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \quad (17)$$

$$\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \quad (18)$$

Where δ, ω, γ and ϕ are the angle of declination, hour angle, azimuth and latitude respectively. γ=0° for a surface facing South, 90° for a surface facing East, 90° for a surface facing West and 180° for a surface facing North.

3. Results and Discussions

We represent in figure 2, the density of the solar flux received by a horizontal surface for each typical day of the twelve months of the typical year considered for the city of Ouagadougou. We observe that the density of the solar flux is higher at the beginning and at the end of the year because of the dry season. The maximum value of the solar flux is around 1000W/m2 and is recorded during the typical day of March.

On figure 3, we represent the evolutions of the solar flux density during the typical year considered on the walls of the habitat according to their orientations. We observe that the east and west facades of the habitat receive approximately the same sunshine. The difference lies in the fact that the sunshine is higher in the morning and very weak in the afternoon on the east facade, this finding is reversed on the west facade.The periods of the year during which the density of the solar flux is important on the east and west facades are observed during the typical days of the months of March to June. The maximum value of sunshine reached on these facades is 540W/m2 and is observable in the month of June. The sunshine received by the south and north facades evolves inversely during the year. For example, the sunshine received on the north face is higher at the beginning and end of the year (January, February and December) and the maximum sunshine value (about 280W/m2) is reached during the typical day. of the month of January. On the other hand, the south facade receives the most sunshine in the middle of the year (April to September). The maximum value reached on this side is around 590W/m2 and is recorded in June. These results are explained by the declination of the sun which is positive in the south and negative in the north.

Figure 4 also presents the evolution of the solar flux density along four orientations. Just like the east and west facades, the north-east and north-west facades receive equivalent amounts of sunshine during the year with maximum sunshine values over 400W/m2 (March and December). Also, for southeast and southwest orientations the amounts of sunshine received are similar. The sunshine on these faces is high in the middle of the year (May to September) with a maximum value of around 630W/m2 during the month of June.

4. Conclusion

The solar flux being a very influential parameter in the thermal and energy behavior of buildings, this study allowed us to have the necessary tools to evaluate the solar radiation arriving on any wall of the envelope of a building. Different models have been proposed for estimating the global radiation arriving on a surface. It therefore appears that the solar flux received on a surface, in addition to being variable depending on the time of year, is also a function of orientation and inclination. Thus, in the case of buildings, for example, exposing the large surfaces of the building according to the southern orientation will be avoided in favor of the northern orientation.

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6. Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

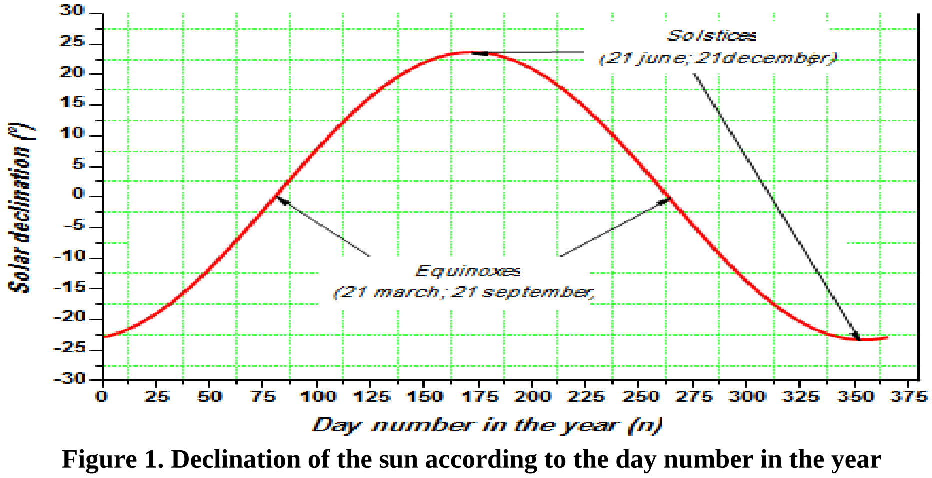

Figure 1. Declination of the sun according to the day number in the year

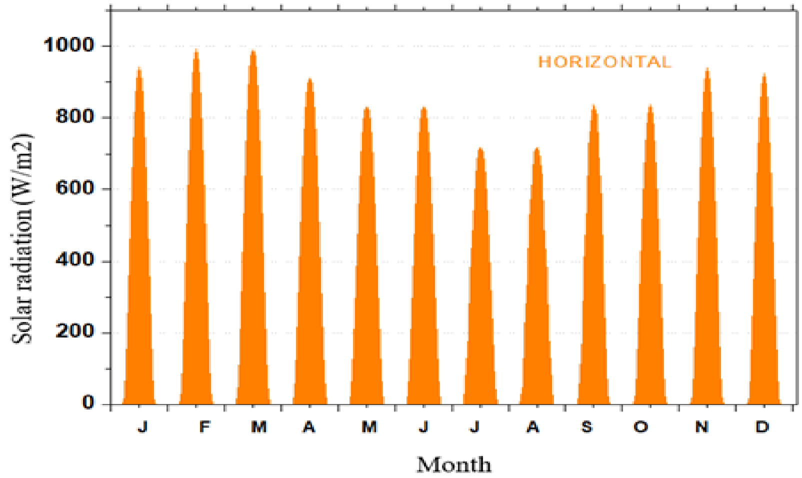

Figure 2.Global solar radiation on a horizontal surface in Ouagadougou

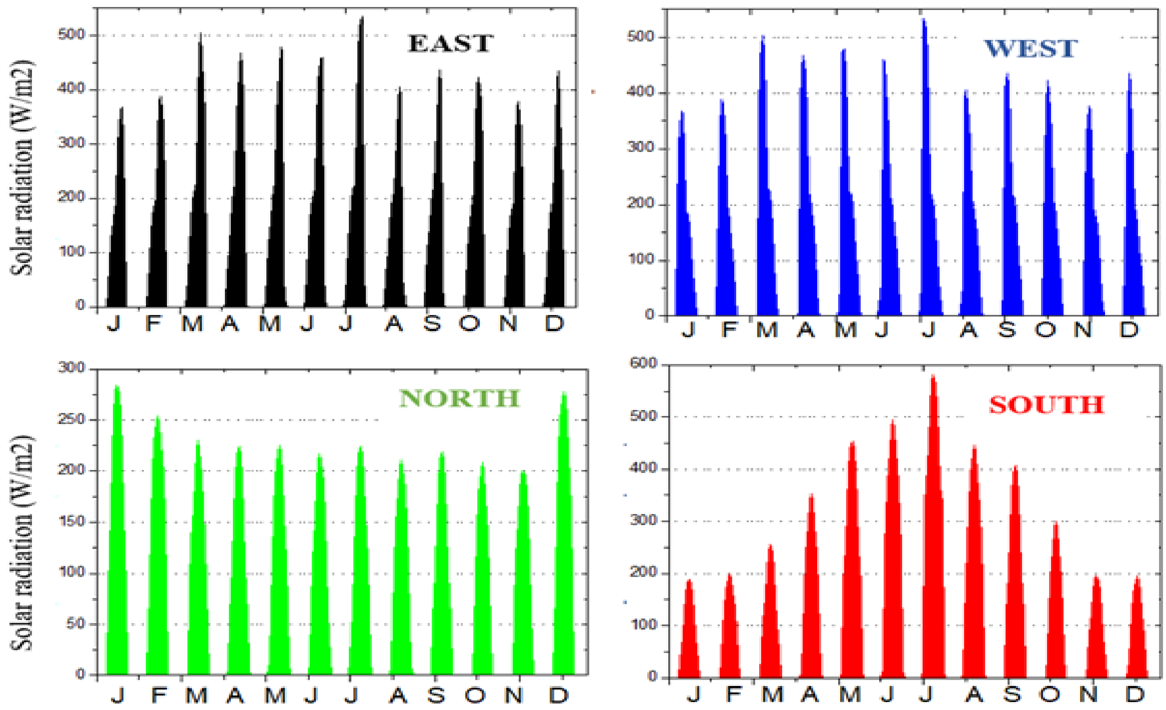

Figure 3.Solar radiation on a vertical surface as a function of orientation (a)

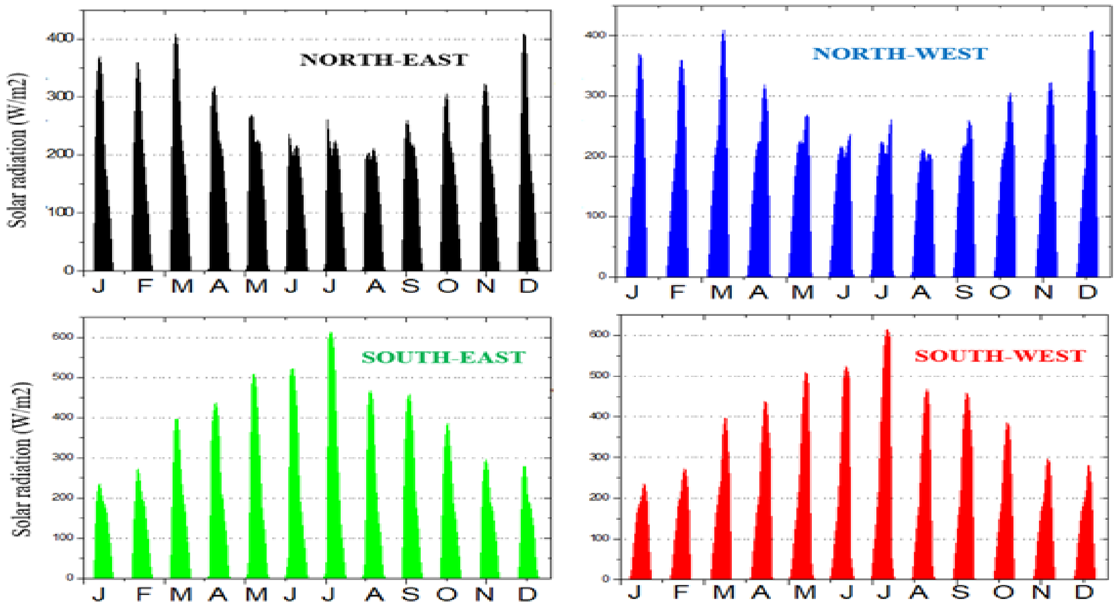

Figure 4. Solar radiation on a vertical surface as a function of orientation (b)

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