Estimation of incident solar radiation on the roof of the cultural and sports university centre of the Foundation University Los Libertadores

S A Jiménez¹, V M Carrillo¹ and L C Rátiva¹
¹Fundación Universitaria Los Libertadores, Bogotá, Colombia.

E-mail: sajimenezc@libertadores.edu.co, lkrativap@libertadores.edu.co

Abstract. This document shows the estimate of the total solar irradiance incident for the set of solar collectors to be located on the roof of cultural and sports university centre (CSUC) of the Foundation University Los Libertadores (FULL) in Bogotá, Colombia, and they will be part of the climate control system of the pool built inside. The calculation was based on experimental data of global solar radiation on the horizontal surface on March, July, October, November and December, through the three most commonly models used to determine the total solar radiation on tilted surfaces: isotropic sky, HDKR and Perez. The results show differences of less than 5% between the values calculated by the three models for December, the month with lower irradiance. For this month, reductions up to 15% and 19% were observed in the estimated irradiance, relative to those obtained on a horizontal surface on a surface under ideal orientation and inclination, respectively.

1. Introduction
Pool heating for swimming is a process that consists on raising and maintain temperature of water on values generally ranging between 22°C and 27°C approx., depending on use, to ensure the comfort and enjoyment of users. When this temperature is below 18°C, the sensation in the pool is unpleasant. This is one of the most profitable ways to use solar energy because the temperatures are not high, and the energy demand matches with periods of increased solar radiation [1].

When any solar thermal system is designed, the solution must ensure the highest energy efficiency with maximum architectural integration [2]. To ensure the first requirement, it should be determined as accurately as possible, both energy demand of the system to be conditioned as solar radiation available at the site where the solar collectors will be located.

Most of the radiation data are available for horizontal surfaces and simultaneously include the Diffuse and the Direct. However, there are a few solar thermal systems in which collectors are set horizontally and in many applications, for aesthetic or architectural reasons, the emplacement of the collector does not allow optimal positions of azimuth and inclination. These situations cause losses of solar radiation and therefore it is important to calculate its magnitude [2].

Some related studies about the use of models for estimating the solar radiation on solar collecting surfaces are: Skeiker [3], Mendoza [4] and Chang [5].

Moreover, among the studies that explicitly report the calculations of radiation data for the design of climate control system using solar energy for pool heating are: Szeicz and McMonagl [6], Rakopoulos and Vazeos [7], Singh et al. [8] and Woolley et al. [9].
In this paper the application of equations of isotropic sky, HDRK and Perez mathematical models are presented for estimating total solar irradiance incident on the roof of CSUC and thus to know if this amount differs significantly from the data on a horizontal surface.

The CSUC of FULL is a three-story building, located in Bogota, Colombia, approximately on 4°39'6" North Latitude and West Longitude 74°03'56.3" and azimuth +102°. Its roof is tilted with two flaps ("two waters"), both with 9° of slope. The enclosures where the water does not fall, end up in a triangular shape.

2. Methodology
Based on 180748 measurements made every minute by a precision spectral pyranometer EPPLEY PSP, from July 9 to 27, 2011, October 29 to December 13, 2011, March 2 to 3, 2012 and March 7 to 10, 2012, from 6:00 to 18:00, horizontal solar irradiance monthly average schedules for five typical days of the months March, July, October, November and December were obtained. These averages and three sky models were used to calculate the monthly hourly averages of the total solar irradiance for tilted surface $G_T$ (CSUC roof) and for the same surface in optimum orientation (inclination=4° and surface azimuth=0°). Relating the averages obtained, inclination and optimum orientation factors $K_1$ y $K_2$ were calculated.

3. Models for calculation of solar radiation on tilted surfaces
The data of solar radiation on tilted surfaces can be measured experimentally or can be estimated by mathematical models. This second approach is the one used in this work.

Equations 1, 2 and 3 show the most used models to calculate the total irradiance on tilted surface $G_T$: isotropic sky, HDRK and Perez [10, 12].

$$G_T = G_b R_b + G_d \left( \frac{1 + \cos \beta}{2} \right) + G_p \left( \frac{1 - \cos \beta}{2} \right)$$

$$G_T = (G_b + G_d A_i) R_b + G_d (1 - A_i) \left( \frac{1 + \cos \beta}{2} \right) \left[ 1 + f \sin^3 \left( \frac{\beta}{2} \right) \right] + G_p \left( \frac{1 - \cos \beta}{2} \right)$$

$$G_T = G_b R_b + G_d (1 - R_1) \left( \frac{1 + \cos \beta}{2} \right) + G_d R_1 + G_d F_2 \sin \beta + G_p \left( \frac{1 - \cos \beta}{2} \right)$$

These three models, with some variations, include direct, diffuse (isotropic, circumsolar and horizon) and reflected contributions (see Figure 1). The latter is not considered here because the CSUC roof is the uppermost surface of those found in the vicinity of the building.

![Figure 1. Direct, diffused and reflected radiation from the floor on a tilted surface, adapted from [10].](image-url)
4. Results and discussion

4.1. Month identification with less favourable irradiance

Figures 2, 3 and 4 show the hourly averages of the total solar irradiance on the tilted surface, estimated from isotropic Sky, HDKR and Perez models, for the months for which experimental data were available.

From the Figures 2, 3 and 4, we can make the following general observations: a) except at 6:00 and 18:00, the figures are very similar, which means that the three models are suitable for predicting total irradiance on tilted surface b) December is having a larger number points of time with lower irradiance.

4.2. Selection of the prediction model

Figure 5 show the hourly averages of the global solar irradiance on the tilted surface, for December, from 6:00 to 18:00, obtained by isotropic sky, HDKR and Perez models. The Perez’s model shows some slightly lower irradiance levels from 7:00 to 9:00, with even lower values from 9:00 to 13:00 and with coinciding values with those of the other models, from 13:00. Following the criteria of the worst case condition, Perez model was selected to predict the values of global solar irradiance on the tilted surface (CSUC’s roof).

4.3. Tilt factors and optimum orientation estimation

Figure 6 shows that on December and according to Perez model, from 7:00 to 14:00, the irradiance for tilted surface with real orientation (9° tilt, 102° azimuth) are below of the corresponding to the horizontal surface and to the tilted surface with optimum orientation (4° tilt, 0° azimuth). From 14:00...
to 18:00 the values match.

Figure 7 shows that lower values, for tilt factors $K_1$ and optimum orientation $K_2$, are presented at morning hours and higher values at afternoon hours. Both coefficients matches approx after 14:00 hours. $K_1$ value ranges between 0.85 y 0.99, with an average value of 0.95; $K_2$ value ranges between 0.81 y 0.99, with an average value of 0.93.

5. Conclusions

Total Solar irradiance values to be taken to design the climate control system of the pool inside the CCDU shall correspond to December.

Isotropic Sky, HDKR and Perez models predict similar values of solar irradiance on the tilted surface with real orientation (CCDU roof). For the calculation of the catchment area, predicted values for December will be used by Perez model.

To ensure maximum architectural integration of solar collectors on the CCDU roof, total solar horizontal irradiance available will be multiplied by a factor $K_1$ equal 0.85.

In the most unfavourable conditions, 19% of the energy will not be catched by the collect surface because it has no an optimal orientation.

References

[1] Méndez J M y Cuervo G R 2008 Energía térmica solar (Madrid: FC Editorial) p 183
[2] Perales T 2008 Instalación de paneles solares térmicos (México: Alfaomega) p 83
[3] Skeiker K 2009 Energy Conversion and Management 50 2439
[4] Mendoza D 2006 Revista Colombiana de Física 38-4 1435
[5] Chang T P 2009 Solar Energy 83 1274
[6] Szefc G and McMonagle R C 1983 Solar Energy 30 247
[7] Rakopoulos C D and Vazeos E 1987 Energy Conversion and Management 27 189
[8] Singh M et al 1989 Energy Conversion and Management 29 239
[9] Woolley J, Harrington C and Modera M 2011 Building and Environment 46 187
[10] Duffie J A y Beckman W A 2006 Solar engineering of thermal process (New York: Wiley) p 9
[11] Manrique J A 1984 Energía solar: Fundamentos y aplicaciones fototérmicas (México: Harla) p 19
[12] Kalogirou S 2014 Solar energy engineering: Processes and systems (UK: Elsevier) p 91