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IMPLEMENTATION OF THE ASHRAE 2009 CLEAR-SKY MODEL PROPOSED BY ASHRAE IN ANSYS FLUENT SOFTWARE

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Abstract. *Thermal comfort in large urban centers has become an issue of increasing concern due to the increase in global temperatures. An important variable for this study is solar radiation. One of the methods developed to determine direct and diffuse radiation is the Clear-Sky model developed by ASHRAE (2009). This work aims to implement the Clear-Sky model in fluent software to be used in computational studies of fluid dynamics. As a performance check, a validation model was developed with data from the city of Maringá - PR, Brazil, and compared with 111,172 hourly radiation data measured by the Meteorological Station installed in the city. An application model was created to verify the performance of the Clear-sky model in three-dimensional bodies. It was found that the application of the Clear-sky model in the Fluent software achieved results close to measured historical data, in addition its application in three-dimensional bodies presented a new possibility to make studies involving computational fluid dynamics.*

Keywords: *Solar Model, Fluent, Clear-Sky Model.*

1. INTRODUCTION

Thermal comfort in large urban centers has become an increasingly worrisome theme due to the rise in global temperature. When it comes to studies involving the optimization of urban environments, energy exchange becomes one of the most important parameters. This phenomenon can occur through radiation, convection or conduction. This work will focus on radiation phenomena.

As for radiation, the main source of this type of energy is the Sun. According to the World Meteorological Organization, the solar constant is frequently used as 1367 $W{\cdot}m^{-2}$ (Iqbal, 1983). Despite being an advance in the study of solar radiation, this value is not the real one focusing on the earth's surface. This is due to the composition of the atmosphere, which ends up interacting with the sun's rays and modifying its trajectory and intensity.

The atmosphere composition presents gas molecules and solid particles, which when hit by the sun's rays absorbs and spreads the energy. This phenomenon is called atmospheric dispersion and ends up affecting the incident radiation on the earth's surface. There are two types of dispersion, the Rayleigh, and the Mie scattering. The first one is caused by small gas molecules that disperse radiation almost uniformly to all sides, while the later one is caused by solid particles (dust or soot) and disperses energy toward the incident rays (Bergman *et al*., 2011).

In view of the effects of direct and diffuse radiation several models have been developed to separate both radiations. Studies developed using a large amount of global data allowed to verify the efficiency of 140 forecast models, involving arid, temperate, tropical, and high albedo regions (Gueymard and Ruiz-Arias, 2016). Also according to the authors, the models proposed by Engerer (2015) and Perez *et al*. (2002) presented the best performance in arid, temperate and tropical regions, presenting for the arid region a mean quadratic root error of 16 (±2.8) % and 15.3 (±3.5) %, respectively. Although the models are increasingly extensive and close to reality, there is still much to advance when it comes to the implementation of radiation models with other phenomena.

To estimate the most applicable diffuse and direct solar radiation, the American Society of Heating, Cooling and Air Conditioning Engineers (ASHRAE) developed a model called Clear-Sky (ASHRAE, 2009). This model is a simplification of the complex REST2 model proposed by Gueymard (2008) and adapted for use worldwide. The Clear-

Sky model allows the calculation of solar radiation based on the position of the sun, which in turn depends on geographical and temporal factors; and the location of the area of interest, which will present its own coefficients in the calculation model.

As studies involving thermal comfort have advanced considerably, several tools have been developed and improved to sustain this development. Among the tools used in these works, computational modeling stands out. Several commercial software has been developed for these purposes including not only radiation models, but also other physical phenomena. ANSYS is a computational modeling software that has a computational fluid dynamics module, Fluent. This module has been used by the academic and technical community as a forecasting and calibration tool, even assisting in proposals for structural optimization. This work aims to perform the implementation of a Clear-Sky model using Fluent software, to perform increasingly complete models involving the urban energy balance.

2. CLEAR-SKY MODEL

Clear-Sky models are models that estimate incident solar radiation considering no effect of cloudiness. One of the most known clear-sky model in the literature is the Bird model, which was elaborated based on five other models and presented a good approximation of rigorous models of prediction of the time (Bird and Hulstrom, 1981). The Bird model needs as input data, the solar constant, the zenith angle, the surface atmospheric pressure, the soil albedo, the water vapor concentration, the total ozone, the turbidity at the wavelength of 0.5 and/or 0.38 μm, and the direct dispersion rate of the aerosol.

In this work the model that will be implemented in Fluent software will be the one proposed by ASHRAE (2009). For the calculation of the model, several values are determined by a set of equations expressed in the technical book of the association (ASHRAE, 2009).

Due to the earth's elliptical orbit there is a variation in the flow of solar extraterrestrial radiation, requiring an adaptation in the original value of the solar constant. This adaptation is expressed by Eq. (1) in which n represents the day of the year and E_{sc} the solar constant in the value of 1367 W·m^{-2}.

$$E_o = E_{sc}\left\{1+0.033\cos\left(360^o\,\frac{(n-3)}{365}\right)\right\} \tag{1}$$

Other important calculation is the correction of solar time due to the speed variation of the Earth's orbit. This correction is necessary because this speed variation is not adapted to watches that operate at a uniform rate. To estimate this variation, called time equation ET, the Eq. (2) is used, in which ET is expressed in minutes and the value of Γ is given by Eq. (3) (Iqbal, 1983).

$$ET = 2.2918\ (0.0075+0.1868\cos(\Gamma)-3.2077\sin(\Gamma)-1.4615\cos(2\Gamma)-4.089\sin(2\Gamma)) \tag{2}$$

$$\Gamma = 360^o\,\frac{n-1}{365} \tag{3}$$

To obtain solar time with local standard time, it is necessary to add the value found in the time equation to local standard time, and then make a correction based on the longitude of the place of interest. Thus, solar time can be described by Eq (4), in which AST is the Apparent Solar Time, in decimal hours; LST is the local default time, in decimal hours; LSM is the Meridian Longitude of Local Time and expressed by Eq. (5), in which TZ is the time zone; and LON is the longitude of the region, in degrees.

$$AST = LST + ET/60 + (\mathrm{LON - LSM})/15 \tag{4}$$

$$\mathrm{LSM} = 15\,\mathrm{TZ} \tag{5}$$

The fact that the Earth's equatorial plane is tilted towards the orbital plane at an angle of 23.45º causes the angle between the line connecting the Earth and the Sun and the equatorial plane to vary throughout the year, even creating the seasons and varying in the day and night periods. This angle δ can be calculated by Eq. (6).

$$\delta = 23.45\sin\left(360^\circ\,\frac{n+284}{365}\right) \tag{6}$$

The Sun, depending on its position in the sky, also influences the estimation of radiation. The solar angle β, is the angle formed by the horizontal plane and a line of the sun beam, ranging from 0 to 90º and expressed by Eq. (7) as a function of the angle of the hour H, latitude L and angle δ.

$$\sin(\beta) = \cos(L)\cos(\delta)\cos(H) + \sin(L)\sin(\delta) \tag{7}$$

The hour angle is defined as the angular displacement of the sun in the west east direction of the local meridian resulting from the rotation of the Earth, which can be calculated according to Eq. (8).

$$H = 15(AST - 12) \tag{8}$$

Still related to the position of the sun there is the angle φ of the solar azimuth which is formed by the angular displacement of the south of the projection, in the horizontal plane of the line of the solar calculated by Eq. (9).

$$\cos(\phi) = \frac{\cos(H)\cos(\delta)\sin(L) - \sin(\delta)\cos(L)}{\cos(\beta)} \tag{9}$$

Between the earth's surface and the radiation from the Sun there is a layer of atmosphere. A parameter that influences direct and diffuse radiation is the relative mass of air m, which represents the ratio between the mass of the atmosphere in the actual path of the sun beam to the ground and the mass that would exists if the sun beam were directly above the surface. The calculation of this value is expressed in Eq. (9) and was proposed by Kasten and Young (1989).

$$m = \frac{1}{\left[\sin(\beta) + 0.50572(6.07995 + \beta)^{-1.6364}\right]} \tag{10}$$

Finally, the calculation of horizontal values of the direct and diffuse component is expressed by Eq. (11) and Eq. (12), in which τ_b and τ_d are monthly averaged values that depend on the location; *ab* and *ad* are exponents of diffuse and direct air mass, calculated by Eq. (13) and Eq. (14).

$$E_b = E_o \ \exp\left[-\tau_b m^{ab}\right] \tag{11}$$

$$E_d = E_o \ \exp\left[-\tau_d m^{ad}\right] \tag{12}$$

$$ab = 1.219 - 0.043\ \tau_b - 0.151\ \tau_d - 0.204\ \tau_b \tau_d \tag{13}$$

$$ad = 0.202 - 0.852\ \tau_b - 0.007\ \tau_d - 0.357\ \tau_b \tau_d \tag{14}$$

In addition to the Clear-Sky model, ASHRAE, also presents weather data from various cities around the world, allowing you to apply this method more easily (ASHRAE, 2009).

The equations presented above are applied in the case where solar beam hits horizontal surfaces, however, sometimes it is necessary to calculate radiation for surfaces with different orientations.

For this case, the first important angle is expressed by the surface between the surface that receives the solar incidence and a horizontal surface. Another angle is the azimuth of the surface as the south displacement of the projection, ranging from -180º to 180º. With this, the surface-solar angle of the azimuth γ is calculated by Eq. (15).

$$\gamma = \phi - \psi \tag{15}$$

Then, the calculation of incidence angle θ is performed which represents the angle between the normal to the surface receiving radiation and sun beam line. This angle is called an angle of incidence and is calculated by Eq. (16).

$$\cos(\theta) = \cos(\beta)\cos(\gamma)\sin(\Sigma) + \sin(\beta)\cos(\Sigma) \tag{16}$$

In this way, the calculation of the incident radiation on a given surface has three components, direct solar radiation ($E_{t,b}$), diffuse solar radiation ($E_{t,d}$) and radiation reflected by the ground ($E_{t,r}$). Total radiation can then be calculated by Eq. 17.

$$E_t = E_{t,b} + E_{t,d} + E_{t,r} \tag{17}$$

Each of the radiation components can be calculated by equations that take into account the angle of incidence, the angle of inclination of the surface and the reflectivity of the ground ρ_g. Eq. 18 calculates direct solar radiation; Eq. 19 and Eq. 20 calculate diffuse solar radiation; and Eq. 21 is used to calculate the radiation reflected by the ground.

$$E_{t,b} = E_b \cos(\theta) \tag{18}$$

$$E_{t,d} = E_d Y \tag{19}$$

$$Y = \max(0.45, 0.55 + 0.437 \cos(\theta) + 0.313 \cos^2(\theta)) \tag{20}$$

$$E_{t,r} = \left(E_b \sin(\beta) + E_d\right) \rho_g \frac{1-\cos(\Sigma)}{2} \tag{21}$$

3. METHODOLOGY

The implementation of the ASHRAE Clear-Sky model in Fluent software is performed through a User Defined Function (UDF) written in C language and compiled in Fluent itself. In the UDF file, all equations of the model were inserted, in addition to the data for calculation.

As a study area, it was chosen the municipality of Maringá in the state of Paraná, Brazil, located at coordinates 23.42 º South and 51.42º West, in the time zone (-3). Although the municipality of study does not present values of τ_b and τ_d, the values of the municipality of Londrina, which is located about 100 km from Maringá were considered (Tab. 1).

Table 1. τ_b e τ_d for the city of Londrina - PR

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
τ_b	0.380	0.378	0.372	0.359	0.343	0.350	0.347	0.401	0.494	0.450	0.384	0.374
τ_d	2.455	2.468	2.481	2.489	2.506	2.443	2.457	2.195	1.884	2.047	2.374	2.467

It is installed in the municipality of Maringá an automatic weather station (Maringá-A835), with extensive radiation data. This weather station is located at coordinates 23.41 º South and 51.93 º West and measures temperature, moisture, pressure, wind velocity, precipitation and dew point. These data were obtained from the National Meteorological Institute (2020) website used as a verification parameter of the model implemented in Fluent.

3.1 Validation of Clear-Sky Model

To compare with the data from the weather station, a model was created in the Fluent software with an area of 1 m² and height of 1 m. The mesh created was uniform with element size of 0.01 m, refinement in curvatures and assembly of "CutCell" meshes, totaling 342,101 elements.

In the Fluent Setup the Radiation module was activated and the "Solar Ray Tracing" model was enabled, in the lightening parameters the UDFs were configured for direct and diffuse radiation. In addition, the software's own solar calculator is used.

Initially, a statistical treatment of hourly total horizontal solar radiation, precipitation and humidity data from the meteorological station was performed. It was performed 12 simulations, one in each month of the year and all on the 21st day of each month. The choice of the 21st day is due to the fact that they are representative days for solar incidence, with the winter solstice on June 21 and summer solstice on December 21 for the southern hemisphere.

With the results of the simulations and the data of the weather station one can verify the performance of the model for the site and for each month of the year.

3.2 Aplication of Clear-Sky Model

Having compared the model with the actual data, a new simulation was built, contemplating a standard building located on Horacio Raccanello Filho Avenue (Fig. 1), in the municipality of Maringá. The purpose of this final modeling is to apply the model and verify how it behaves for three-dimensional bodies.

Figure 1. Horacio Raccanello Filho Avenue

The dimensions of the building adopted for modeling was 40 m front, 25 m deep and 40 m high inserted in the center of a prism with 320x200x160 m (Fig. 2). The mesh adopted for the model used the "Cutcell" method and with greater refining near the building and on the ground, allowing to capture more accurately the solar rays (Fig. 2). In total the mesh reached 576,533 elements, with the most refined elements in the order of 1 m³ in volume. The two simulated days were June 21 and December 21, seeking the situations found on the solstices, with less and more solar radiation respectively.

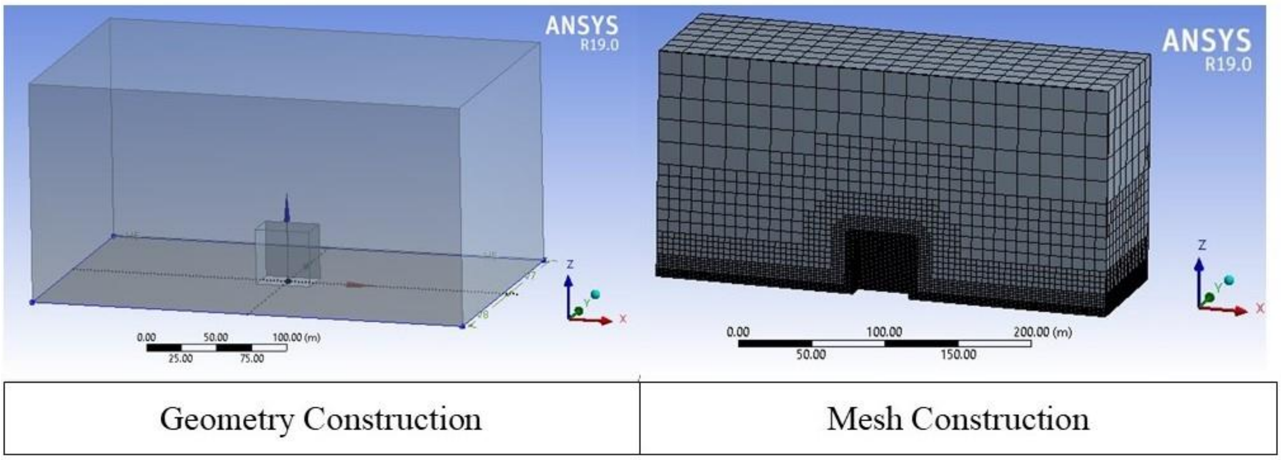

Figure 2. Constructed mesh and geometry

4. RESULTS

The weather station data is shown in Fig. 3 in the form of boxplot charts for the all data set that was in each month. The choice of data representation in boxplots is due to the possibility of verifying how they are statistically distributed. It is observed that the months with the lowest variation of data were the months from April to September. A total of 111,172 hourly radiation data were used from 11/22/2006 to 04/08/2020.

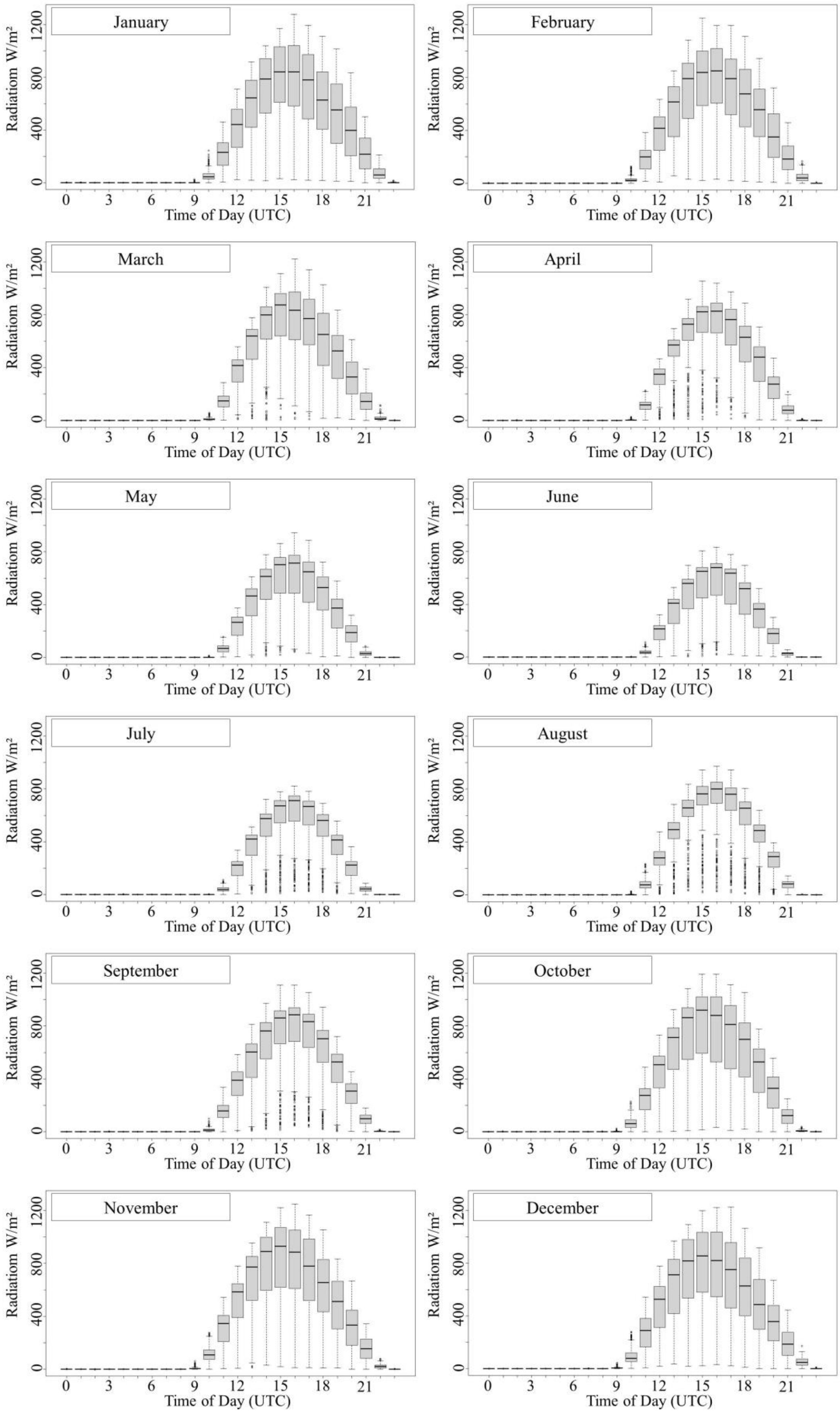

Figure 3. Boxplot radiation data times for each month

The comparison between the Clear-Sky model calculated in Fluent, using the τ_b and τ_d data from the city of Londrina, with the statistical data treated from the weather station in the city of Maringá showed a greater proximity in the months with less data variability. The results of the comparison can be seen in Fig. 4, where Mean represents the mean of the data measured by the weather station, for each month and hour, and Clear-Sky Model represents the result of the modeling developed in Fluent.

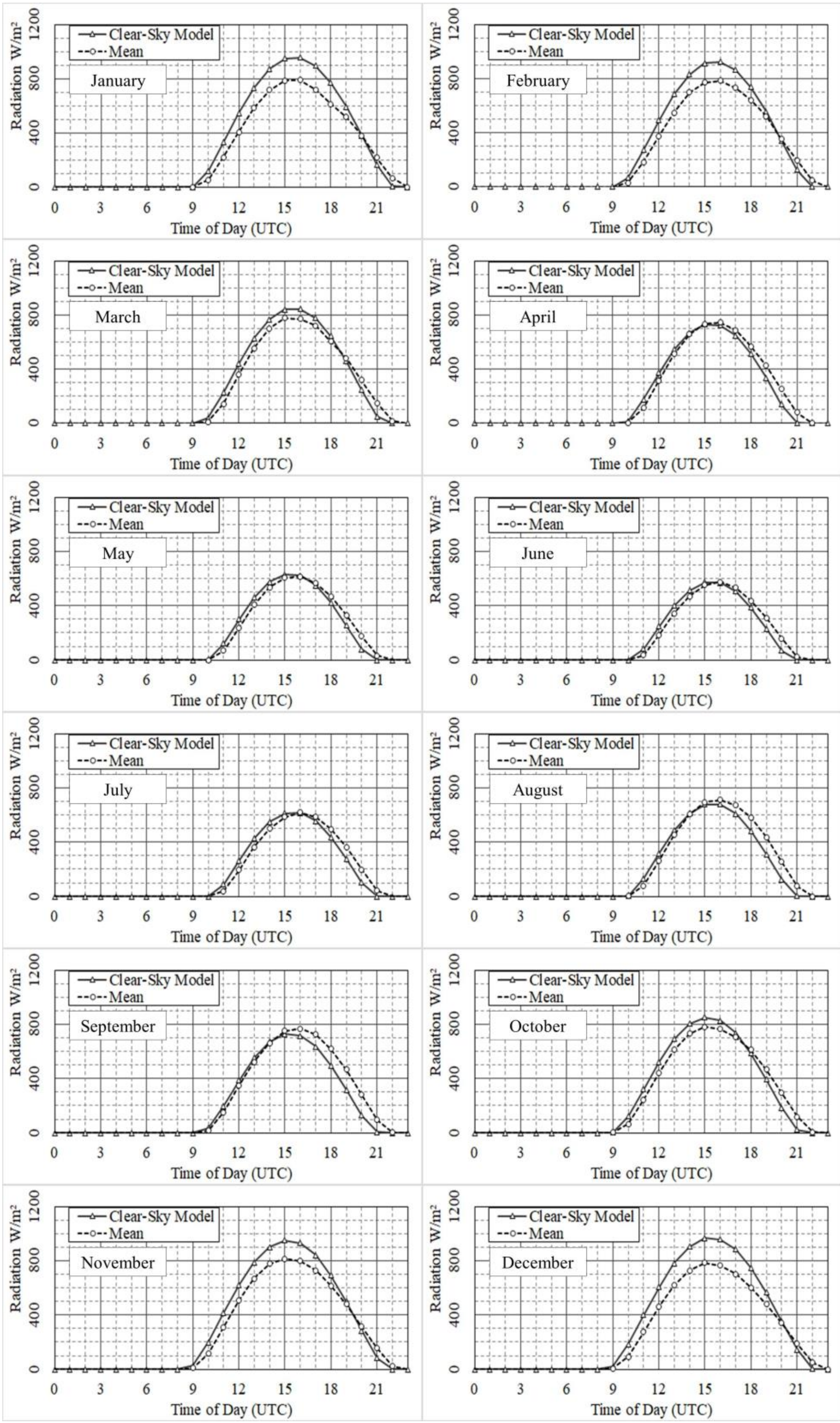

Figure 4. Comparison of clear-sky method in Fluent and values from the Automatic Weather Station

In order to quantify the accuracy of the model, the Root Mean Square Error was calculated. In addition, it was identified that the months with the highest variability of the data were months with higher average rainfall. To verify whether precipitation influences the accuracy of the model, these two data were calculated in graphic form in Fig. 5.

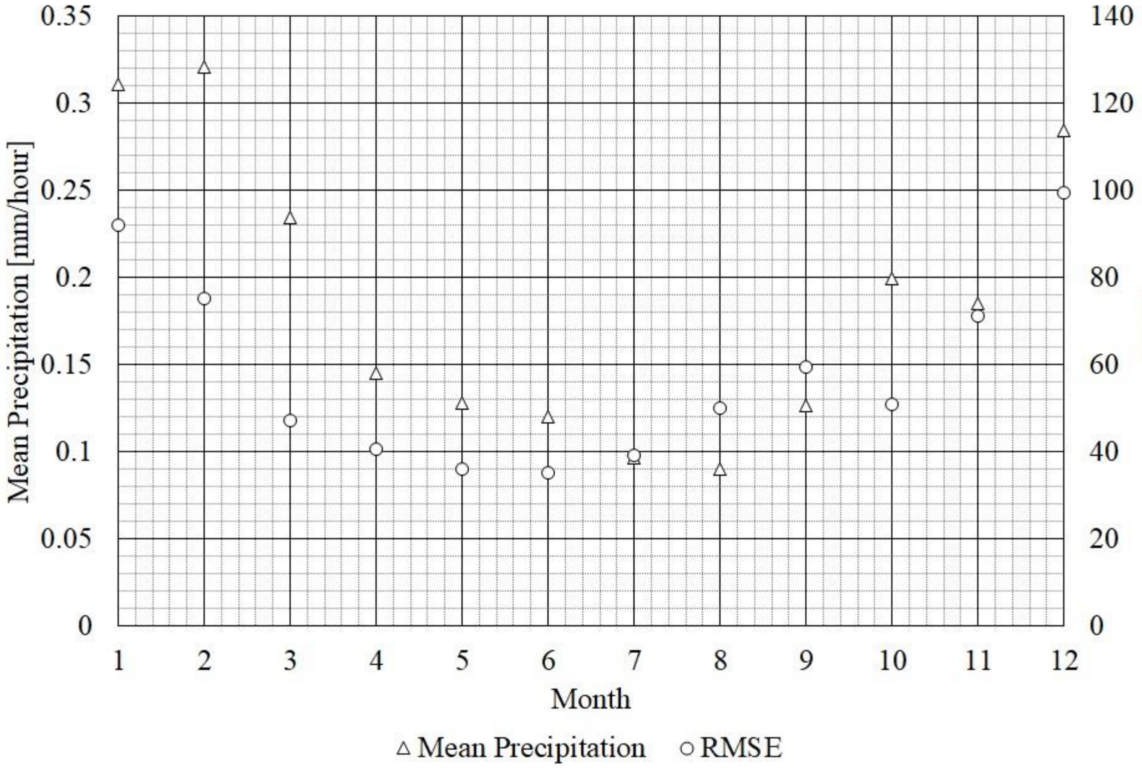

Figure 5. Relation between Root Mean Square Error and Mean precipitation

Analyzing Fig. 5 it is observed that there is a relationship between the Root Mean Square Error and the Mean Precipitation. This may be due to the cloud cover that prevents radiation from presenting the standard values of clear sky. Thus, for a better comparison, it would be necessary another parameter, such as the cloud cover index, to perform a selection of the data measured by the weather station. In any case, the results in general showed a behavior close to the data measured by the meteorological station.

Despite the proximity between the data measured by the station and the simulated data, there is a variation between them. It is believed that the variation between the measured data and the Clear-Sky model may be due to several factors, such as the use of the τb and τd values in the city of Londrina, part of the radiation reflected by the structures around the Meteorological Station that do not was considered in the model, or the cloud cover that influences the intensity of radiation.

Other studies involving the application of the Clear-Sky Model presented results similar to those found in this study. The research developed by Jamil and Khan (2014) applies the Clear-Sky Model in the city of Aligarh, India, and found a relationship between the modeled data and the measured data very close to that of this work, with some variations. Another study developed to verify the applicability of the Clear-Sky Model was accomplished in Erzurum, Turkey and presented a good approximation between the data measured and calculated by the model (Bakirci, 2009). In addition, a study of application of the Clear-Sky model in Arab countries presented RMSE values ranging from 42 to 124 $W.m^{-2}$ for application of the model without any adjustment, very close to the RMSE values found in this study from 35 to 99 $W.m^{-2}$ (Alsadi and Nassar, 2016). Despite the studies carried out by Jamil and Khan (2014), Bakirci (2009) and Alsadi and Nassar (2016) using the 1985 ASHRAE Clear-Sky model, they are important data to demonstrate the capability of this tool in an earlier version.

Fig. 4 shows a shift in the graph of simulated data in Fluent with the data measured by the weather station. This is probably due to the correction of the solar time in the Clear-Sky model. It is possible to verify the feasibility of applying the method in Fluent software, in addition to the calculated result, which despite not presenting a perfect match achieved data close to the measured data.

In addition, the application of the Clear-sky model in a three-dimensional body presented the following results expressed in Fig. 6 and Fig. 7.

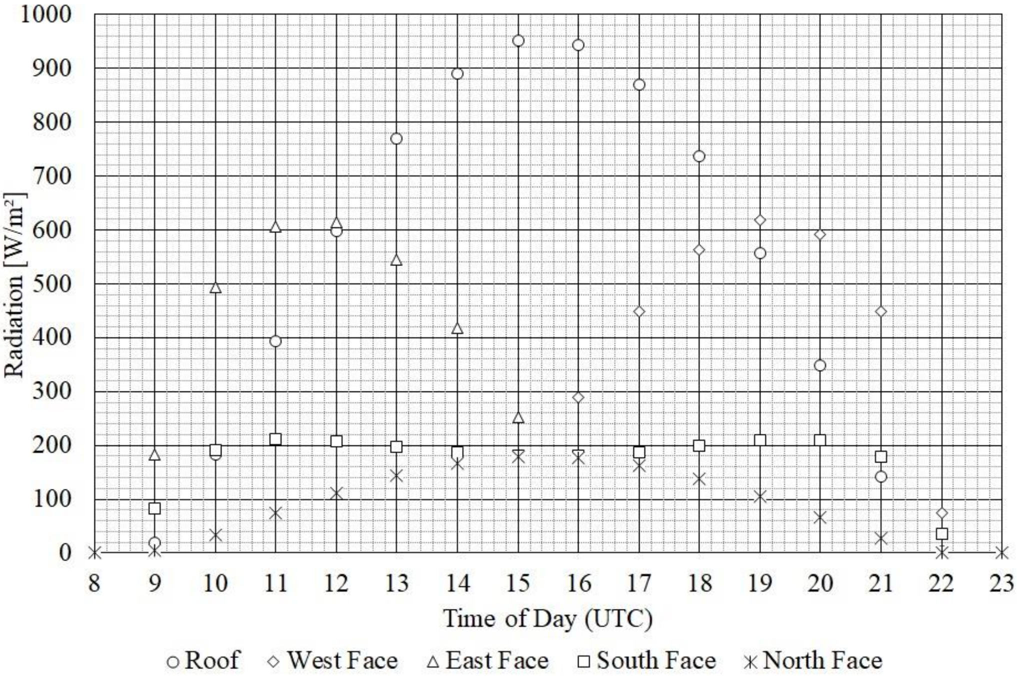

Figure 6. Weighted average by the area of Radiation on each side of the building - Simulation 21 December

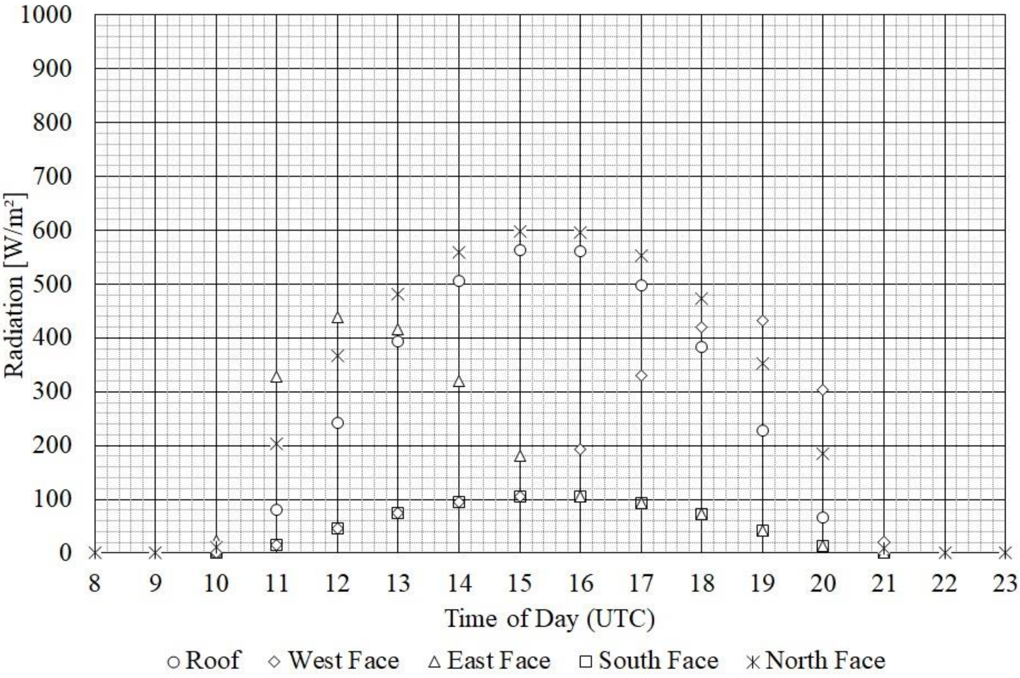

Figure 7. Weighted average by the area of Radiation on each side of the building - Simulation 21 June

What can be seen in the graph of radiation incidence on each facade is that, as Avenida Horacio Raccanello Filho is aligned with the east-west axis, the incidence of the sun is symmetrical. On the summer solstice, according to the Clear-sky model, solar radiation on the roof of the building can reach values very close to 980 $W.m^{-2}$, while the east facade (in the morning) and the west facade (in the afternoon) reach more than 600 $W.m^{-2}$. In the winter solstice, the model presented the north face as the one with the highest incidence of radiation reaching almost 600 $W.m^{-2}$.

It was observed that the Clear-sky model presents interesting approximations for regions close to the places that with official data of τ_b and τ_d. In addition, the applicability of the Clear-sky model in Fluent software allows the construction of a simulation more complex.

Finally, the analysis of a construction model demonstrated the efficiency of the model in three-dimensional geometries, and can also be used for radiation estimates on facades and buildings, being able to change the days of the year, the hours of the day and even the orientation of the building in time of geometry construction.

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