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INVESTIGATION OF APPLICABILITY OF ASHRAE CLEAR-SKY MODEL TO IZMIR, TURKEY

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Abstract: Since the ASHRAE clear-sky model gives maximum radiation level on the surface, this model is used for solar heat load calculation of air conditioning systems and building designs. This study deals with the solar-radiation variation over a horizontal surface calculated by the ASHRAE clear-sky model with measurements for Izmir, Turkey (latitude:39°24' N; longitude: 27° 15', altitude: 30m). In the past, various empirical correlations have been developed in order to estimate the global clear sky solar radiation around the world. In this study, a new correlation is also developed to establish a relationship between hourly global solar radiation and zenith angle. The new model is then compared with ASHRAE clear-sky model through correlations available in the literature in terms of the widely used statistical indicators, namely; the mean bias error (MBE), root mean square error (RMSE) and t-statistic (t-stat) tests.
The new model predicts the hourly global clear sky solar radiation values as a function of zenith angle better than other available models for Izmir in Turkey.
Keywords: ASHRAE clear-sky model, correlation, error analysis, solar energy

İZMİR İLİNE ASHRAE AÇIK GÜN MODELİNİN UYGULANABİLİRLİĞİNİN İRDELENMESİ

Özet: ASHRAE açık gün modeli yüzey üzerine gelen en yüksek ışınım şiddetini verdiği için, havalandırma sistemlerinin ve yapı tasarımlarının güneş ısı yükünü hesaplamak için kullanılmaktadır. Bu çalışmada, ASHRAE açık gün modeli ile hesaplanan yatay yüzey üzerindeki güneş ışınımı değişimi, ölçüm sonuçları ile karşılaştırılmıştır. Literatürde, farklı ülkeler için toplam güneş ışınımı şiddetini veren çeşitli deneysel bağıntılar mevcuttur. Bu çalışmada, aynı zamanda zenit açısının fonksiyonu olarak toplam saatlik güneş ışınımı veren yeni bir bağıntı geliştirilmiştir. Bu yeni model daha sonra ASHRAE açık gün modeli ve literatürdeki mevcut korelâsyonlarla, ortalama sapma hatası, ortalama karekök hatası ve t-istatistik olarak adlandırılan istatistiksel yöntemler ile karşılaştırılmıştır.
Sonuç olarak, zenit açısının fonksiyonu olarak toplam saatlik güneş ışınımı veren yeni modelin İzmir için diğer modellerden daha iyi sonuçlar verdiği ortaya konmuştur.
Anahtar Kelimeler: ASHRAE açık gün modeli, korelasyon, hata analizi, güneş enerjisi

NOMENCLATURE

A	apparent solar radiation constant (-)
B	atmospheric extinction coefficient (-)
C	diffuse radiation factor (-)
h	solar altitude (°)
I	hourly clear sky global radiation (Wm^{-2})
I_{bn}	hourly beam radiation in the direction of rays (Wm^{-2})
I_d	hourly clear sky diffuse radiation (Wm^{-2})
δ	declination angle (°)
ϕ	latitude of site (°)
θ_z	zenith angle (°)
ω	hour angle (°)

INTRODUCTION

Solar radiation is a major contributor to the heat gain of a building. When the sky is clear, the building heat gain from solar radiation is particularly high. ASHRAE has a model, which can estimate the maximum radiation level on the surface when the sky is clear. Therefore, the ASHRAE clear sky model is commonly used as a basic tool for solar heat load calculation of air conditioning systems and building designs among the engineering and the architectural communities (ASHRAE 1985; 2001).

The global solar radiation and bright sunshine hours are measured on horizontal surfaces in many countries. Therefore, solar radiation components such as diffuse and direct are calculated and derived by empirical formulae. There are several studies dealing with ASHRAE clear-sky model in the literature. Parishwad et. al. (2000) defined a procedure for the estimation of direct, diffuse and global hourly solar radiation on a horizontal surface for any location in India. Al-Sanea et al. (2004) studied ASHRAE clear-sky model to estimate the monthly average hourly global solar radiation on horizontal surfaces in Riyadh and found adjustment factors for the model. Bakırcı (2009) investigated solar radiation variation on horizontal surfaces by the ASHRAE clear-sky model and compared with measurements for Erzurum, Turkey. Lingamgunta and Veziroglu (2004) derived for estimating the daily clear sky radiation as a function of the day of the year and the latitude and altitude of locations.

There are five simple correlations giving the hourly global clear sky solar radiation as a function of zenith angle. These correlations are due to Hourwitz, Berger–Duffie, Adnot–Bourges–Campana–Gicquel, Kasten–Czeplak and Robledo-Soler (Robledo and Soler, 2000; Lingamgunta and Veziroglu, 2004).

In the present work, the solar radiation variation on a horizontal surface calculated by the ASHRAE clear-sky model is compared with measurements for Izmir, Turkey. Accordingly, global clear sky solar radiation estimation correlations are reviewed and a new correlation is proposed as a function of zenith angle. Finally, ASHRAE clear-sky model, correlations in the literature and a new correlation are tested in terms of statistical error methods.

THE ASHRAE CLEAR-SKY MODEL AND EXISTING CORRELATIONS

The ASHRAE clear-sky model is a semi-empirical approach and it is described in ASHRAE (2001). The direct solar radiation incident I_{bn} on a surface oriented normal to the sun's ray is represented by

$$I_{bn} = A\exp(-B/\sin h) = A\exp(-B/\cos\theta_z) \quad (1)$$

where A is the solar irradiation just beyond the atmosphere, B is the atmospheric extinction coefficient, h solar altitude and θ_z is the zenith angle.

The zenith angle and solar altitude are given by equation, respectively

$$\cos\theta_Z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \quad (2)$$

and

$$\sin h = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \quad (3)$$

In Eqs. (2) and (3), ϕ is the latitude of the station, δ is the solar declination and ω is the hour angle.

The solar declination (δ) is given as (Duffie and Beckman, 2006)

$$\delta = 23.45\times\sin\left(\frac{360}{365}(n+284)\right) \quad (4)$$

where n is the numbers of the year starting from January 1. The values of n that represent months are given in Table 1.

The hour angle (ω) is an angular measure of time and is equivalent to 15^o per hour in the morning (+) and afternoon (-). It is measured from noon-based local solar time *(LST)* from the equation given by

$$\omega = (LST-12)\times 15 \quad (5)$$

Local solar time (*LST*) is calculated from the local standard time *(CT)* and the equation of time *(ET)* as follows.

$$LST = CT + \left(\frac{1}{15}\right)(L_{std} - L_{loc}) + ET - DT \quad (6)$$

where L_{std} is the standard meridian for the local time zone, L_{loc} is the longitude of actual location and *DT* is the daylight savings time correlation (*DT* = 0 if not on daylight savings time, otherwise *DT* is equal to the number of hours that the time is advanced for daylight savings time, usually 1hr). The equation of time *(ET)* is calculated as follows.

$$ET = 9.87\sin 2B_n - 7.53\cos B_n - 1.5\sin B_n \quad (7)$$

where B_n is given as,

$$B_n = \frac{360(n-81)}{364} \quad (8)$$

The clear sky model approximates the diffuse radiation falling on a horizontal surface as a fraction of the direct normal irradiation.

$$I_d = CI_{bn} \quad (9)$$

where C is the diffuse radiation factor.

The hourly global radiation is equal to sum of the diffuse and direct solar radiation amounts and it is calculated by following equation.

$$I = I_{bn}.\cos(\theta_z) + I_d \qquad (10)$$

The input to the ASHRAE clear-sky model is, thus, complete by specifying values for parameters, namely, *n*, δ , *A, B, C, ET,* φ and, *LST*. The solar data given by ASHRAE (1985) for each month are available in Table 1 for the first five parameters. Other parameters are specific to the location of interest and accordingly, their values are given for Izmir in this article. The local standard time (*LST*) is now the only varying parameter, which is input for calculations at any required time during the day.

Table 1. The constants *A*, *B*, *C* and related parameters of the ASHRAE model for clear sky days on the twenty-first day of each month (ASHRAE, 1985)

Months	*n*	δ (°)	*A* (W/m²)	*B*	*C*
January	21	-20.14	1229.475	0.142	0.058
February	52	-11.23	1213.7125	0.144	0.06
March	80	-0.41	1185.34	0.156	0.071
April	111	11.57	1134.9	0.18	0.097
May	141	20.13	1103.375	0.196	0.121
June	172	23.44	1087.6125	0.205	0.134
July	202	20.44	1084.46	0.207	0.136
August	233	11.75	1106.5275	0.201	0.122
September	264	-0.21	1150.6625	0.177	0.092
October	294	-11.76	1191.645	0.16	0.073
November	325	-20.45	1220.0175	0.149	0.063
December	355	-23.45	1232.6275	0.142	0.057

Solar radiation variation over the horizontal surface for representative days (twenty-first day of each month) is calculated using Eqs. (1-10). Also, various correlations for clear-sky solar radiation are defined in the literature and these correlations are given in Eqs. (11-15).

The Hourwitz correlation (Model I)

$$I = 1098\cos\theta_z \exp(-0.057/\cos\theta_z) \qquad (11)$$

The Berger-Duffie correlation (Model II)

$$I = 1350 \times 0.70 \times \cos\theta_z \qquad (12)$$

Adnot–Bourges–Campana–Gicquel correlation (Model III)

$$I = 951.39\cos^{1.15}\theta_z \qquad (13)$$

Kasten–Czeplak correlation (Model IV)

$$I = 910\cos\theta_z - 30 \qquad (14)$$

The Robledo-Soler correlation (Model V)

$$I = 1159.24(\cos\theta_z)^{1.179} - e^{-0.0019(-\pi/2-\theta_z)} \qquad (15)$$

DATA SOURCES AND APPLICATION OF ASHRAE MODEL TO IZMIR

The hourly irradiations on a horizontal surface are measured continuously at all meteorological stations in Turkey. In this study, the hourly measured irradiation data on horizontal surfaces in years of 1995, 2004 and 2005 are used to calculate the solar energy design parameters for Izmir, which is the 3rd largest city in Turkey and the 2nd largest sea port. The source of data is the Turkish State Meteorology Agency, known succinctly as DMI, in Turkey. Using Eqs. (1)-(10) and Table 1, hourly clear sky radiation has been evaluated for the twenty-first day of each month for the Izmir City, using a Visual Basic computer program that calculated hourly direct, diffuse and global solar irradiation amounts for 81 of cities in Turkey as in Figure 1.

METHODS OF MODEL EVALUATION

The performance of the models is evaluated in terms of the following statistical error tests: the mean bias error (MBE), root mean square error (RMSE) and t-statistic.

$$MBE = \frac{\sum_{i=1}^{k}(H_{ic} - H_{im})}{k} \qquad (16)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{k}(H_{ic} - H_{im})^2}{k}} \qquad (17)$$

and

$$t-stat = \left(\frac{(k-1)MBE^2}{RMSE^2 - MBE^2}\right)^{0,5} \qquad (18)$$

where H_{im} is the *i-th* measured value, H_{ic} is the i-th calculated value and *k* is the total number of observations. The *MBE* provides information on the long-term performance of the correlations by allowing a comparison of the actual deviation between calculated and measured values term by term. The ideal value of *MBE* is ‘zero’. *RMSE* provides information on the short-term performance. The value of *RMSE* is always positive, representing ‘zero’ in the ideal case. The smaller the value of t is, the better the performance of the model. In order to determine whether a model’s estimates are statistically significant, one simply has to determine a critical *t* value obtainable from standard statistical tables, i.e., $t_{\alpha/2}$ at the level of significance and *(k-1)* degrees-of-freedom. For the model’s estimates to be judged statistically significant at the 1-α confidence level, the calculated *t* value must be less than the critical *t* value (Stone, 1993).

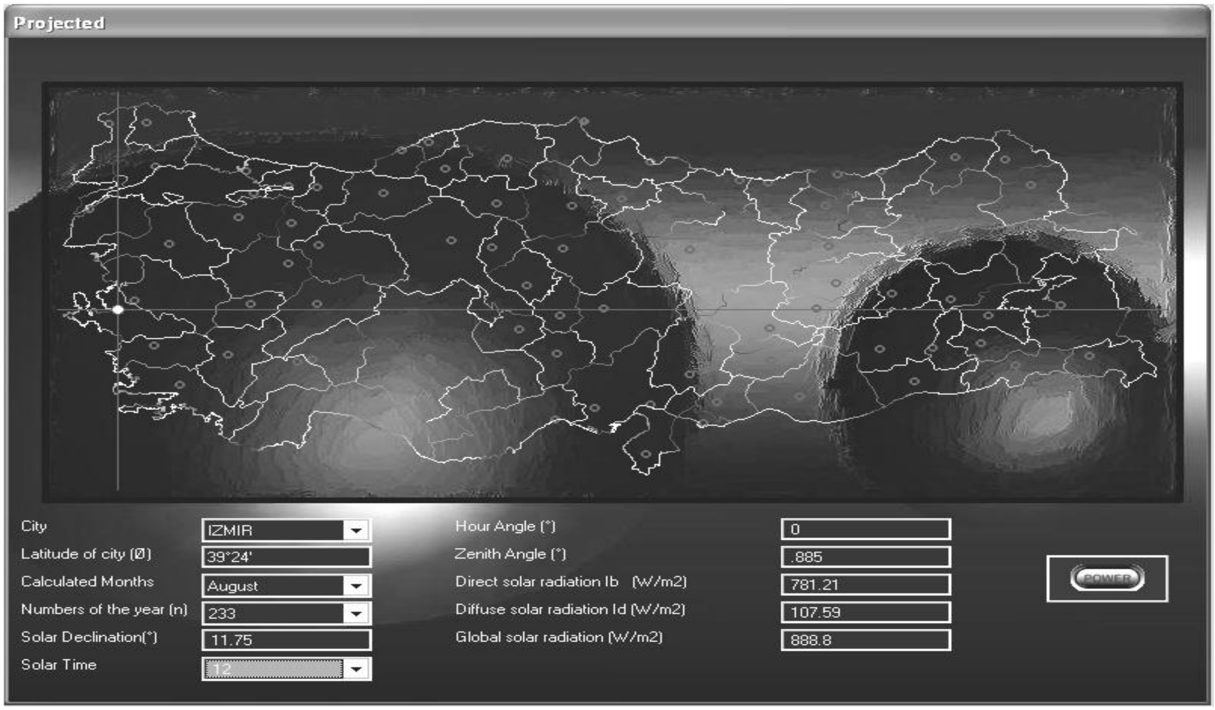

Figure 1. Print screen view of visual basic computer program

RESULTS AND DISCUSSION

The values of the ASHRAE model and measures of the hourly clear sky solar radiation *(I)* on the horizontal surface are given in Figures 2-5 for the winter, spring, summer and autumn seasons respectively.

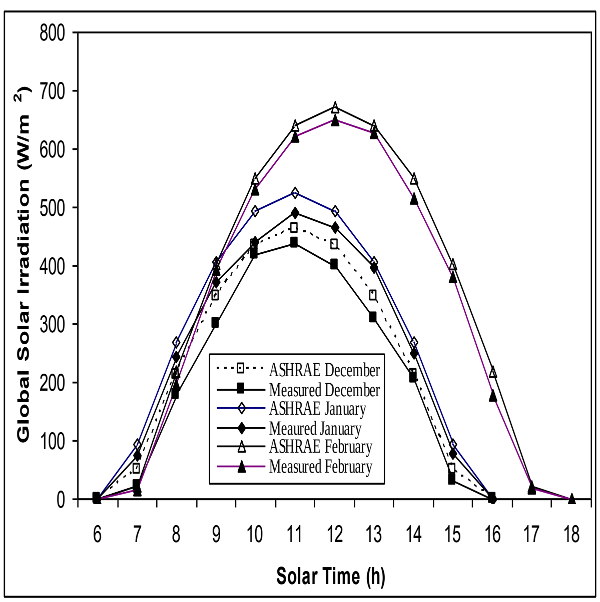

Figure 2. The values of the ASHRAE model and measures of the hourly clear sky solar radiation (I, Wm^{-2}) on the horizontal surface for the winter season

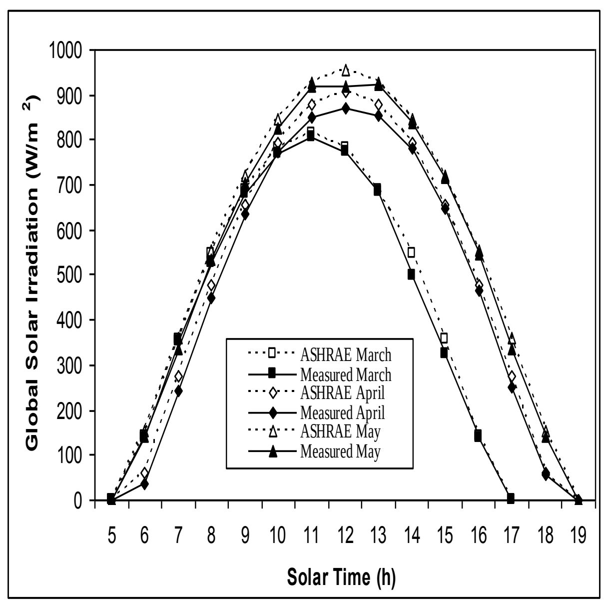

Figure 3. The values of the ASHRAE model and measures of the hourly clear sky solar radiation (I, Wm^{-2}) on the horizontal surface for the spring season

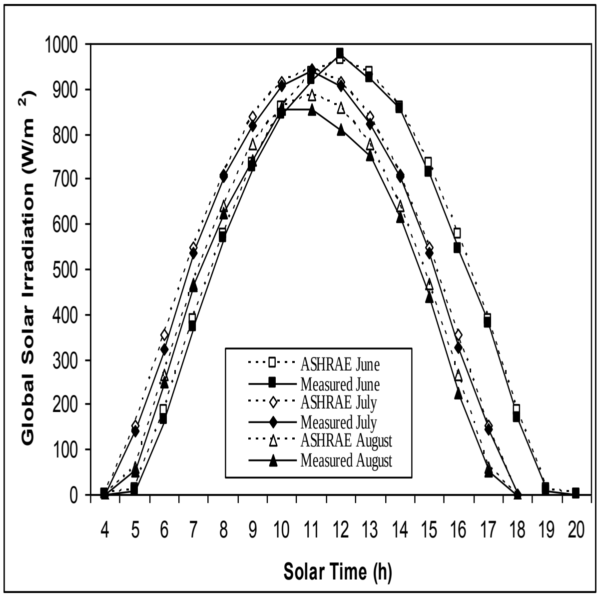

Figure 4. The values of the ASHRAE model and measures of the hourly clear sky solar radiation (I,Wm^{-2}) on the horizontal surface for the summer season

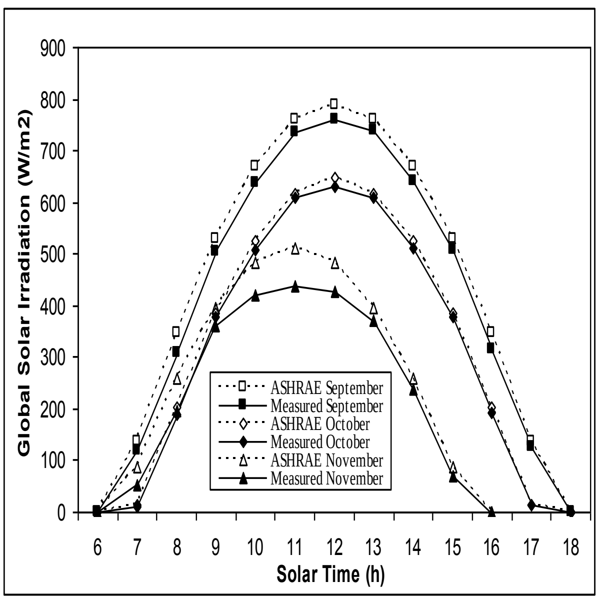

Figure 5. The values of the ASHRAE model and measures of the hourly clear sky solar radiation (I,Wm^{-2}) on the horizontal surface for the autumn season

The new model is developed by taking sum of sin functions and given below.

$$I = 2099\sin(0.006751\theta_z + 2.529) + 59.93\sin(0.078040\theta_z - 2.14) \quad (19)$$

Eq. (19) is obtained by curve fitting procedure in MATLAB as shown in Fig. 6.

The values of the proposed new model and measures of the hourly clear sky radiation *(I)* on the horizontal surface are given in Figures 7 and 8 for months of December-May and June-November respectively.

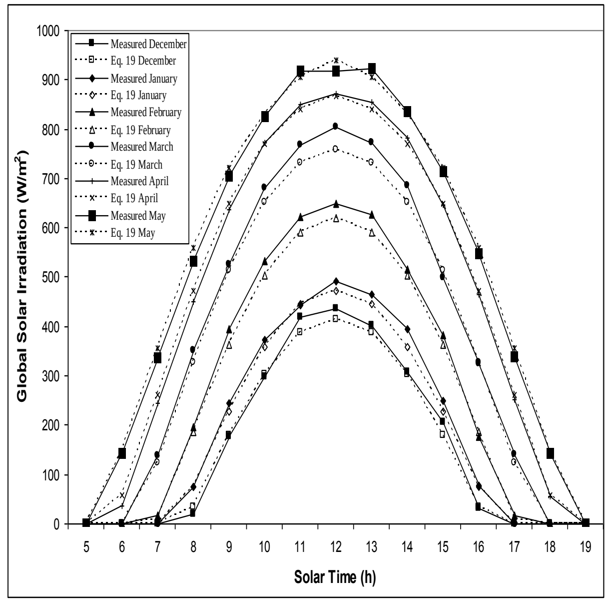

Figure 7. The values of the proposed new model (Eq. 19) and measures of the hourly clear sky solar radiation (I,Wm^{-2}) on the horizontal surface for months of December-May

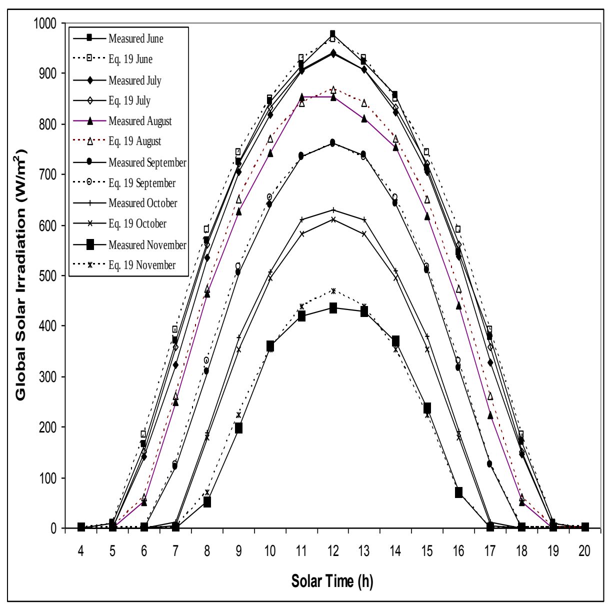

Figure 8. The values of the proposed new model (Eq. 19) and measures of the hourly clear sky solar radiation (I,Wm^{-2}) on the horizontal surface for months of June-November

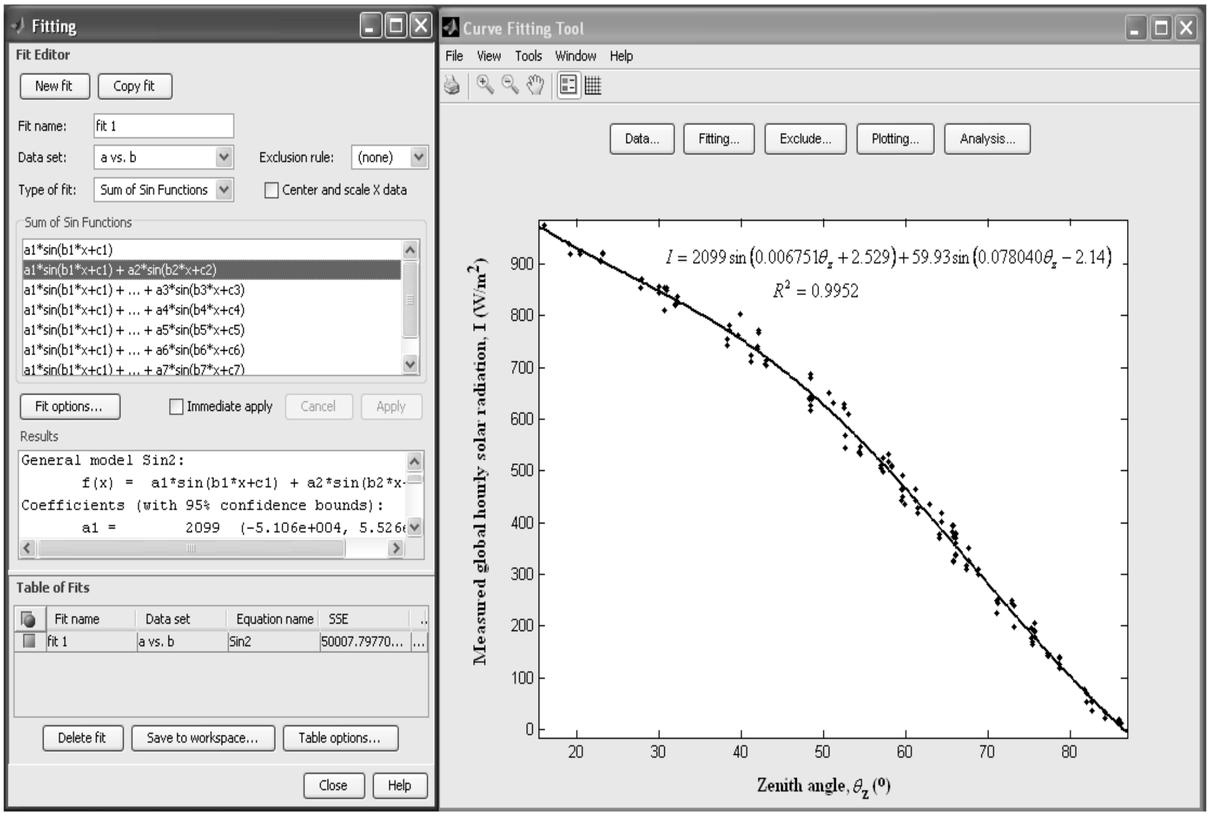

Figure 6. Measured global hourly solar radiation against zenith angle for clear sky

The values of calculated global hourly solar radiation based on ASHRAE model, existing models in the literature and proposed new correlation are compared with measures and given in Figures (9-12) for months of January, April, July and October respectively.

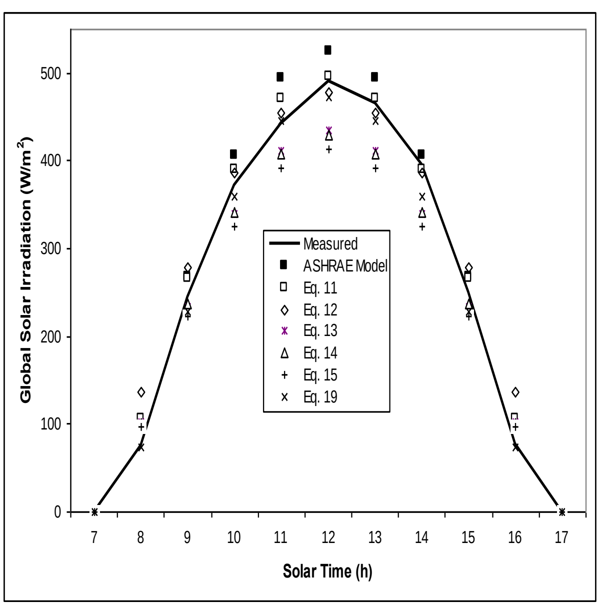

Figure 9. The values of the models and measures of the hourly clear sky radiation on the horizontal surface in the month of January

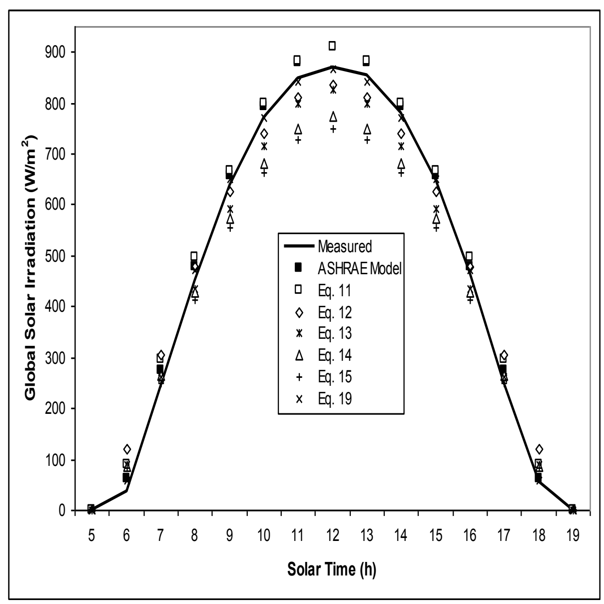

Figure 10. The values of the models and measures of the hourly clear sky radiation on the horizontal surface in the month of April

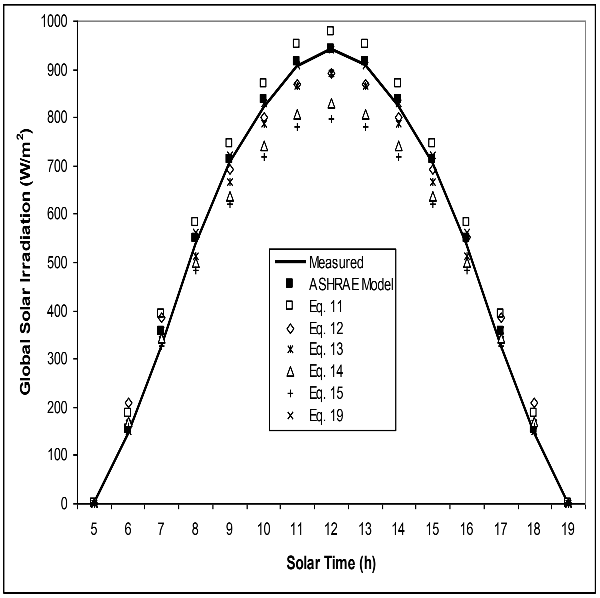

Figure 11. The values of the models and measures of the hourly clear sky radiation on the horizontal surface in the month of July

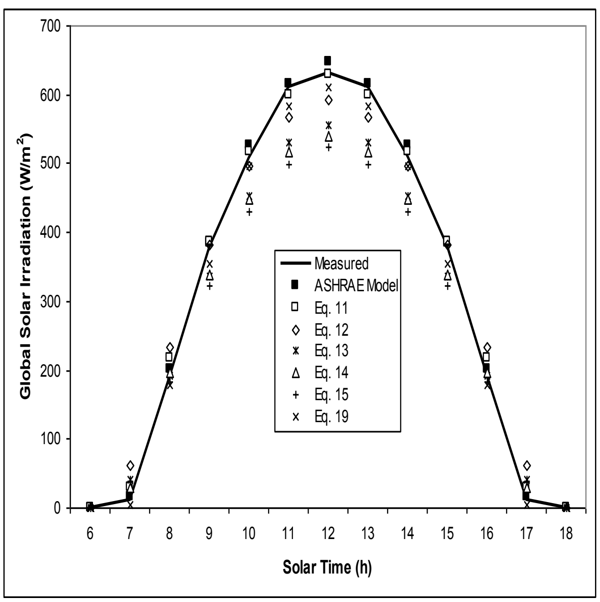

Figure 12. The values of the models and measures of the hourly clear sky radiation on the horizontal surface in the month of October

The values of calculated *MBE*, *RMSE* and *t-stat* based on ASHRAE model, existing model in the literature and proposed new correlation are given in Table 2.

Table 2. Values of calculated *MBE, RMSE* and *t-stat* *(t-critic=2.576 for α=0.01 and k=138)*

Models	*MBE*	*RMSE*	*t-stat*
ASHRAE Model- (Eqs. 1-10)	19.66	24.15	16.40
Model I- (Eq. 11)	30.17	36.54	17.13
Model II- (Eq. 12)	10.43	42.60	2.95
Model III- (Eq. 13)	-22.99	43.04	7.39
Model IV- (Eq. 14)	-37.26	61.69	8.87
Model V-(Eq.15)	-52.54	76.18	11.15
Model VI- Author's approximation (Eq.19)	**0.7**	**19.05**	**0.43**

From the result of Table 2, it is seen that, the new correlation (Model VI) yield better results in the terms of *MBE*, *RMSE* and *t-stat* for Izmir.

CONCLUSIONS

Several meteorological parameters data for the Izmir province in Turkey have been obtained, investigated and analyzed.

Applicability of ASHRAE clear sky model results twenty-first day of each month. For the other days of year A, B and C constants must be carried out by linear interpolation.

It must be taken into consideration that the results of new model calculation are clear sky day and incident maximum solar radiation to the surface. Therefore, these values cannot be used for the solar energy water heating system directly.

In this study, existing correlations in the literature and new model developed by author are tested against experimental results and it is found that the new model predicts the values of global clear sky solar radiation as a function of zenith angle for Izmir in Turkey better than available models. Furthermore, until solar radiation is measured in more stations, the suggested relation can be applied to any site in Izmir province.

It is also expected that the models developed here will be very helpful to solar engineers, architects, agriculturists and hydrologists dealing with the many applications of solar energy in estimating the horizontal solar radiation for the cities and possibly elsewhere with similar climatic conditions.

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