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Prediction of the daily global solar irradiance received on a horizontal surface -New approach

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Abstract:- A general distribution function q (t) W/m^{2}for clear days is suggested to predict the global solar irradiance incident on a horizontal surface as a function of the local day time and the maximum daily value of the incident solar irradiance q_{max}. Moreover, the authors suggested a form to express q_{max}in terms of the solar constant. The value of the solar constant is also adjusted to its variation with the distance between earth and the sun.

This is done to get a complete theoretical expression for q (t) rather than semi- empirical formulae introduced in previous trials. Comparison between the computed values according to the introduced theoretical formula of q (t) and the corresponding published experimental data recorded in Barcelona(Spain) , Hong Kong (China), Cairo(Egypt), Makkah ,Jeddah(Saudi Arabia) is made.Good fitting is obtained except for few extreme points.

Keywords:- Prediction of solar irradiance, Daily global solar radiation, Solar distribution function for clear days, Computation on theoretical basis of $q_{max.}$.

I. INTRODUCTION

The prediction of the global solar radiation incident on a horizontal surface is important in solar energy exploitation. For example, the performance of a solar cell is a function of the received incident solar irradiance(defined as : the radiant energy received by unit area of a surface normal to the pencil of solar rays per unit time W/m^2) . Several attempts have been made to predict the daily values of the global solar irradiance q(t) W/m^2, where " t " is the local day time in with different degrees of fitting accuracy . (El-Adawi*et.al*.,1986) introduced a power expression in terms of $|t-t_r|$ with parameters t_r(sunrise), t_d (the length of the solar day), t_s (sunset). Good fitting was obtained between experimental and corresponding calculated values with maximum error ≈11%. In such a trial the authors suggested an expression to estimate the value of q_{max}in terms of a solar constant. (Shalaby, 1994) expressed q(t) as a polynomial in $|t-t_0|$with a certain correction factor F(t) and parameters t_r,t_s,t_0,t_d . Where $t_0=(t_s-t_r)/2=t_d/2$. Computations revealed that the relative error did not exceed 16%. (El- Adawi*et.al*.andNuaim, 2001)introduced an expression of q(t) as a polynomial in(t/t_d) with a correction factor sin(π t/t_d)with maximum error 15% . (El- Adawi*et.al*. ,2002)expressed q(t) as a polynomial in(t/t_d) with a correction factor in terms of t_0,t_d. Maximum relative error 12 % was obtained. The evaluation of the q_{max} in terms of the solar constant is also suggested in(El- Adawi, 2002). Noticing that the suggestion to estimate the value of q_{max} in terms of the solar constant in the previous trials was not tested through any concrete computations. While semi-empirical formulae are introduced in which q_{max} is taken as an experimental input.

The present trial represents an approach to the problem of evaluation of the average global solar irradiance incident on a horizontal surface .The suggested formula is an exponential function in time. The aim of the trial is to get better fitting with the experimental data. Moreover, q_{max} in terms of the solar constant is estimated theoretically in order to have a closed system.

II. THE SUGGESTED MODEL

The experimental measurements for the considered distribution q(t) ,W/m^{2}for clear sky(El-Adawi et al.,1986; Shalaby , 1994; Quraishee, 1969 ; Munroe, 1980 ; Tiwari, 1997 ; Leung, 1980 ; Villarrubia et al. 1980; El-Bar, 1983; EL-Gendi, 1983; Katsoulis and Parachistopoulos, 1978; Khogali and Ramadan, 1982; Harty et al.,1999; Cooper, 1969)show a symmetrical distribution that passes through a maximum value q_{max} at the midday time " $t_0=t_d/2$ "between sunrise " t_r" and sunset " t_s" in hours .In the present trial ,the distribution function q(t) ,W/m^2 for the hourly daily global irradiance received on a horizontal surface is such that, it satisfies the following conditions :

at $t= t_r$ $q(t_r)=0$ (1)
at $t= t_s$ $q(t_s)=0$ (2)

at $t= t_0$ $q(t_0)=q_{max.}$ (3)

att= t_0 $\frac{\partial q(t)}{\partial t}\Big|_{t=t_0} = 0$ (4)

The suggested distribution is in the form:

$q(t)= q_{max}\, e^{-\frac{(t-t_0)^2}{(t_s-t)(t-t_r)}}$ (5)

This form satisfies the above mentioned conditions(equations 1-4).

The length of the solar day is given as (Duffieeand Beckman 1974; Cooper, 1969):

$t_d=\frac{12}{15}\cos^{-1}(-\tan\varphi\tan\delta)$(6)

where:

Latitude φ , is the angle made by the radial line joining the given location to the center of the earth with its projection on the equatorial plane.

The solar declination angle δ , is the angle between the line joining the centers of the sun and the earth and its projection on the equatorial plane , is given as:

$\delta=23.45\sin 360\left(\frac{284+n}{365}\right)$ (7)

($1\leq n\leq 365$) starting from 1 January.

Where n is the day of the year.

Following (El-Adawi et al., 1986; El-Adawi, 2002; Wieder, 1982; Kondratyev, 1969)we can suggest the estimation of q_{max} in terms of the solar constant to be in the form:

$q_{max}= \alpha\, s'$ (8)

where:

s' is the extraterrestrial solar constant adjusted for the variation of the distance between the sun and the earth and along the time of the year, given as (Tiwari, 1997)

$s' = s\left(1+0.033\cos\left(\frac{360+n}{365}\right)\right)$(9)

Where:

S =1353(Rai, 1989) is the solar constant .

$\alpha=\frac{(\Upsilon^+-\Upsilon^-)}{(1+G)(\Upsilon^++A-BR)}e^{\Upsilon^-\tau}\mu_0$ (10)

$\gamma^{\pm}=\frac{1}{2}(C-A)\pm\frac{1}{2}[(C-A)^2-4BD]^{\frac{1}{2}}$ (11)

$A=\frac{2-\omega_0}{2\mu_0}$ (12)

$B=\omega_0$ (13)

$C= 2-\omega_0$ (14)

$D=\frac{\omega_0}{2\mu_0}$ (15)

$\omega_0=\frac{\tau^s}{\tau}$ where τ^s and τ are the optical thickness due to scattering and total optical thickness (scattering and absorption) .

$G=-[\frac{\Upsilon^-+A-BR}{\Upsilon^++A-BR}]e^{(\Upsilon^--\Upsilon^+)\tau}$ (16)

R is the reflectivity of the underlying terrain ,

$\mu_0=\cos Z$ (17)

$Z = \left| D' - L' \right|$ (18)

Z is the solar zenith angle and D' is the solar codeclinations which is the complementary angle of the declination, L' is the observer colatitudes which is the complementary angle of the latitude.

III. COMPUTATION

In the following q_{max} is computed according to equation (8) for Jeddah and Makkah only because the day of the year is available to the authors for these two cities .Computations are made at R=0.4 (Hrens , 2006), ω_0=0.5 (El-Adawiet al.,1986).Moreover,t_d =18.5hr for Jeddah and t_d =18.66 hr for Makkah. The obtained c-omputed values are as follows :

q_{max}(Jeddah)=856.8W/m^2, while the experimental value is 915 W/m^2 with relative error 6% ,and

q_{max}(Makkah)=878W/m^2 ,while the experimental value is 938 W/m^2 with relative error 6%.

These two values of q_{max} that are computed theoretically are inserted in equation (5) to fit the corresponding published experimental data for Jeddahand Makkah. The obtained results are illustrated in figures (1) and(2) respectively. We considered the published experimental values of q_{max} for Hong Kong ,Barcelona and Egypt in fitting process to compute the corresponding q(t) for such cities, since the day number is not available for the authors. The computed values of q(t) are compared with the corresponding experimental values. The obtained results for Hong Kong, Barcelona and Egypt are illustrated graphically in Figures(3-11).

As a measure to the degree of fitting , the percentage relative error defined as $\left| \frac{q_{\exp} - q_{cal}}{q_{cal}} \right|$ is computed for each point for the corresponding curve .

IV. RESULTS AND DISCUSSION

The comparison between the published experimental data and the corresponding calculated values obtained using eq.(5) are illustrated graphically in Figures(1-11).The results show that, bad fitting is obtained usually at the extreme points of the distribution near sunrise and sunset hours where the level of solar isolation is not effective for practical exploitation of solar energy .

This situation is attributed to the fact, that the model is oriented to clear sky. While several parameters affect such distribution function such as sunshine hours ,the declination angle, the latitude ,the altitude ,the relative humidity (Quraishee, 1969; lin and Jordan, 1960; Sharma and Pal , 1965).It is also a function of such variables as the nature and the extent of cloud cover , the aerosol and water vapor content of the atmosphere (Munroe, 1980) .As a result some experimental points give large relative error such as the point indicated in figure (4) with relative error 81%.Other than the extreme points the obtained relative errors are within 16% .This indicates that the suggested formula to calculate the daily hourly solar irradiance is acceptable.

V. CONCLUSIONS

The comparison between the predicted global solar radiation q (t) W/m^2 incident on a horizontal surface and the corresponding experimental data shows in general satisfactorily agreement for points other than the extreme points(~16%). The advantages of the introduced model is that q(t) is given in terms of well established parameters such as the length of the solar day t_d and t_0=t_d/2 for symmetrical distribution. Moreover q_{max}can be estimated in terms of the solar constant adjusted for the variation of the distance between the sun and the earth along the time of the year .This means that the trial represents a closed theoretical system to evaluate the incident daily global solar radiation.

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Global solar radiation intensity (W/m^2) received on a horizontal surface in Jeddah on (9/4/1982) located at 40̊ 25` E, 41̊ 23 `N (El-Bar, 1983)

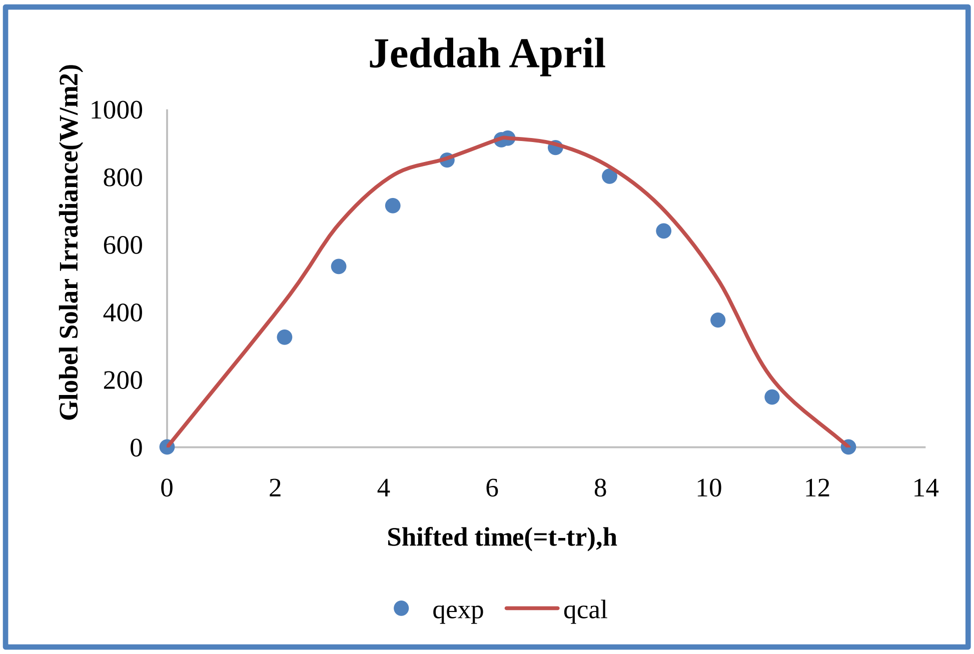

Fig.1.Experimental and calculated data for Jeddah April

(The maximum relative error equals to 12%)

Global solar radiation intensity (W/m^2) received on a horizontal surface
In Makkah on (9/4/1982) April located at 38.5 °E, 21.5°N (EL-Gendi, 1983)

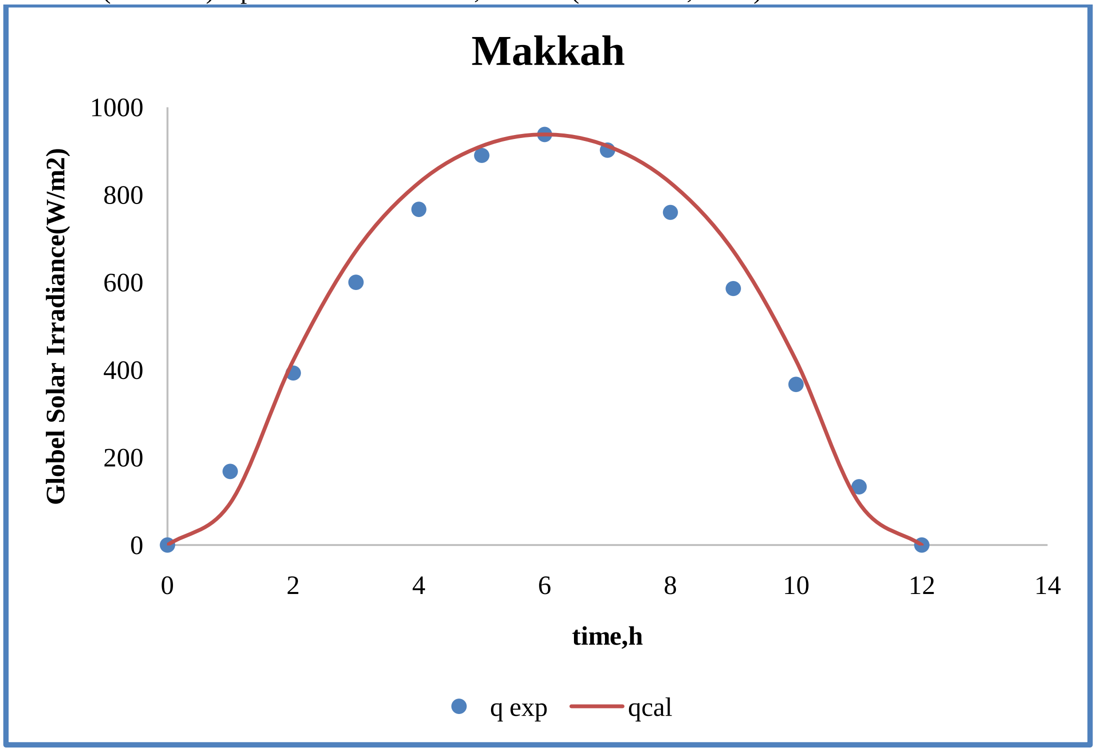

Fig.2. Experimental and calculated data for Makkah, April
(The maximum relative error equals to 10%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Hong Kong on December (1979) located at 114̊ 10`E, 22̊ 19` N (Leung, 1980)

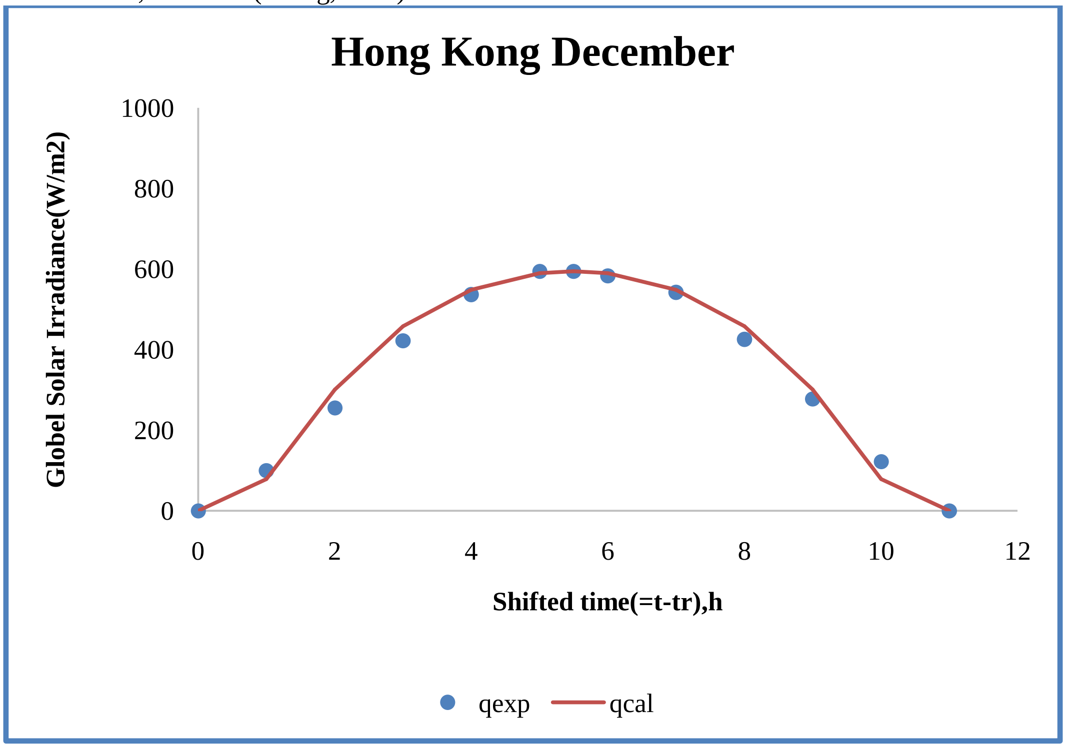

Fig.3. Experimental and calculated data for Hong Kong, December
(The maximum relative error equals to 9%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Hong Kong on November (1979) located at 114° 10`E, 22° 19` N (Leung, 1980)

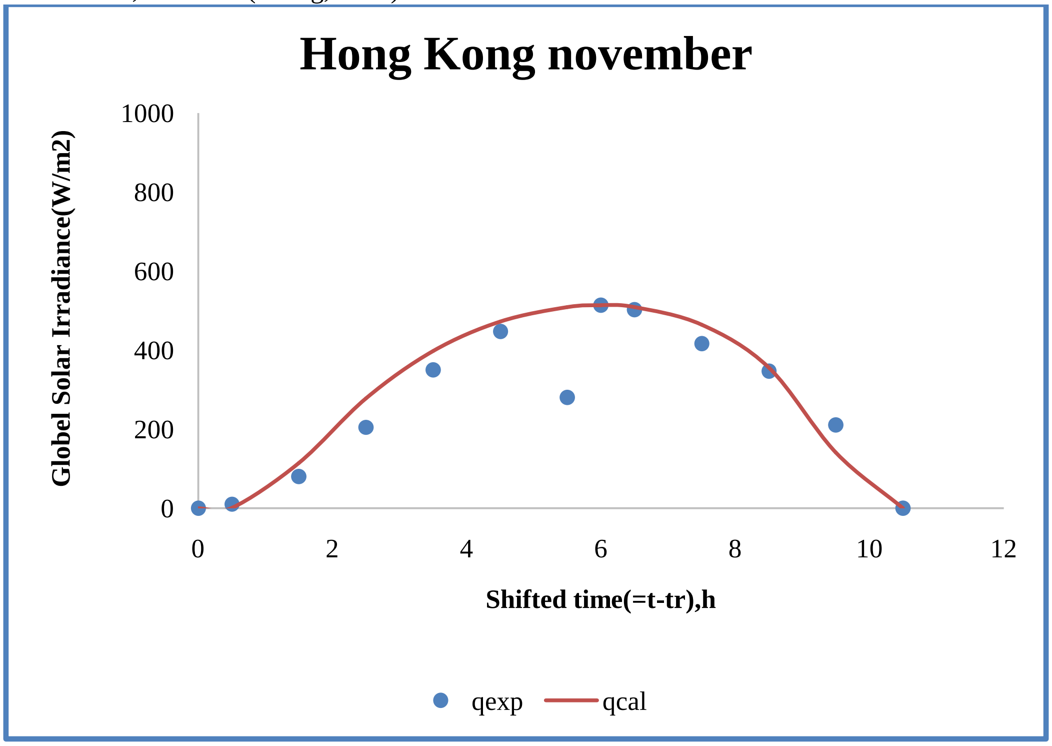

Fig. 4.Experimental and calculated data for Hong Kong, November
(The maximum relative error equals to 28%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Hong Kong on January (1979) located at 114° 10`E, 22° 19` N (Leung, 1980)

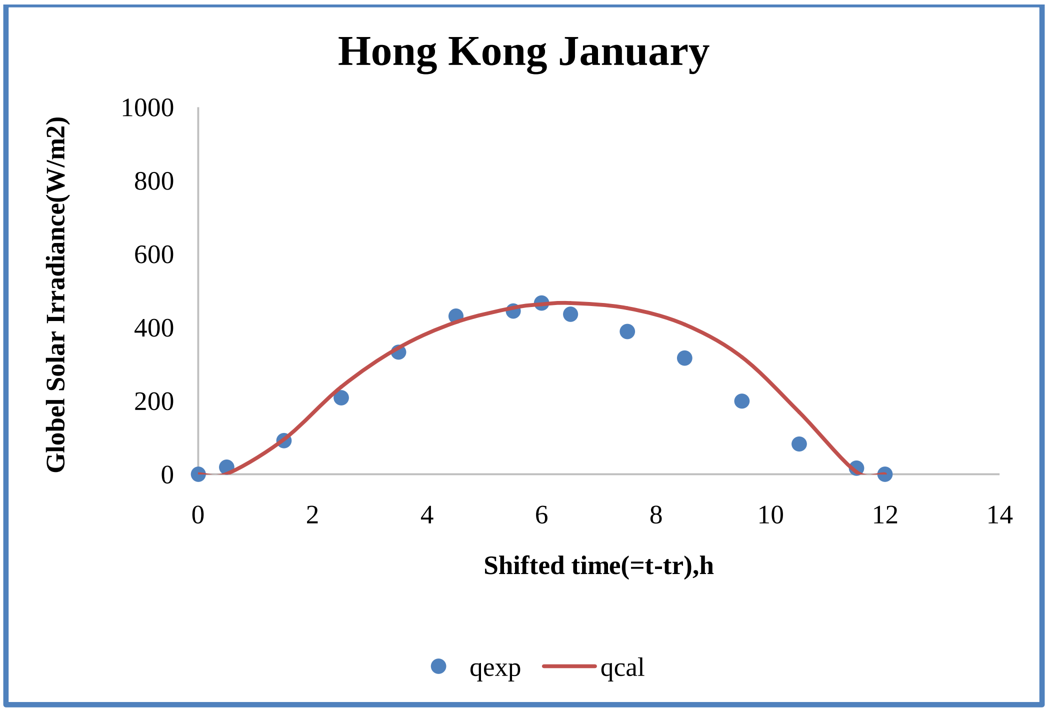

Fig.5.Experimental and calculated data for Hong Kong, January
(The maximum relative error equals to 28%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Hong Kong on April (1979) located at114° 10 `E, 22° 19`N (Leung, 1980)

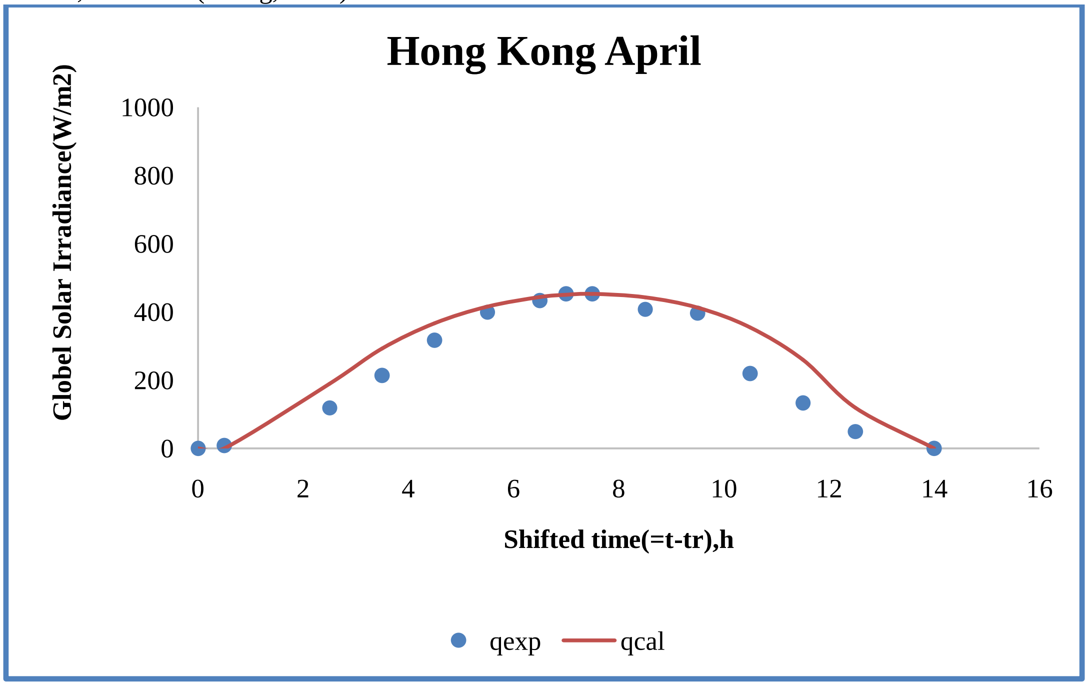

Fig.6.Experimental and calculated data for Hong Kong, April
(The maximum relative error equals to 35%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Barcelona on December (1973-1975) located at 2° 7` E, 41̊ 23` N (Villarrubia et al., 1980)

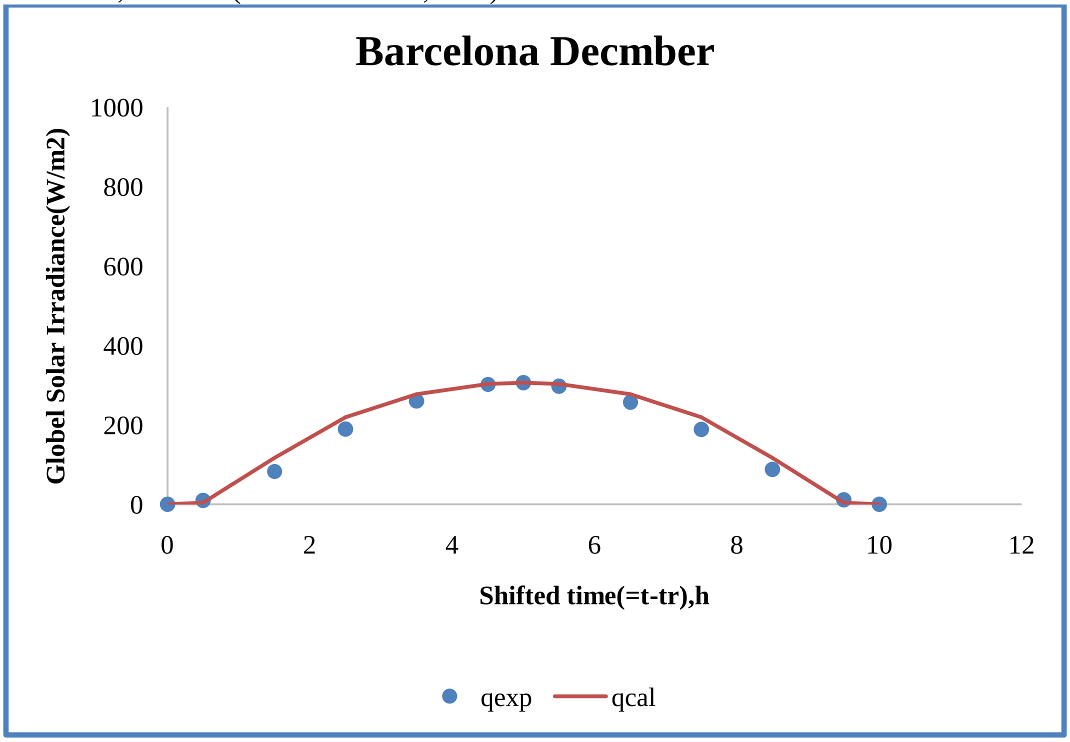

Fig. 7.Experimental and calculated data for Barcelona, December
(The maximum relative error equals to 21%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Egypt (Cairo) on July (1980) located at 23̊ 58` N (Cairo, 1980)

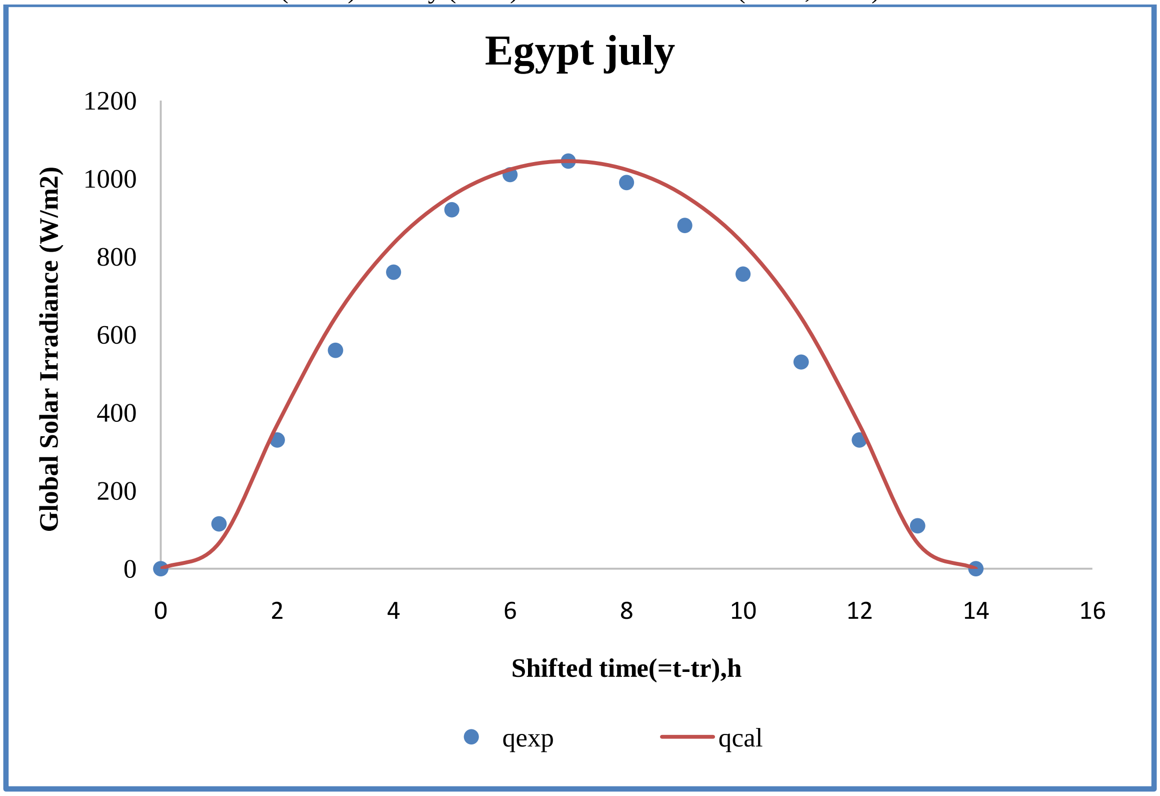

Fig.8.Experimental and calculated data for Egypt, July
(The maximum relative error equals to 11%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Egypt(Cairo) onMarch (1980) located at 23̊ 58` N (Cairo- Al-Ahram, 1980)

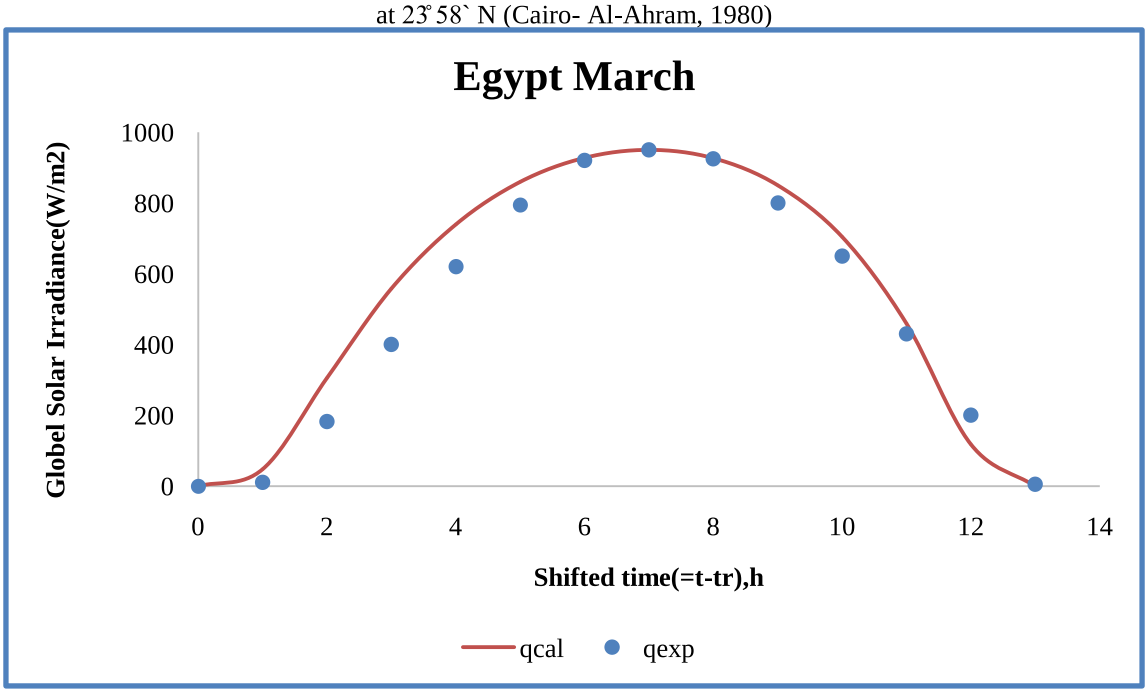

Fig. 9. Experimental and calculated data for Egypt, March
(The maximum relative error equals to 20%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Egypt (Cairo) on June (1980) located at 23̊ 58` N (Cairo- Al-Ahram, 1980)

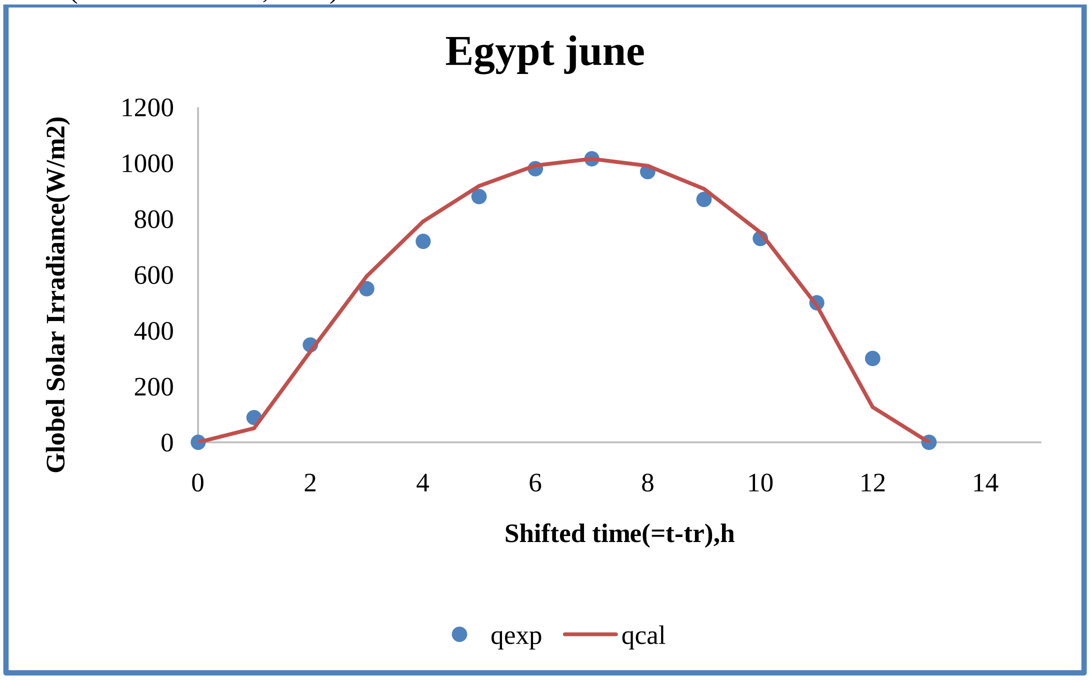

Fig. 10. Experimental and calculated data for Egypt, June
(The maximum relative error equals to 12%)

Global solar radiation intensity (W/m^2) received on a horizontal surface in Egypt (Cairo) on September (1980) located at 23̊ 58` N (Cairo- Al-Ahram, 1980)

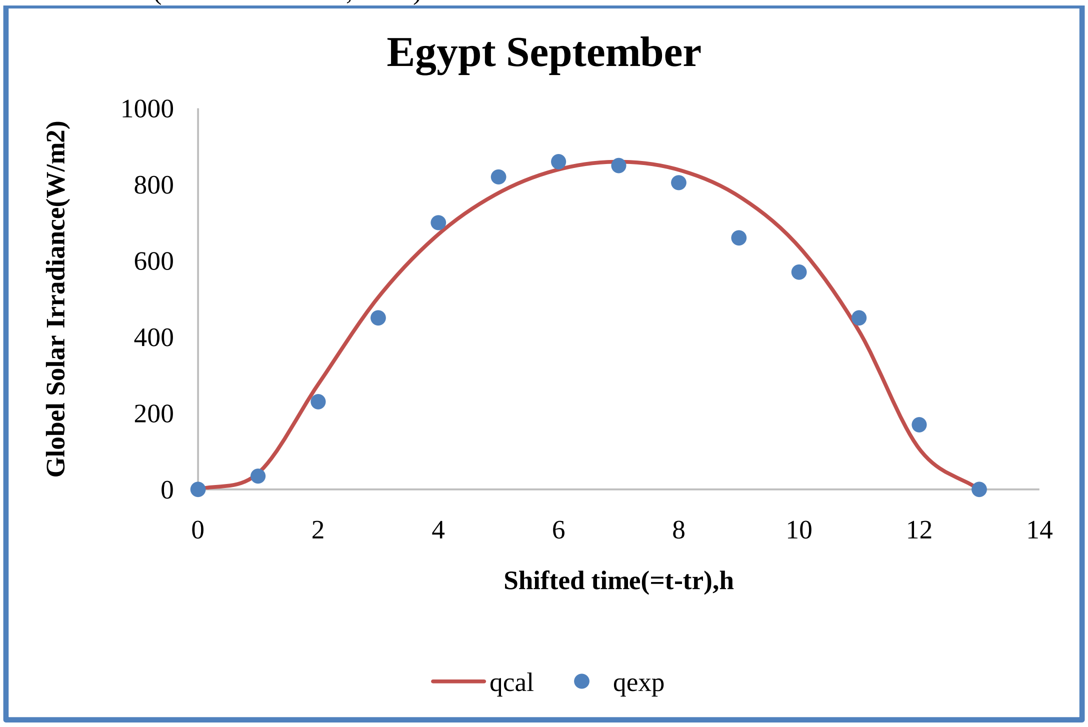

Fig. 11. Experimental and calculated data for Egypt, September
(The maximum relative error equals to 11%)