

The analysis of the characteristics of the solar radiation climate of the daily global radiation and diffuse radiation in Amman, Jordan

Mohammed Awwad Ali Al-Dabbas

faculty of engineering / mechanical department Mutah university
Mutah-Karak-Jordan
P.O.Box:(7), Zip code:(61710)
Mobile:00962-795580449 Fax:00962-3-2375540
E-mail: madabbas@yahoo.com

ABSTRACT

The global and diffuse solar radiation on the horizontal surface at Amman-Jordan during the period from January 2008 to December 2008 is analyzed and presented in this paper. The annual mean of the daily global and diffused solar radiation is about 20.3875MJ/m² and 4.5 MJ/ m² respectively. On yearly average basis the percentage frequency of cloudily days ($K_T < 0.30$) is quite low, namely 9.5%, whereas that for clear days is quite high ($K_T > 0.70$) 52.6% the average monthly clearness index varies from 0.757 in January to 0.564 in December while the average monthly diffuse fraction ranges between 0.320 in January and 0.163 in July. The highest fraction of the days radiation was observed in the moderate radiation period (9-11+13-15) and confined between 51% in winter and 37% in summer.

Keywords: Hourly diffuse, Solar radiation; Clearness index, Daily global; Amman-Jordan

TERMONOLOGY

G_{on} : Extraterrestrial radiation

N: number of day in the year.

ϕ : Latitude

δ : Declination

ω : Hour angle

N: number of the day light hours

ω_s : Sun set hour angle

H: monthly global average of daily solar radiation

H_d : monthly diffuse average of daily solar radiation

H_o : daily extraterrestrial radiation on horizontal surface

I: monthly average global of hourly solar radiation.

I_d : Monthly average diffuse of hourly solar.

n : monthly average daily hours of bright sunshine.

r_1 : Ratio of hourly to daily global radiation

r_d : Ratio of hourly to daily diffuse radiation

K_d : diffuse fraction of global radiation

K_T : Monthly average of daily clearness index

Introduction

Knowledge of the incoming solar radiation is a fundamental importance for all of the solar energy researches and development programs. They are being undertaken in various countries. Actually daily radiation on horizontal surface is measured at most recording stations. However the mean daily radiation is not always the most appropriate figure to characterize the potential utility of the solar energy utilization system while designing solar energy system. One also needs to know radiation values at hourly interval hourly values of solar radiation allow us to derive very precise information about the performance of the solar energy system. We can get specific knowledge about the climatology parameter, the global and diffuse solar radiation. They are of vital importance as forcing functions for climate and supplement to the more conventional and non renewable sources of energy. Hence detailed studies of daily and hourly solar radiation under local conditions have been carried out in various places.

In this paper, the monthly average of daily total of extraterrestrial radiation global radiation and diffuse radiation in Amman are analyzed. In additions seasonal variation are discussed. Also the monthly average global and diffuse radiation for each hour of the day between 4a.m and 7a.m are presented and studied. A frequency histogram of the clearness index and diffuse fraction of global radiation are also presented and discussed.

Literature review

The importance of knowing the temporal and spatial variations of diffuse solar- radiation has been explored in several papers [1–2]. However, solar-radiation data are frequently available from only a few stations and over short periods of time. An alternative procedure to obtain solar-radiation data is using numerical modeling, but the main problem is the need for an appropriate representation of cloud effects [3]. These problems are particularly severe in tropical regions, like london, where cloud activity is a dominant feature of local climate and the solar metric network is sparse with most of the stations located in urban areas.

A common alternative is to estimate the diffuse component of solar radiation from empirical relationships derived from statistical analysis of direct and global solar-radiation; temporal series are observed [4-8]. These empirical models are based on the correlation between hourly, daily and monthly values of the clearness index (energy flux received from the Sun over the energy flux received at the top of the atmosphere) and diffuse fraction (diffuse/total solar radiation). The empirical relationships used to estimate the hourly diffuse component of solar radiation are, in general, expressed in terms of nth-degree polynomials which are dependent on latitude, perceptible water-content, atmospheric turbidity, surface albedo, altitude and solar elevation angle [9,10].

Solar Radiation Data Bases

When designing a solar energy system, the best way to predict its energy-production performance would be to know what the minute-by-minute solar irradiance levels will be, over the lifetime of the system, and at the exact location where the system will be built. Since weather patterns are somewhat random in time and place, and are extremely difficult to predict, the system designer is forced to accept historical data, recorded at a different location, with values reconstructed from incomplete data records. Because of the inherent variability of future solar irradiance, however, historical records are an extremely useful analytical tool, appropriate for a wide range of applications. However, the designer must not be deluded to believe that system performance predicted using even the best historical data, will represent the future output of the system.

Clearness Index

Often, solar radiation levels are plotted in order to gain insight into the local region and to permit extrapolation between sites where accurate databases exist. A concept used to normalize these maps, and to present location-specific solar radiation data is the clearness index, $\overline{K_T}$ which is the ratio global

horizontal solar radiation at a site to the extraterrestrial horizontal solar radiation above that site

$$\bar{K}_T = \frac{H_{t,h}}{H_{o,b}} \dots\dots\dots (1)$$

Analytical Models of Solar Irradiance

A Simple Half-Sine Model

Often, a simple analytical model of clear-day solar irradiance, the only input required is the times of sunrise, sunset, the peak; noontime solar irradiance

$$I = I_{noon} \left[\frac{180(t - t_{sunrise})}{(t_{sunset} - t_{sunrise})} \right] \dots\dots\dots (2)$$

where t is the time in hours (24-hour clock), and the sine term is in degrees. Since this model produces negative values after sunset, a logical check for this in programs using this model must be implemented.

Hottel’s Clear-Day Model

The analysis of a solar energy system design is typically initiated by predicting its performance over a "typical" "clear" day. There are a number of clear-day mathematical solar irradiance models that may be used to predict the expected maximum hour-by-hour solar irradiance. An extensive discussion of various solar irradiance models may be found in Iqbal [3].

A simple clear-day direct solar irradiance model by Hottel[11-13], has been selected for presentation here. The Hottel’s clear-day model of direct normal solar irradiance is based on atmospheric transmittance calculations using the 1962 U.S. Standard Atmosphere as follows:

$$I_{b,n} = I_o \left(a_o + a_1 e^{-k \frac{1}{\cos \theta_z}} \right) \dots\dots\dots(3)$$

where I_o is the extraterrestrial radiation and θ_z the solar zenith angle . The term in brackets may be regarded as an atmospheric transmittance for direct radiation. The parameters a₀, a₁, and k are given below for a "clear" and an "urban haze" atmosphere, The three constants in Equation are :

The constants $a_o^* = r_o \cdot a_o^*$, $a_1^* = r_1 \cdot a_1^*$, $k = r_k \cdot k^*$ for a standard atmosphere with a visibility of 23 km can be calculated from the following relationship by assuming that

the observation altitude is less than 2.5 km:

$$a_o^* = 0.4237 - 0.00821(6 - A)^2 \dots\dots\dots(4)$$

$$a_1^* = 0.5055 + 0.00595(6.5 - A)^2 \dots\dots\dots(5)$$

$$k^* = 0.2711 + 0.01858(2.5 - A)^2 \dots\dots\dots(6)$$

where A is the local elevation in kilometers.

For the urban 5-km (3.1-mi.) visibility haze model, the parameters are

$$a_o = 0.2538 - 0.0063((6 - A)^2) \dots\dots\dots(7)$$

$$a_1 = 0.7678 + 0.0010((6.5 - A)^2) \dots\dots\dots(8)$$

$$k = 0.249 + 0.081((2.5 - A)^2) \dots\dots\dots(9)$$

The diffuse solar irradiance on a horizontal surface may be calculated as

$$I_{d,h} = I_o \cos \theta_z \left[0.2710 - 0.2939 \left(a_o + a_1 e^{-k \frac{1}{\cos \theta_z}} \right) \right] \dots\dots\dots(10)$$

CLIMATE REGIONS

The surface radiation methodologies developed and verified in one region of the globe may not produce reasonable results in other climate regions. Issues are (1) predominant cloud types may be different (thicker or thinner), (2) atmospheric aerosols may be more or less absorbing, (3) surfaces may have large differences in albedo, and (4) seasonal wind patterns may transport significant pollutants either in or out of the region. Ignoring regional differences has resulted in surface insolation bias errors as large as 35% [14].

The monthly average clearness index, k, is defined as the monthly average horizontal insolation impinging on the Earth's surface, H, divided by the monthly average incoming top-of-atmosphere horizontal insolation, Ho. The parameter combines total atmospheric transmissivity losses from cloud amount, thickness, and absorption; aerosol absorption and scattering; as well as molecular, ozone, and water vapor absorption. Clearness index is used in a number of energy industry equipment design procedures.

HORIZONTAL DIFFUSE AND SOLAR BEAM DIRECT NORMAL RADIATION

Estimates of horizontal diffuse, H_d , and direct normal radiation, are needed for hardware system design parameters such as solar panel tilt, solar concentrator size, day lighting, as well as agricultural and hydrology applications. There are no known methods of estimating these two parameters over the globe with proven accuracy.

Monthly Horizontal Diffuse Methods

Historic studies [15-23], for example as well as more recent researches indicate that ground site measurements of diffuse radiation are less accurate than once believed to be because of thermodynamic imbalances within some operational instruments if "shadow band" or "shadow disk" techniques are used. Important errors appear to be a function of cloud fraction suggesting daily changes in uncertainty.

The monthly diffuse to monthly horizontal insolation ratio is estimated from cubic polynomial equations in terms of insolation clearness index as follows:

$$H_d = H[1.39 - 3.569 K_T + 4.189 K_T^2 - 2.13 K_T^3] \dots\dots\dots(11)$$

The diffuse to horizontal insolation ratio is estimated as: $\frac{H_d}{H} = [a + (b * k)]$

To characterize objectively the climatic behaviour of the diffuse solar-radiation, this choice was based on the fact that most of the expressions, available in the literature for hourly values, are fourth-degree polynomials allowing a straightforward comparison with previous works.

$$H_d = H[0.90 + 1.1 K_T + 4.5 K_T^2 - 0.001 K_T^3 + 3.14 K_T^4] \quad \text{-----(12)}$$

EXTRATERRESTRIAL RADIATION ON HORIZONTAL SURFACE:-

At any point of time the solar radiation outside the atmosphere incident on a horizontal plane is:-

$$G_o = G_{sc} (1 + 0.033 \cos(\frac{360n}{365})) (\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega) \quad \text{----(13)}$$

where G_{sc} the solar constant, and n is the day by the year and the declination(δ) is:

$$\delta = 23.45 \sin(\frac{360(284+n)}{365}) \quad \text{-----(14)}$$

It is often necessary for calculation of daily solar radiation to have the integrated daily extraterrestrial radiation on horizontal surface H_o . Thus H_o is obtained by integrating equation (2) over the period from sunrise to sunset,

$$H_o = \frac{24 * 3600 G_{sc}}{3.14} (1 + 0.033 \cos(\frac{360n}{365})) (\cos \phi \cos \delta \sin \omega_s + \frac{2 * 3.14 * \omega_s}{360} \sin \phi \sin \delta) \quad \text{----(15)}$$

The monthly mean daily extraterrestrial radiation, \bar{H}_o is useful quantity. For Latitude in the ranges +60 to -60, it can be calculated using equation (3) using n and δ for the mean day of the month. But in this paper we will use month by month basis (i.e calculate H_o , for all days of month then we divide the sum of H_o , over the total number of day of that month).

The monthly average of average of daily solar radiation is calculated as follows:

$$\bar{H} = \bar{H}_o (0.18 + 0.62 \frac{n}{N}) \quad \text{-----(16)}$$

Where n is the sunshine hours and listed in the table (1) while N in the number of daylight hours and given as: $N = \frac{2}{15} \cos^{-1}(\tan \phi \tan \delta) \quad \text{----(17)}$

The monthly average daily global radiation is related to monthly mean daily extraterrestrial radiation as:-

$$\bar{H} = \bar{H}_o (10.18 + \frac{0.62n}{N}) \quad \text{-----(18)}$$

and the ratio H/H_o is termed monthly clearness index \bar{K}_T i.e:-

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_o} \quad \text{-----(19)}$$

the monthly average daily diffuse radiation is related to monthly average daily global radiation as:-

$$H_d = H[1.39 - 4.027 K_T + 5.531 K_T^2 - 3.108 K_T^3] \quad \text{-----(20)}$$

The ratio H_d/H is termed monthly clearness index i.e.:-

$$K_d = \frac{H_d}{H} \quad \text{-----(21)}$$

PREDICTION OF HOURLY RADIATION FROM DAILY DATA

Many of the transient process in solar energy application can be approximate by using long term average of hourly radiation measured values of hourly global and diffuse radiation. But these aren't generally readily available. It is therefore necessary to develop a method for predicting the hourly values from the daily data. The work of Liu and Jordan has held to generalized charts of the ratio of average hourly total to daily total radiation as function of hour relative to solar noon and the day length. Days are assumed to be symmetrical about solar noon and the hours indicated by their mid points, however, in most practical application in engineering and architecture, the effect of the asymmetry of solar radiation around the solar noon are of very minor importance. The method of Liu and Jordan which applies a similar approach to that followed by whiller in cltimating the average hourly global radiation, appears adequate and quite accurate as far as the predictions of diffuse radiation is concerned.

$$r_d = \frac{\text{hourly diffuse radiation}}{\text{daily diffuse radiation}}$$

$$r_d = \frac{3.14}{24} \left[\frac{\cos\left(\frac{\omega}{57.3}\right) - \cos\left(\frac{\omega_s}{57.3}\right)}{\sin\left(\frac{\omega_s}{57.3}\right) - \frac{3.14}{180} * \omega_s * \cos\left(\frac{\omega_s}{57.3}\right)} \right] \text{-----(22)}$$

ω_i is the hour angle in degree(to the hour mid-point)and ω_s is the sunset hour angle, which is given by:- $\omega_s = \cos^{-1}(- \tan \phi \tan \delta)$ ------(23)

In further investigation by collares -pereia and rabi new data were combined with the earlier results to produce the plots of r_t and r_i is given by:-

$$r_t = \frac{\text{hourly global radiation}}{\text{daily global radiation}}$$

$$r_t = \frac{3.14}{24} \left[\left[a + b \cos\left(\frac{\omega}{57.3}\right) \right] - \left[\frac{\cos\left(\frac{\omega}{57.3}\right) - \cos\left(\frac{\omega_s}{57.3}\right)}{\sin\left(\frac{\omega_s}{57.3}\right) - \frac{3.14}{180} * \omega_s * \cos\left(\frac{\omega_s}{57.3}\right)} \right] \right] \text{.....(24)}$$

RESULT & Discussion

Histogram of frequencies of clearness index and diffuse fraction of global radiation.

Because of the variability of the weather, the distribution of solar radiation is mostly irregular, both in time and in space. Therefore, the clearness index K_T and the diffuse fraction of global radiation K_d are useful under average condition as measure of cloudiness and other atmospheric constituents which attenuate the solar radiation. A study of the percentage frequency distribution of K_T , K_d is also important since it gives us information about the percentage frequency to have clear or cloudy days. For this purpose we have calculated on daily basis, the ratio of K_T and K_d from measured data of global radiation, diffuse radiation, and estimate value of extraterrestrial at Amman. Then, the percentage frequency of K_T and K_d have been determined and are shown in figures (1a-1d)

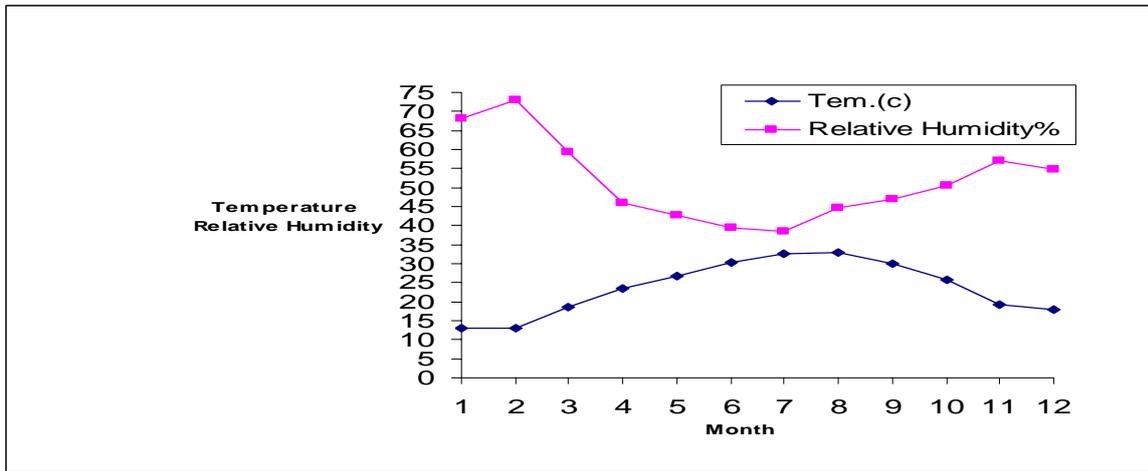


Figure 1a: Temperature & Relative Humidity of Amman city in 2008

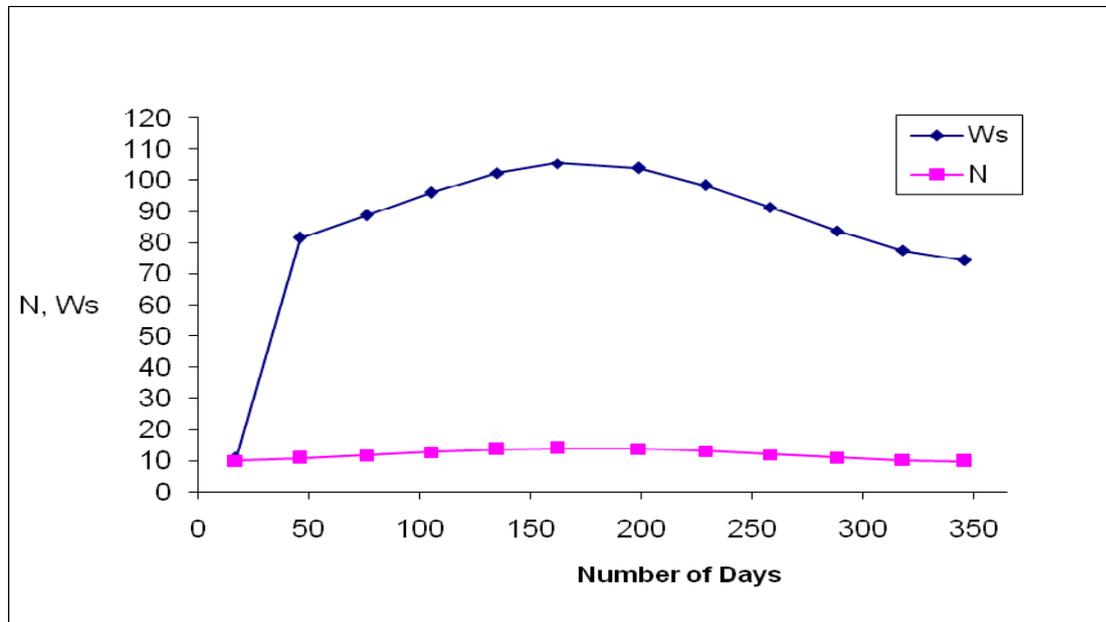


Figure 1b : Number of the day light hours & sun set hour angle in Amman city in 2008

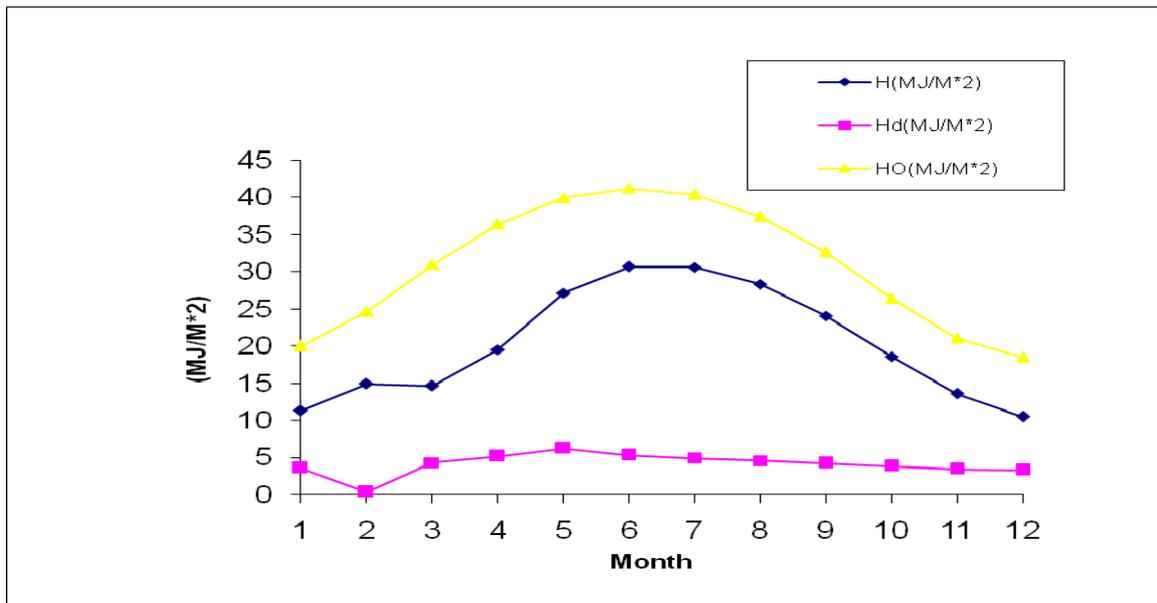


Figure 1c: The solar incident radiation in Amman city in 2008

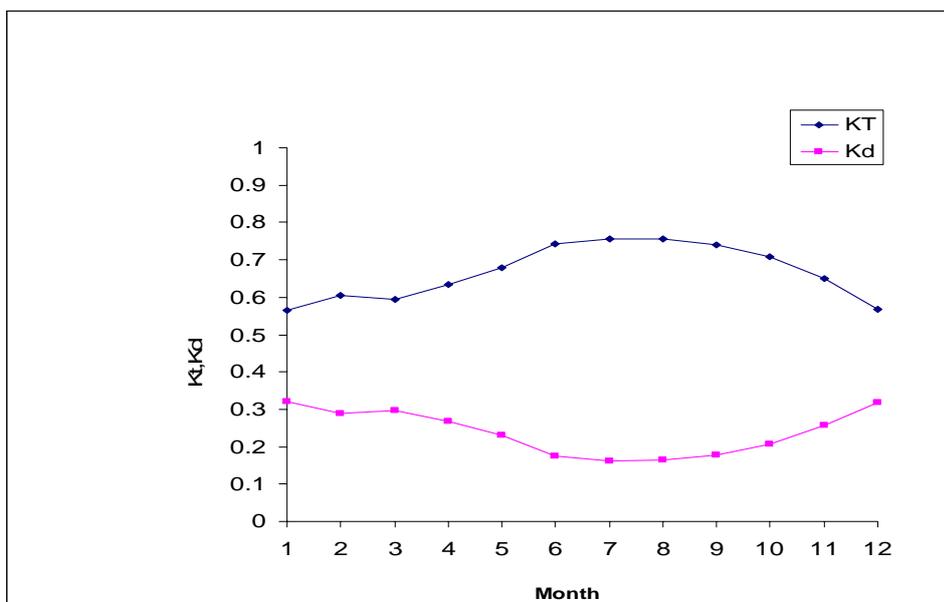


Figure 1d: Monthly average of daily clearness index , diffuse fraction of global radiation(Kt & Kd)

MONTHLY VARIATION OF GLOBAL AND DIFFUSE RADIATION

The monthly average of daily global radiation, diffuse radiation and the extraterrestrial radiation on horizontal surface are shown in figure (2a). The annual mean of daily global and diffuse radiation at Amman is about $20.387 \text{ MJ}/\text{m}^2$, $4.5 \text{ MJ}/\text{m}^2$, with seasonal variation from $10.57 \text{ MJ}/\text{m}^2$ for global radiation and $3.362 \text{ MJ}/\text{m}^2$ for diffuse radiation in mid-winter to $30.74 \text{ MJ}/\text{m}^2$ for global radiation and $6.31 \text{ MJ}/\text{m}^2$ for diffuse radiation in mid summer.

The summer period (April-September) contributes about 75.7% of the annual means of daily global and diffuse radiation. December contributes, the least, being responsible for only about 56.4% of the annual global and diffuse radiation [24-26].

Figure 2b show a plot of monthly average of daily clearness index and diffuse fraction of global radiation. It appears that the monthly variations are consistent since the maximum of K_d correspond to the minimum value of K_T . The highest K_T values occur in July ($K_T = 0.757$) and the lowest

values occur in January ($K_T=0.564$). The highest K_d values on the other hand, occur in January ($K_d=0.32$) and the lowest occur in values July ($K_d=0.163$).

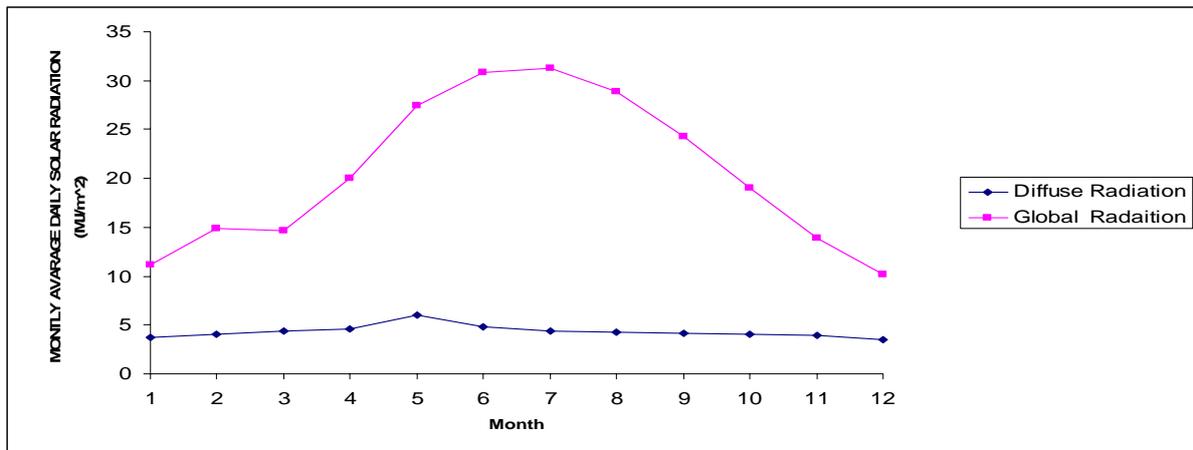


Figure 2a : Monthly Average Daily Solar Radiation MJ/m²

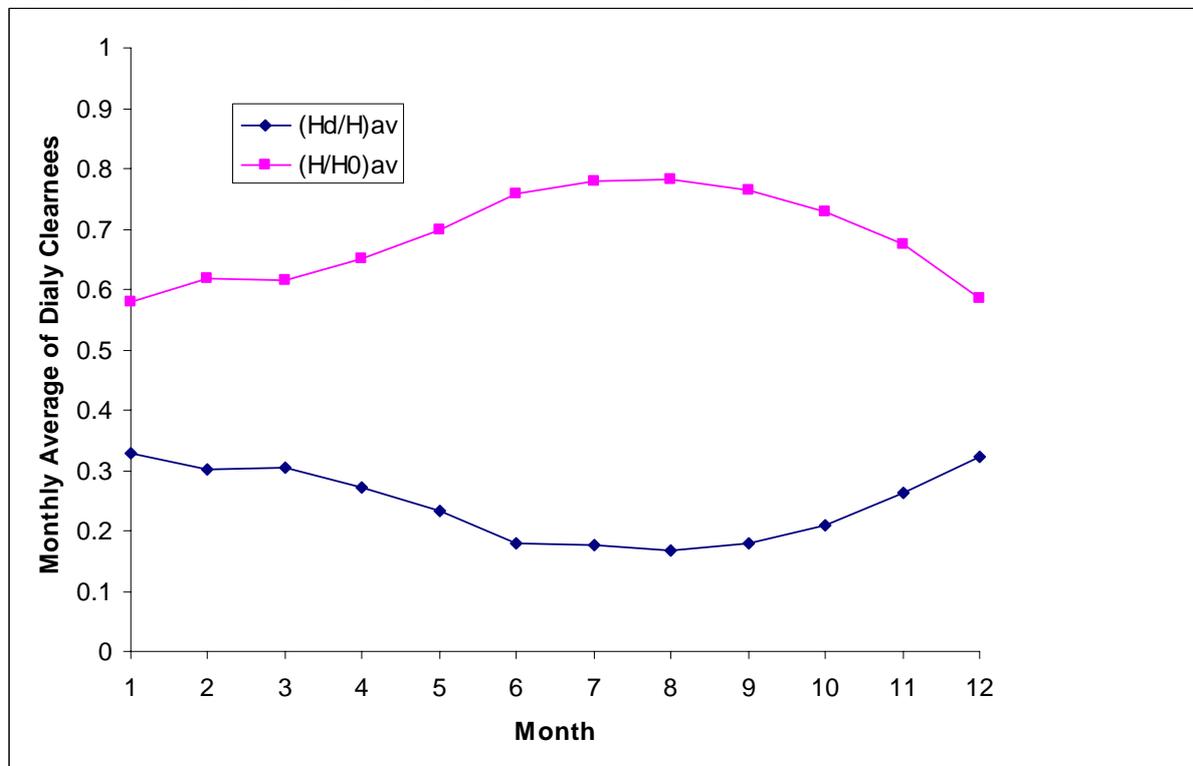


Figure 2b: Monthly Average Daily Clearness Index

HOURLY DISTRIBUTION OF GLOBAL AND DIFFUSE RADIATION

The monthly average hourly global and diffuse radiation between 4:00-12:00 and 12:00-20:00 local time are plotted in figures 3 and 4. From these figures we found that the maximum monthly means of hourly radiation occurs in June at noon $975 \frac{w}{m^2hr}$ for global radiation and $197 \frac{w}{m^2hr}$ for diffuse in

February. Radiation and the minima occur in December $415 \frac{w}{m^2hr}$ for global radiation in December

and $53 \frac{w}{m^2hr}$ for October for diffuse. Also we note that there is symmetry in the variation which is caused by decrease of atmospheric transparency in the afternoon hours.

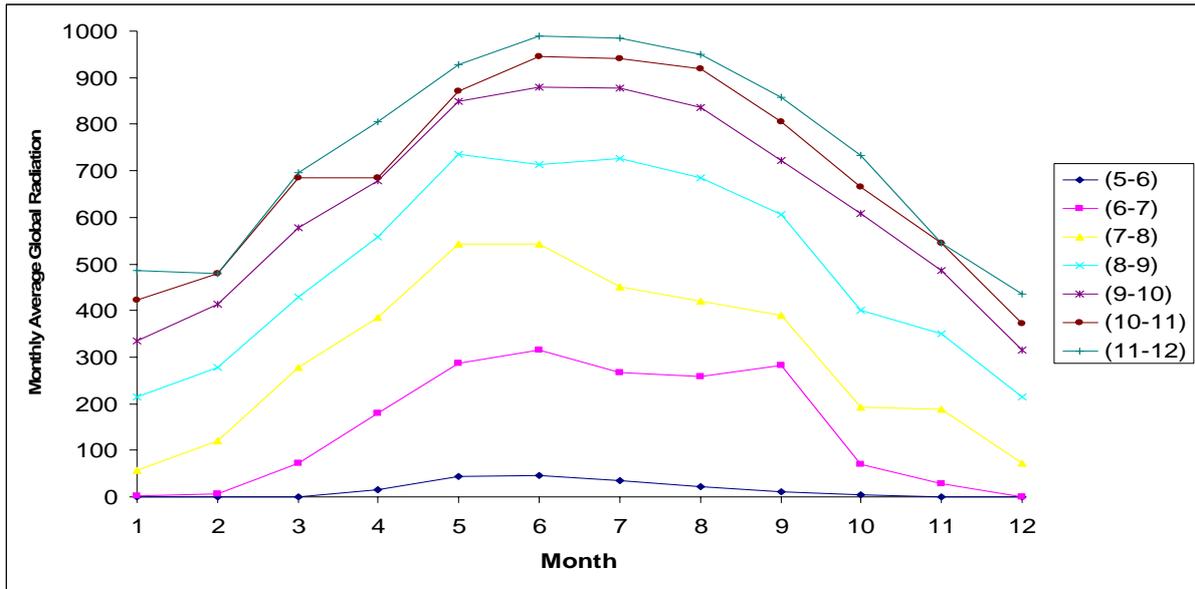


Figure 3 Monthly Average Global Solar Radiation MJ/m²

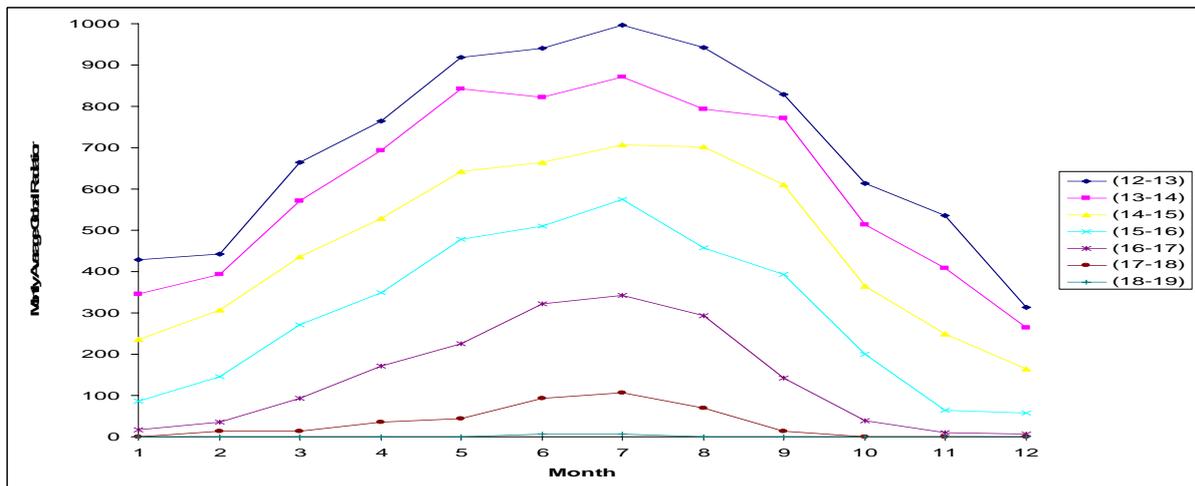


Figure 4 Monthly Average Global Radiation MJ/m²

Hourly Radiation from Daily Radiation:-

Figures 5, 6 demonstrate the verification of equation (8) where the solid lines are obtained from the right hand side of that equation. The measured data in this diagram represent mean values of the hours pairs (1/2,3/2,5/2,7/2).

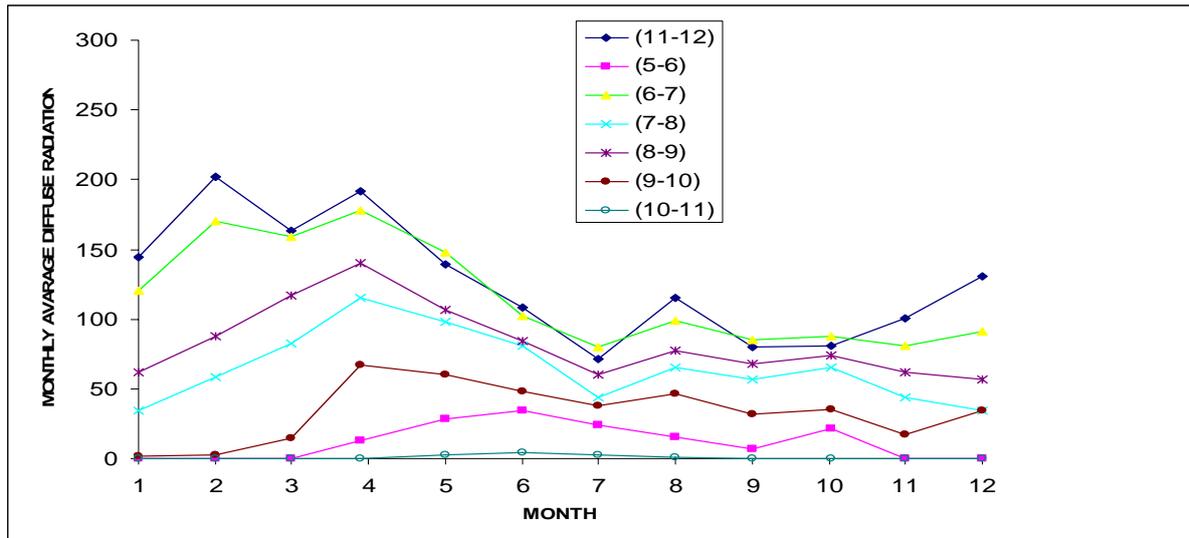


Figure 5 Monthly Average Diffuse Solar Radiation MJ/m²

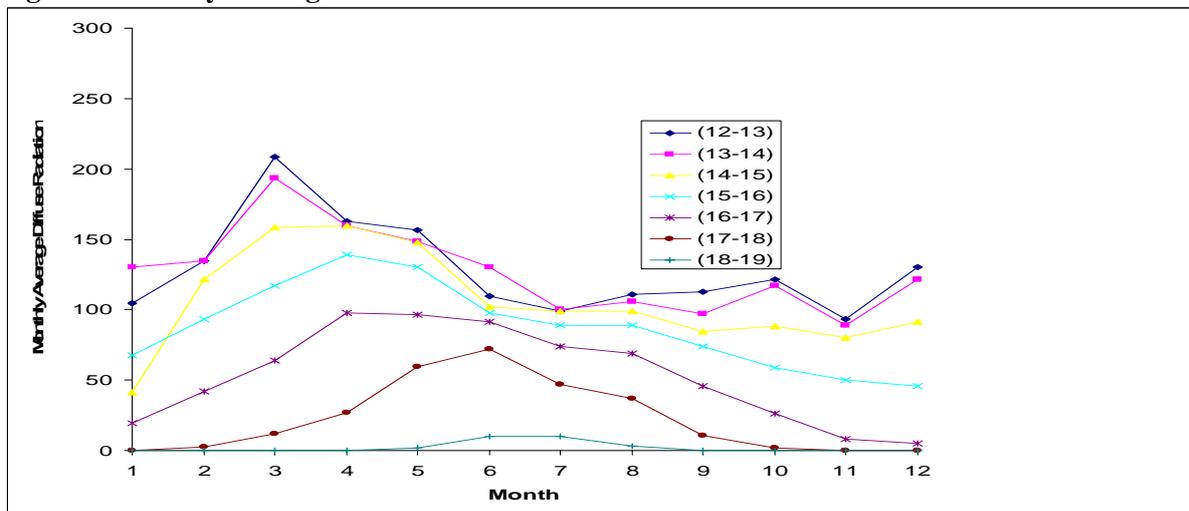


Figure 6 Monthly Average Diffuse Solar Radiation MJ/m²

Histogram of frequencies of clearness index and diffuse fraction of global radiation.

A frequency histogram over the year is shown in figures 7 and 8 appears that the distribution of K_T skews toward high values and is sharply peaked in the range $0.6 < K_T < 0.7$. The data in this range of K_T represent 52.6% of the total data, more of these percentages are observed in the summer than in winter. The percentage frequency of cloudy days ($K_T < 0.30$) is quite low, viz 9.5%, whereas that for cloud days is quite high ($K_T > 0.7$). Thus 12.4%, the intermediate range of $0.30 < K_T < 0.70$ represent partly cloudy skies for Amman and contribute 78% of the data points. So it appears that the skies over Amman are fairly clear during most of the year.

A reverse behavior was observed in the distribution of K_d where the histogram skews toward low values of K_d and peak falls too near $K_d = 0.2$ with 41% of the total days lying in this range. It is obvious to note that; the days which fall within that range were associated with the days which have K_T values around 0.7. This is expected since both K_T and K_d are dependently affected by the state of the sky (dust contents, cloud coverage, amount of precipitable water vapour, and so on) which varies with time of the day and year. Hence increasing K_T value accompanied the decrease in K_d .

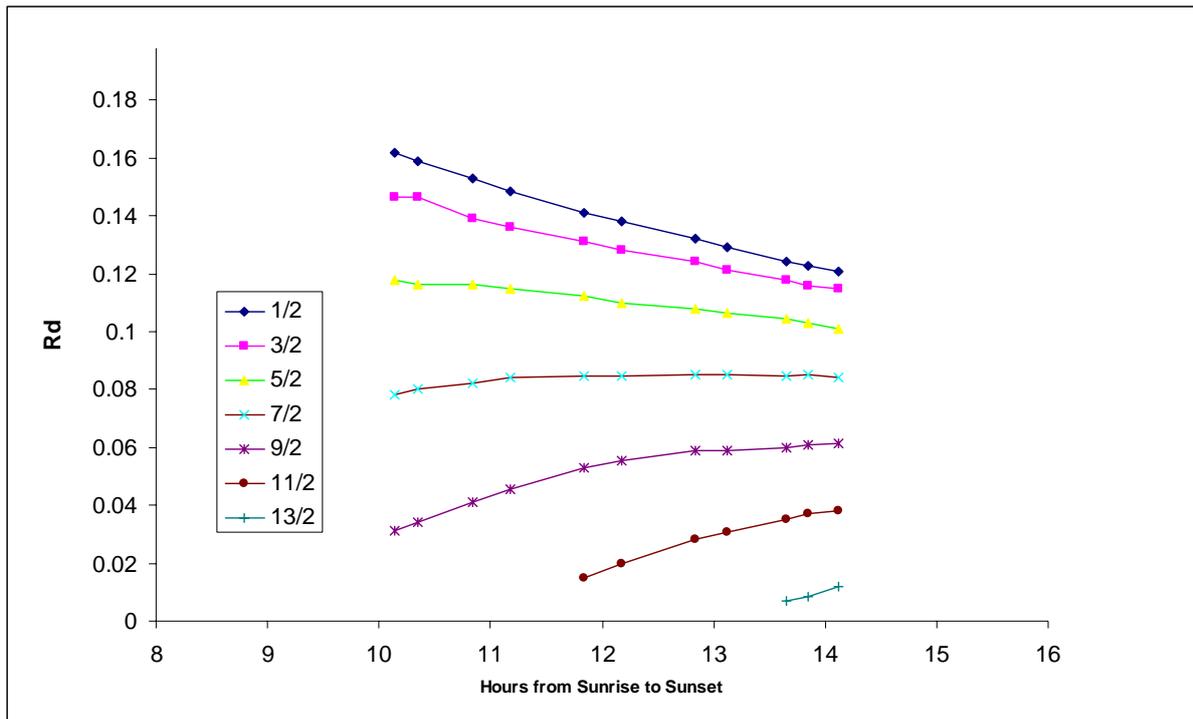


Figure 7 The distribution fraction ratio of hourly to daily diffuse radiation R_d

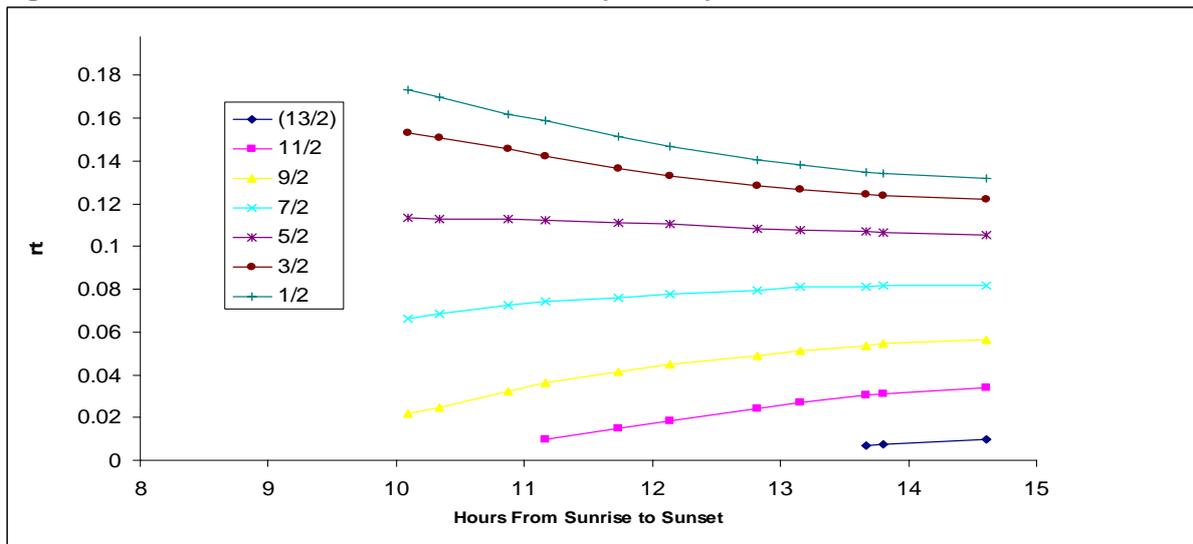


Figure 8 The distribution fraction ratio of hourly to daily global radiation r_g

Distribution of Hourly Radiation as a Fraction of Day's Radiation:-

At any time of the year and at a specified location at latitudes lower than 50, approximately 90% of the days radiation is received during the middle two-thirds of the day. This means that for a given fixed-position solar energy devices, practically all the useful heat gain, come from the middle two thirds of the day. This observation indicates that at both early morning and late afternoon, the solar radiation data are of little practical consequence in such application. The day's radiation can be classified into 3 periods:-

1. peak radiation period,(11-13) as shown in figure
2. moderate radiation period :(9-11)+(13-15) as shown in figure
3. low radiation period (7-9)+(15-17) as shown in figure

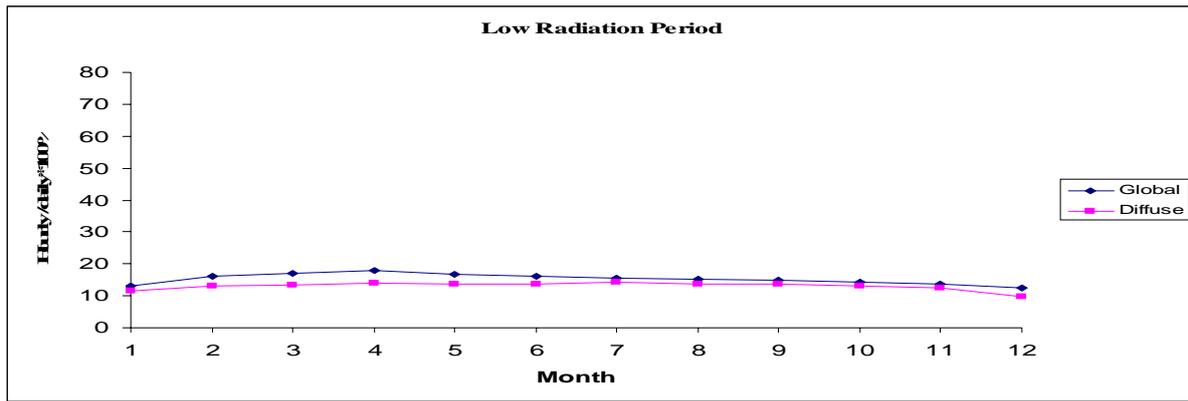


Figure 9 Distribution of Hourly Radiation as A Fraction of Day's Radiation

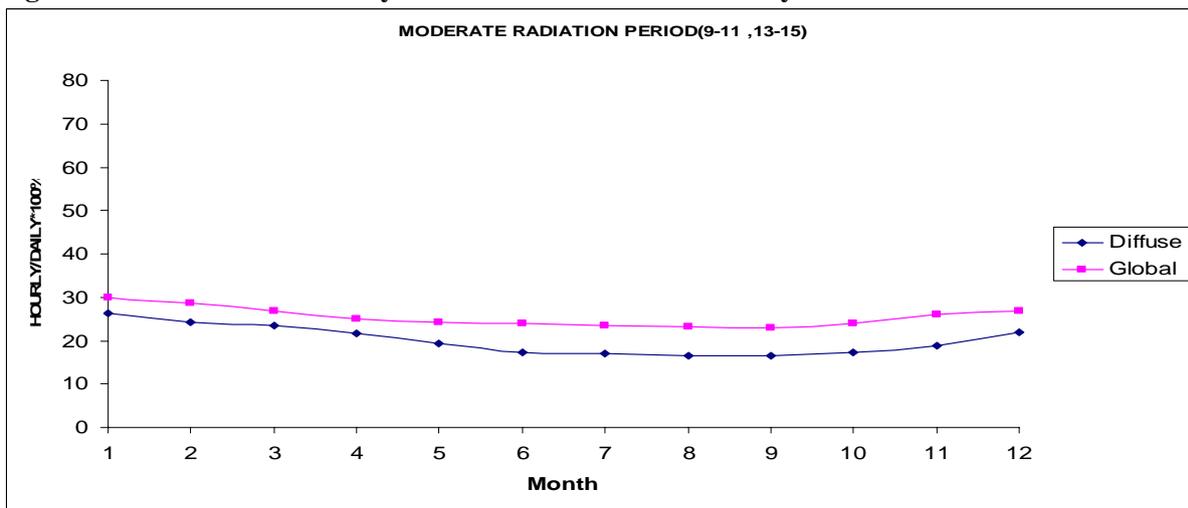


Figure 10 Distribution of Hourly Radiation as A Fraction of Day's Radiation

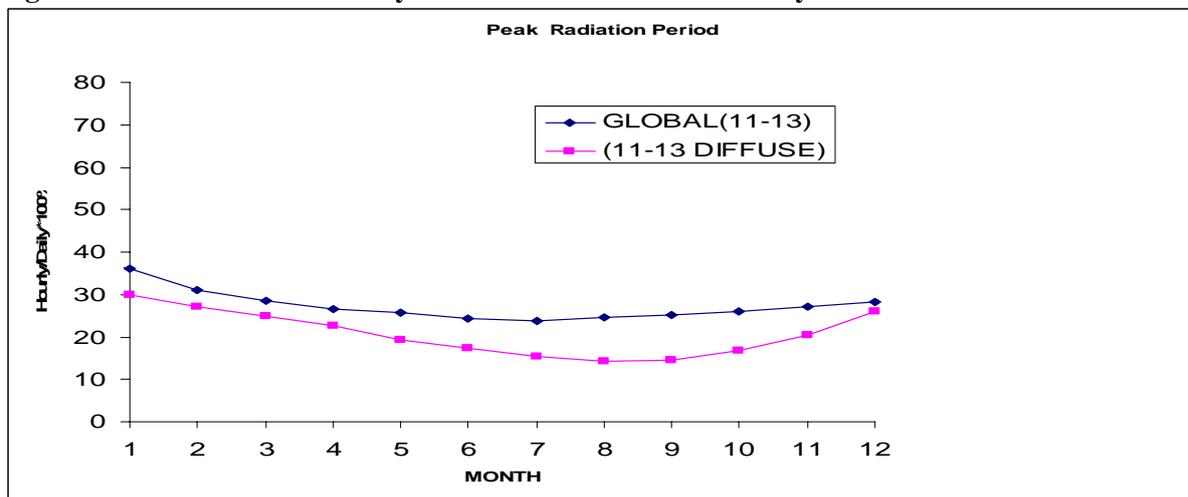


Figure 11 Distribution of Hourly Radiation as a Fraction of Day's Radiation

On basis of monthly average of hourly global and diffuse radiation for Amman, we calculated the percentage of radiation in the above mentioned time Interval as function of days radiation which is presented graphically in figures (12-13)

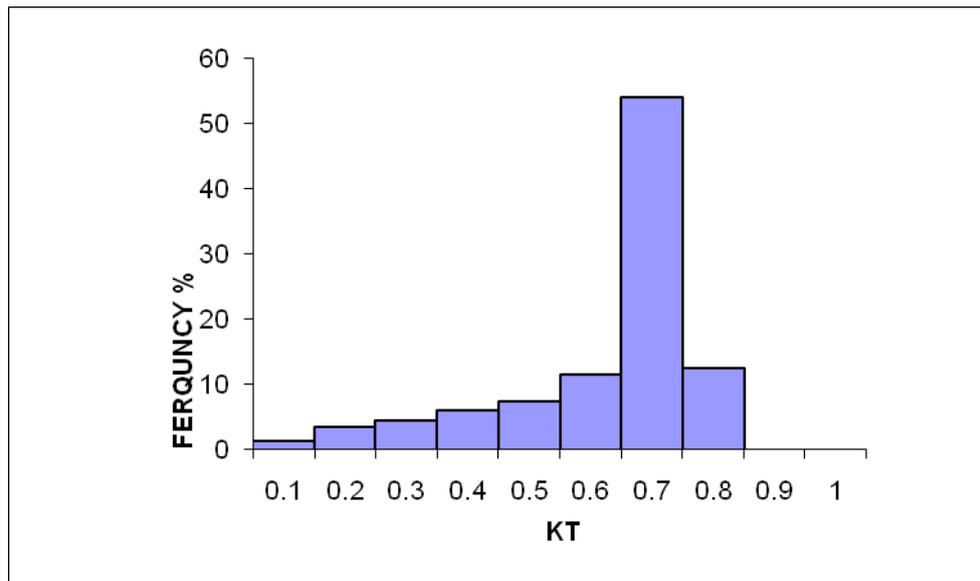


Figure 12 :The Histogram distribution of Frequencies of Clearness Index and Diffuse Fraction of Global Radiation

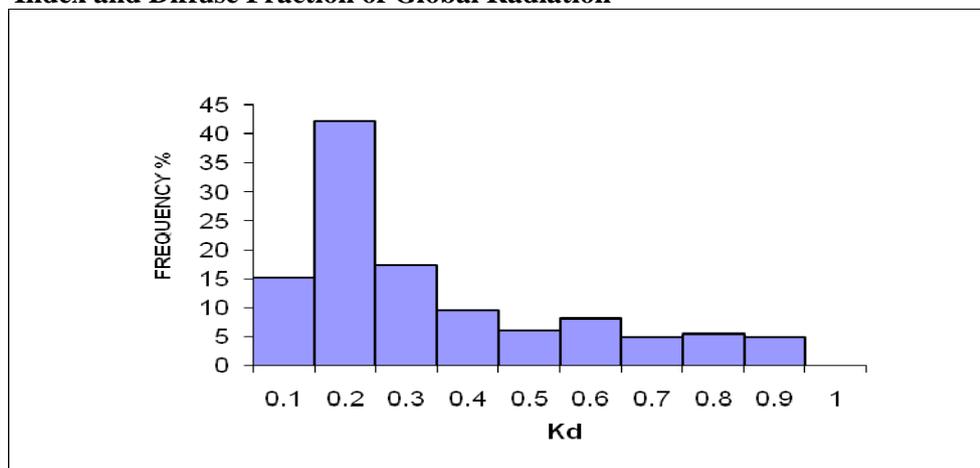


Figure 13 : Histogram of diffuse solar-radiation

CONCLUSION

In summarizing the result obtained with regard to the global and diffuse solar radiation calculation in Amman It may be concluded that:

1. The annual means of daily global and diffuse solar radiation is about 20.36MJ/m² and 4.bOMJ/m² respectively.
2. The maximum monthly means of hourly radiation occurs in June at noon belong 975 W/m²hr for global radiation and 104W/m²hr for diffuse radiation .The mm. occurs in December, being 415W/m²hr for global radiation and 123W/m²hr for the diffuse radiation.
3. The highest K_T values occur in July ($K_T=0.757$) and the lowest value in January ($K_T=0.564$), while the highest K_d values occurs in January ($K_d=0.320$) and the lowest value occurs in JULY ($K_d=0.163$).
4. The peak of the frequency histogram of K_T falls in the range of $.6 < K_T < .70$,the data in this range of K_T contributes 52.6% of the total data .the peak of the frequency histogram of K_d lie around $K_d=0.1-0.2$ with 41.2% of the total days observed in this range.

5. The highest seasonal change in the fraction of the three radiation periods were observed in the moderate radiation period, ranging between 51% in winter and 37% in summer.

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