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A Model for Modification of Air in a Small Town by Using the Evaporative Cooling Method.

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Abstract: *In this study a new model for quantifying the effect of evaporative cooling produced by the evapotranspiration from trees on the air temperature of Ali- Al Sharqi town, south of Iraq, (lat. 32.1°N, long 46.85°E) was suggested. The ASCE and FAO Penman Monteith model was used to calculate the actual evapotranspiration from a tree in the selected town. The dispersion of moisture from trees in the neighborhood in the three dimensions by using the Gaussian dispersion model was estimated. The decreasing of air temperature due to the moisture added by trees on a specific control volume was calculated by using the psychometric chart. The maximum cooling degree achieved by the suggested model reached to 2.6 °C in July while minimum value was (1.8 °C) and appeared in April. The results of applying the model on a hot and dry day indicated that the higher cooling degree can be obtained reach to 3.6 °C at the noon time.*
Keywords*: Air temperature; Evapotranspiration; Evaporative cooling; Gaussian model; Trees.*

I. Introduction

From the point of view of energy conservation, a tree can be regarded as a natural "evaporative cooler" using up to 100 gallons of water a day [1]. This rate of evapotranspiration translates into a cooling potential of 230,000 kcal/day, this cooling effect is the primary cause of 5°C differences in net peak noontime temperatures observed between forests and open terrain, and the 3°C difference found in noontime air temperatures over irrigated millet fields as compared to bare ground [2]. Temperature measurements in suburban areas recorded similar but smaller variations in daytime peaks of 2°C to 3°C between neighborhoods under mature tree canopies and newer areas with no trees.

Decreasing of air temperature due to the effects of tree has been documented in the past through many studies. Some of these studies depend on field measurements [3,4,5,6,7,8], and the other kind of studies use a simulation models based upon the theoretical principles of evaporative cooling process[9,10,11,12].

One of the most important preliminary attempts to model the effect of trees on temperature, humidity, winds speed and solar gain in urban climates using information from existing agricultural and meteorological studies is presented by Huang et al., 1987[11]. This model has the following limitations:

1- The air over the city is well mixed with no differences in potential temperatures and humidity ratios (i.e. the only temperature differences are due to adiabatic laps rate), and
2- The cooling effect of evapotranspiration from an increased number of trees is uniform throughout the urban microclimate.
3- The use of potential evapotranspiration compromises on accuracy as it only predicts the maximum evapotranspiration possible assuming ample supply of water and favorable conditions. Tree in the city considered may not experience these conditions.

To counter the above- mentioned limitations, and to develop a model for predicting climate modification, a new approach was adopted for this study.

II. Model description

To develop a quantitative model for microclimate modifications due to evapotranspiration it is necessary first to determine the amount of evapotranspiration as a function of time and ambient conditions, and then to relate that amount of added moisture to changes in the microclimate. To estimate the amount of plant evapotranspiration, an empirical model is employed. This model consisted of the following steps:

1.2 Estimating Evapotranspiration

Evapotranspiration for a particular crop (ET_c) is determined by multiplying a crop coefficient (K_c) by the reference evapotranspiration $ET_\circ$.[13].

$$ET_c = K_c ET_\circ \tag{1}$$

For a single tree, the volumetric rate of evapotranspiration V_{ET} is obtained by multiplying the crown area A_c by the ET_c.

$$V_{ET} = ET_c A_c = K_c ET_\circ A_c \tag{2}$$

To estimate the evapotranspiration rate for the selected town we used the 'ASCE and FAO Penman Monteith' method [14,15]. The general equation of this method detailed as following:

$$ET_{\circ} = \frac{\left(\dfrac{\Delta(R_n - G) + K_{time}\,\rho_a c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)}\right)}{\lambda} \tag{3}$$

where

$ET_{\circ}$ is the reference evapotranspiration, mm. day^{-1} or mm. h^{-1}
R_n is the net radiation, MJ. m^{-2} day^{-1} or MJ. m^{-2} h^{-1}
G is the soil heat flux, MJ. m^{-2} day^{-1} or MJ. m^{-2} h^{-1}
$(e_s - e_a)$ represents the vapor pressure deficit of the air, hpa
e_s is saturation vapour pressure of the air, hpa
e_a is the actual vapour pressure of the air, hpa
ρ_a is the mean air density at constant air pressure, kg.m^{-3}
c_p is the specific heat of the air, MJ kg^{-1} ^{0}C^{-1}
Δ is the slope of saturation vapour pressre temp relationship, Hp ^{0}C^{-1}
γ is the Psychometric constant, hpa ^{0}C^{-1}
r_s is the (bulk) surface resistance, s m^{-1}
r_a is the aerodynamic resistance, s m^{-1}
λ is latent heat of vaporization, MJ kg^{-1}
K_{time} is a units conversion, equal to 86400 s day^{-1} for ET in mm day^{-1} and equals 3600 s h^{-1} for ET in mm h^{-1}

2.2 Moisture advection across the neighborhood

From the point of view of dispersion, the case of moisture being released by a tree, is similar to that of any other source, say an industrial plant, releasing a gas from its stack. Since water vapour behaves as a perfect gas, this analogy implies that equations used to describe pollution dispersion can be applied to vapour from a tree. Dispersion of moisture can be calculated using a simple gaussian dispersion model described below as referenced from Oke (1987) [16].

$$\chi_{(x,y,z,H)} = \frac{X}{\pi\sigma_y\sigma_z\bar{u}}\,exp\left[\frac{y^2}{2{\sigma_y}^2}\right] \times \left[exp - \left(\frac{(z-H)^2}{2{\sigma_Z}^2}\right) + exp\left(-\frac{(z+H)^2}{2{\sigma_Z}^2}\right)\right] \tag{4}$$

where

χ Concentration of pollution at any point in a plume (kg. m^{-3}, more reasonably g. m^{-3})
X Rate of emission from the source (g. s^{-1})
$\sigma_y \sigma_z$ Horizontal and vertical standard deviation of the poullutant distribution in the y and z direction (m)
$\bar{u}$ Mean horizontal wind speed through the depth of the plume (m.s^{-1})
H Height of tree from base of trunk to center of foliage (m)

A tree can be assumed to be a stack projection, of Height H, which releases vapour at a steady rate X, calculated by using the model for evapotranspiration described earlier.

3.2 Moisture dispersion within neighborhood

Using the equations (3) and (4), rate of evapotranspiration and moisture dispersion from a single tree can be determined. The same method is now applied to a single control volume of dimension (length 20m, width 20m) contains 13 trees and a volume of air above and around it. The upper limit of the control volume is defined by the blending height which is a function of the height of the roughness elements (trees) contained in the volume.

The neighborhood is broken in too many such control volumes. The phenomenon of advection of moisture can now be treated as advection from one control volume to the next (adjacent) control volume and so on.

Calculations are done for each control volume, and solved for the resultant relative humidity of the air in that volume.

The geometry of the neighborhood is interpreted, in two dimensions to represent the neighborhood plan, for the worksheet calculations. Trees are identified by marking cells in the worksheet as “1”s and free space as “2”severy cell represents a square of 1 meter by 1 meter.

4.2 Calculating temperature in a control volume

Using the Gaussian dispersion equation, the pattern of moisture dispersion can be calculated for any height of observation. To quantify the decrease in temperature due to evapotranspiration of trees in a control volume, it is first required that total moisture content in a control volume be calculated. This is done by creating moisture contours for a plane of observation at every meter of height starting from the ground level (z=0) to the top of the control volume ($z=h_{cv}$, where h_{cv} is the height of the control volume), shown schematically in Figure (1). A summation of these values is done to obtain the moisture content of the control volume in grams of moisture

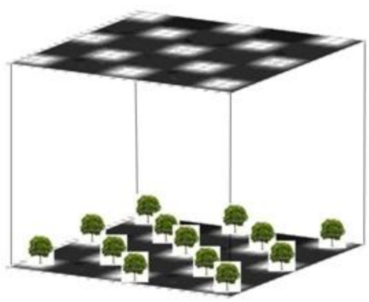


Fig. 1. A control volume with moisture concentration at two planes of observation at the base z=0 and top $z=h_{cv}$

Once this quantity of moisture is calculated, and then the decrease in dry bulb temperature can be calculated assuming the evaporation process is adiabatic and using the psychometric chart as in the case of an evaporative cooler.
All suggested model calculations have been done by using a Fortran90 program which is written to perform all these calculations.

III. Results and Discussions

Ali-Al Sharqi (lat. 32.1°N, long 46.85°E) is a small urban town in the south of Iraq, it was chosen for the purposes of model applications, because the climatic conditions of this town are very suitable for the requirements of evaporative cooling applications.

The monthly average data for four parameters (air temperature, relative humidity, wind speed, solar radiation) and for a period of 30 years (1980-2000) for the selected town were used as an input data for the model. All the data were obtained from the recorded Iraqi meteorological organization and seismology for this selected town. The first and most important procedure in the application of the suggested model is the reference evapotransipiration calculations of the selected town (Ali- Al-sharqi) by using the 'ASCE and FAO Penman Monteith' Method. The variation of reference evapotranspiration and evapotranspiration for a single crop (ET_c) (we take the value of olives tree crop coefficient which is equal to 1.15) for six months is illustrated in Figure (2).This Figure shows that the high value of evapotranspiration in this town appears in June and July where it reaches 15.5 $mm.day^{-1}$ for the selected crop, and that is corresponding to the high values of air temperature and wind speed which were recorded in these months. The lower value of evaporatranspiration for these six months takes place in April.

The volumetric rate of evapotanspiration in ($m^3.day^{-1}$) for a single tree with a crown area equal to (9 m^2) for the selected town is calculated and shown in the Figure (3). The maximum value of the volumetric rate of evapotranspiration usually appears in July, where it reaches 0.0217 $m^3.day^{-1}$. The lowest value is of 0.014 which appears in April.

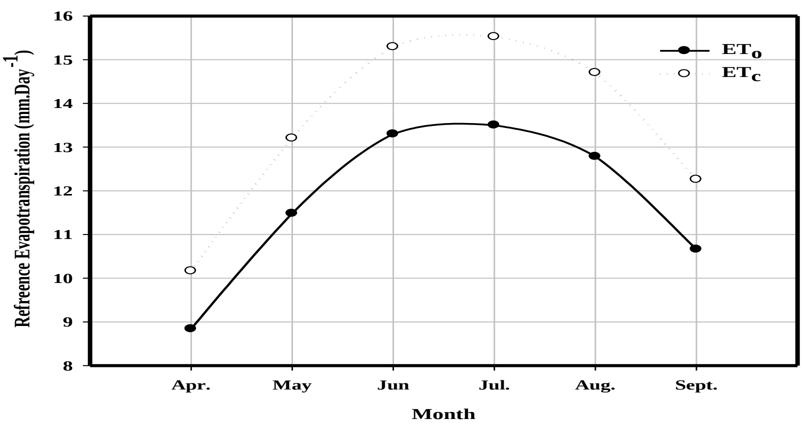


Fig. 2. The values of reference evapotranspiration and evapotranspiration for a single crop in April to Sep. period for Ali AL-Sharqi.

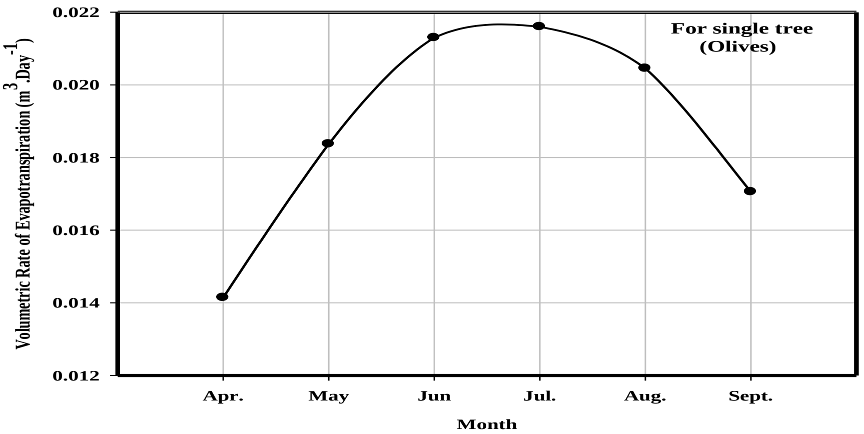


Fig. 3. Volumetric rates of evapotranspiration for a single tree at Ali AL-Sharqi.

The moisture dispersion from a single tree (crown area=9 m^2, K_c=1.15, height=4 m) for three dimensions (downwind (x), crosswind (y) and z) was calculated for July and for 10 heights (from z=0m to z=10 m). Tables (1 and 2) show the results of these calculations for 2 heights (z=0m and z=10 m), the calculation of downwind direction dispersion was found to ring (0.1 m to 15 m) , while the crosswind direction dispersion ranged from (0 to 4m) for both sides of the tree.
Emission rate of source (tree) X ($g.s^{-1}$) =7.5,
Atmospheric Stability rating = B
Wind speed u ($m.s^{-1}$) = 4, Tree Height (m) =4

Table 1. Calculations of dispersion from single tree at the height of 0 m

Crosswind / *Downwind*	-4	-3	-2	-1	0	1	2	3	4
0.1	0	0	0	0	1.004	0	0	0	0
1	0	0	0	0.0013	0.130	0.0013	0	0	0
2	0	0	0.0007	0.0229	0.072	0.0229	0.0007	0	0
3	0	0.00026	0.0035	0.026	0.0514	0.026	0.0035	0.00026	0
4	0	0.0022	0.0082	0.027	0.0407	0.027	0.0082	0.0022	0
5	0.00048	0.006	0.011	0.0263	0.0343	0.0263	0.011	0.006	0.00048
6	0.00013	0.009	0.013	0.024	0.0297	0.024	0.013	0.009	0.00013
7	0.00025	0.013	0.0148	0.022	0.0266	0.022	0.0148	0.013	0.00025
8	0.00379	0.015	0.0152	0.021	0.0241	0.021	0.0152	0.015	0.00379
9	0.0049	0.017	0.0152	0.020	0.0221	0.020	0.0152	0.017	0.0049
10	0.0059	0.0177	0.0150	0.019	0.020	0.019	0.0150	0.0177	0.0059
11	0.0067	0.0180	0.0147	0.018	0.019	0.018	0.0147	0.0180	0.0067
12	0.0074	0.0182	0.0145	0.017	0.018	0.017	0.0145	0.0182	0.0074
13	0.007	0.0180	0.0141	0.016	0.017	0.016	0.0141	0.0180	0.007

Table 2. Calculations of dispersion from single tree at the height of 10 m.

Crosswind / *Downwind*	-4	-3	-2	-1	0	1	2	3	4
0.1	0	0	0	0	0.418	0	0	0	0
1	0	0	0	0.00055	0.054	0.00055	0	0	0
2	0	0	0.00030	0.0096	0.030	0.0096	0.00030	0	0
3	0	0	0.0015	0.0111	0.021	0.0111	0.0015	0	0
4	0	0.00047	0.0035	0.0116	0.017	0.0116	0.0035	0.00047	0
5	0.0002	0.00133	0.0050	0.0112	0.014	0.0112	0.0050	0.00133	0.0002
6	0.00058	0.0022	0.0058	0.0105	0.012	0.0105	0.0058	0.0022	0.00058
7	0.0011	0.0030	0.0063	0.0090	0.011	0.0090	0.0063	0.0030	0.0011
8	0.0016	0.0036	0.0065	0.0093	0.010	0.0093	0.0065	0.0036	0.0016

9	0.0021	0.0041	0.0066	0.0088	0.0096	0.0088	0.0066	0.0041	0.0021
10	0.0026	0.0044	0.0060	0.0083	0.009	0.0083	0.0060	0.0044	0.0026
11	0.0029	0.0046	0.0065	0.0079	0.0084	0.0079	0.0065	0.0046	0.0029
12	0.0032	0.0048	0.0064	0.0076	0.0080	0.0076	0.0064	0.0048	0.0032
13	0.0035	0.00494	0.0062	0.0072	0.0076	0.0072	0.0062	0.00494	0.0035

From these tables we can notice the following points:

1- For all heights, the higher concentration of moisture is found near the source (single tree) i.e. at crosswind distance and downwind distance equal to zero, and this concentration starts to decrease away from the source.
2- In the cross wind direction no significant concentration appears after 4 m distance for all heights
3- In the downwind direction, the most important concentrations appear in the first fourth meters from the source and after that the concentrations will become less significant
4- As seen from the table (5.10), no important concentration can be obtained above this height, and that is related to the height of the source and the stability condition.

Figure (3) shows the variation of vapor concentration with height for several downwind distances along the line of the tree (y=0). It shows how the concentration reduces as the height increases. The study suggests that the concentration becomes practically almost zero at 13m above the tree.

The graph in figure (4) represents the concentration profiles of water vapour, crosswind and downwind from the tree at ground level (z=0). The concentration decreases downwind and crosswind in a different profile as shown in this graph

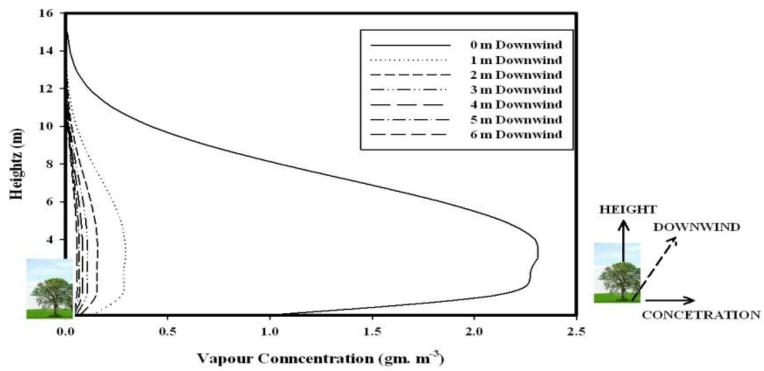


Fig. 3. Concentration profiles downwind showing variation with height.

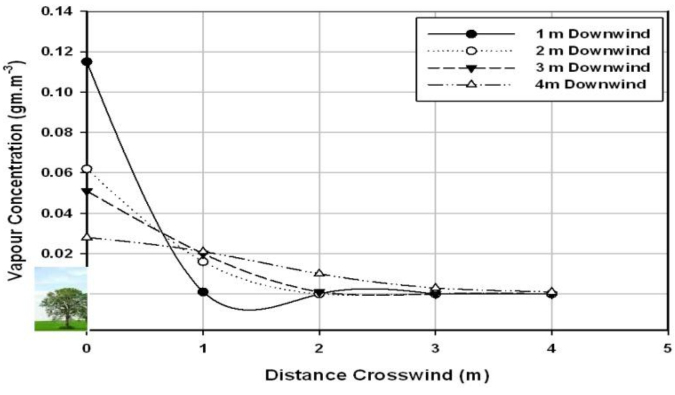
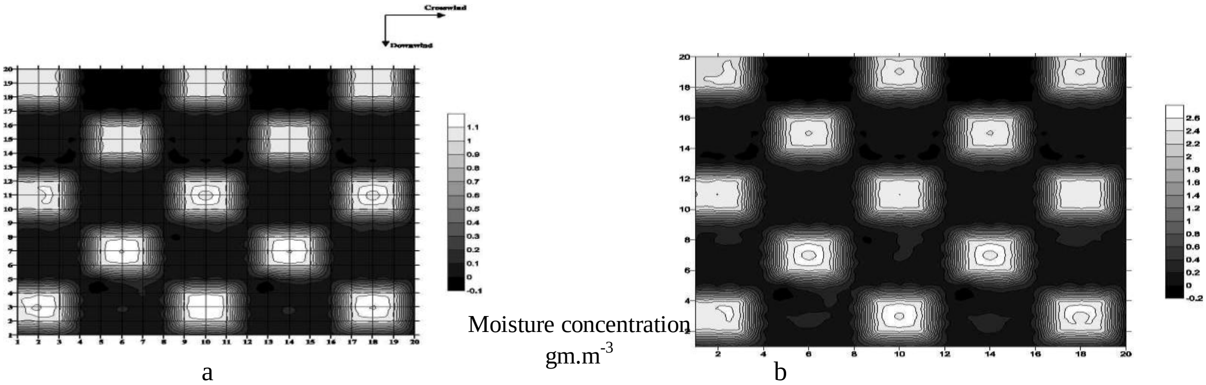


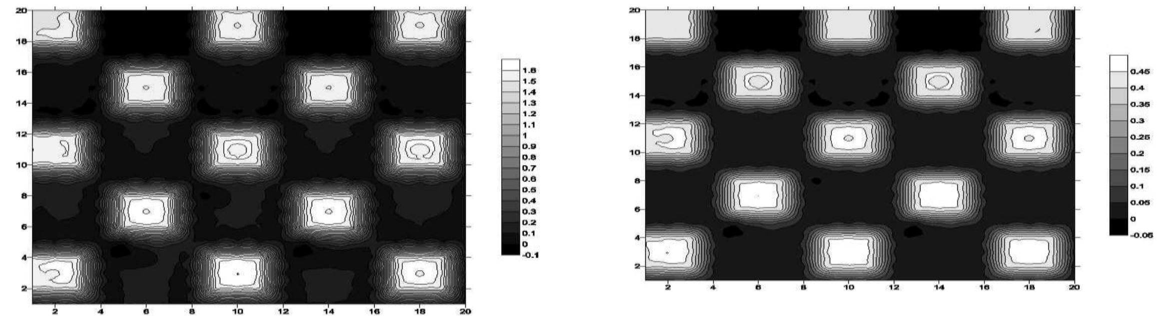
Fig. 4. Concentration for distances crosswind and downwind from single tree.

Figures (5and 6) show the contour plots of moisture concentration in the control volume of 13 trees for four heights (0, 3,7,10 m) by using the data of Ali Al-Sharqi town in July. A higher concentrations of moisture appeared at the height of 3m and that is due to the higher concentration from After this height the concentrations of moisture starts to decrease until it reaches the lowest value at the top of the control volume (z=10m). a single tree which is calculated at this height. Figures also show that the concentrations of moisture increase downwind in the control volume, and that's because of the effects of the moisture contribution from other trees that lie in the downwind direction, and this can be seen clearly for all heights at the beginning of the control volume (upper side of figures), where the concentrations are high only around the trees while they are relatively very low in the crosswind direction of the trees, and then starts to increase downwind inside the control volume. The calculation of the moisture concentration dispersion in the control volume also indicates that the arrangement of trees in a staggered array will clearly reduce the effects of the increasing of moisture which come from one tree to the other tree that lies in the downwind direction. The crosswind distance between trees that are put in the control volume planning also contributed to the decreasing of the wind speed reduction which is caused by the effects from other tree lie in the crosswind direction.



a b

Fig. 5. Contour plot of moisture concentration for the control volume at tow height a:z=0, b: z= 3 m



"a" "b"

Fig. 6. Contour plot of moisture concentration for the control volume at tow height a:z=7, b: z= 10 m

To quantify the temperature decreasing which was obtained by the application of the suggested model, the total moisture content (m_{total}) in the control volume in grams was calculated. This is done by the summation of the values of the moisture for each level in the control volume(m_i) from the ground level (i=0) to the top of the control volume (i=h_{cv} where h_{cv} is the height of control volume),

$$m_{total} = \sum_{i=0}^{i=10} m_i \tag{5}$$

Figure (7) shows the result of these calculations in July and for the heights from (0-10m) for Ali AL-Sharqi.

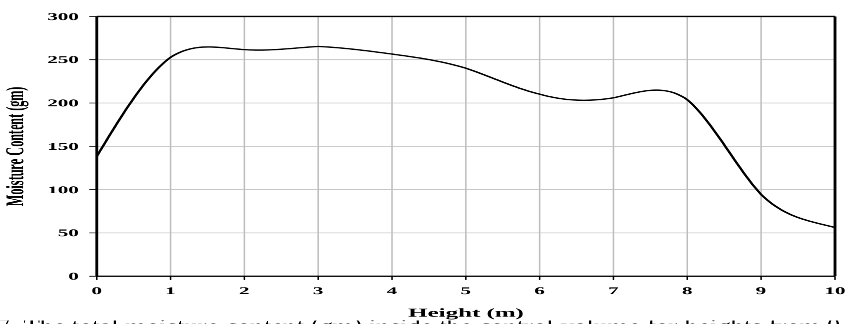


Fig. 7. The total moisture content (gm) inside the control volume for heights from 0 to 10 m

This Figure shows that the concentration began to increase from ground level until it reached the highest value at the level of 3m and then started to decrease upward, where it reached to the lower value at the level of 10m. By using the psychometric chart the dry bulb temperature depression in July for Ali AL-Sharqi was estimated, and it is found that the temperature depression reached 2.7 °C in this month. The same calculations were done for other months of the hot season and the result of these calculations is illustrated in Figure(8).The range of cooling degree obtained by this suggested model was ranging between 1.8 in April and 2.7 in July.

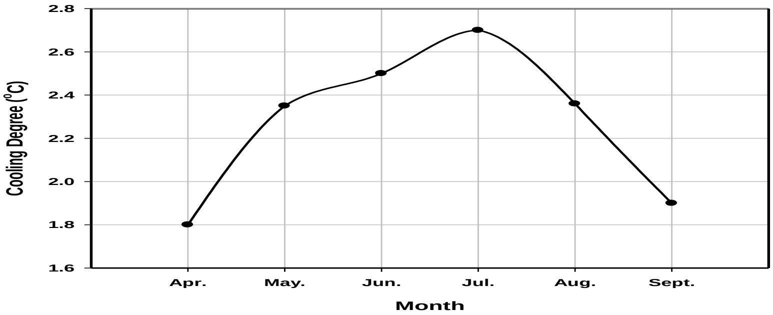


Fig. 8. The cooling degree obtained for the six months for Ali-AL-Sharqi.

Same calculation was done in a selected hot day to visualize the diurnal change of cooling degree which can be obtained from this model, these calculations were for four times a day (00,06,12,18), and Figure (9) shows the result of this calculation. Maximum cooling degree reached 3.6 $^{\circ}$C at the time of 12 while minimum value was only 1.4 $^{\circ}$C at the time 00

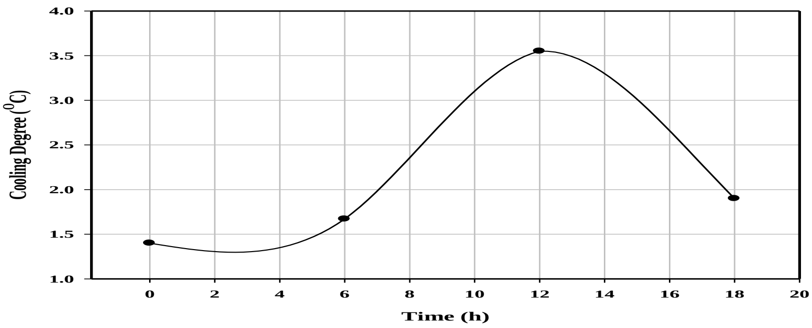


Fig. 9. The diurnal change of cooling degree obtained for a selected hot day.

IV. Conclusions

The results of the model indicated that the higher concentration of moisture is on the downwind line of the trees and the most significant values it's among the forth meters away from the tree and the concentrations is negligible after 15m from the tree. The results also showed that the values of cooling degree which can be obtained from this model was between 2.7 $^{\circ}$C in July and 1.8 $^{\circ}$C in April and the maximum value of a diurnal cooling degree was 3.6 at the noontime.

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