DEVELOPMENT AND VERIFICATION OF A MODEL FOR PREDICTING FOG OVER COOLING PONDS

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ABSTRACT

At low atmospheric temperatures, between 5°C and -20°C, water evaporated from an open water surface, such as a power plant cooling pond, can cause frequent fog formations. To study the environmental effect of proposed cooling pond designs, a simulation model was developed which provided the following: the amount of water evaporated from the surface of the pond as a function of the pond surface temperatures and atmospheric conditions (the source terms); the diffusion of the water vapor and liquid water content by the atmosphere, and the resulting spatial distribution of quantity of liquid water in the atmosphere, which defines the visibility ranges. The model was tested and verified for an operating cooling pond and applied to design cooling ponds.

INTRODUCTION

Fog can be formed from cooling pond surface evaporation throughout the year. In the warmer months, the atmosphere can retain considerable quantities of water in the vapor stage. High atmospheric relative humidity is required for significant fog to originate from the pond. Fogging in summer is therefore associated closely with conditions conducive to natural fog formations.

At extremely low temperature (below about -20 degrees C) the water vapor usually condenses directly into the solid phase as ice crystals. In between the warm air temperatures and cold air temperatures is the region of air temperatures varying between -20°C and +5°C, where water droplets in fog can exist as liquid water, and yet where generally low air temperatures can hold only limited amounts of water in the vapor stage. When the air temperatures are below freezing, and water droplets exist in the liquid phase, the drops are said to be "supercooled."

The purpose of the study was to develop an analytical model to predict the occurrence of fog from cooling ponds, associated with atmospheric temperatures where limited quantities of evaporated water is retained in the vapor phase. The model was verified using data collected over an actual lake. The model was designed to be applied to a proposed cooling pond for a nuclear power plant.

APPROACH

PROBLEM DEFINITION

There are three questions to be answered by the analysis of cooling pond fogging:

a) Under what conditions of cooling pond temperatures, and atmospheric temperatures, relative humidity and wind does fog form?
b) When fog forms, what is its distribution over the pond and the adjoining land surfaces?
c) What are the visibilities in the fog associated with the various pond and atmosphere initial conditions, and the resulting geographical extent of the visibility restrictions?

ANALYSIS

Four equations were used to analyze the problem. The first describes the condensed water per unit volume needed to produce varying visibilities. The second gives the water vapor needed to saturate the air so condensation can proceed. The third equation describes the evaporative water per unit area being supplied by the surface of the pond. The fourth equation describes the transport and dispersion of the water droplets across the pond to the adjoining land surface.

The first equation is semi-empirical[1,2] and relates to liquid water content. It takes the following form:

$$w = \frac{c}{V} k \ r \quad \text{(cgs units)} \qquad (1)$$

where w is the liquid water content in air to produce the visibility, V. The term c represents an empirical constant, and k is a factor which accounts for drop size distribution around the average radius, r. This formula represents one portion of the amount of water needed from the pond evaporation to produce a fog of a given visibility.

The second equation specifies the remainder of the water needed to be supplied by the pond. For a given set of initial conditions of the atmosphere in terms of temperature and specific humidity, some water is required to bring the air up to saturation. This equation takes the form of:

$$q = q_s - q_a \tag{2}$$

where q is the amount of moisture in mass of water per mass of air to be added to the air at initial conditions of q_a to attain saturation, q_s.

The above two equations describe the "demand" upon each unit surface area of the pond for water evaporation to produce a fog of a given visibility range. The air above the pond recieves the evaporated water from the unit surface area and is transported with the wind, receiving subsequent contributions from the pond and diffusing some of this water to adjacent parcels of air. It eventually arrives over the receptor points of interest over the pond and land surfaces with a certain quantity of water in vapor and liquid stages. This quantity is the result of water received directly from the pond surface, or indirectly through exchanges with adjacent parcels of air containing water, minus that water given to adjacent parcels, also through the exchange process.

The third equation[3,4,5] describes the evaporation, E, from a unit surface of the pond per unit of time.

$$E = \frac{\kappa^2 \rho (q_1 - q_2)(u_2 - u_1)}{\{\ln (h_2/h_1)\}^2} \quad \text{(cgs units)} \tag{3}$$

where κ is Von Karman's coefficient, ρ is the density of air, q_1 and q_2 are the specific humidities at the pond surface and at an elevated point, u_2 and u_1 are the wind speeds at the elevated point and near the surface, and h_2 and h_1 are the heights at the elevated point and near the surface.

The fourth equation describes the change in the quantity of interest (moisture in a unit volume of air mass) at a point of interest (a series of receptor points on a grid around the pond) at various times. If we represent moisture in a unit volume of air by χ, the fourth equation expresses the change of χ with time:

$$\frac{\delta\chi}{\delta t} = -u\cdot\nabla\chi + \nabla\cdot K\nabla\chi + E + C \tag{4}$$

where u is the wind speed, ∇ is the del operator, K is a diffusion parameter, E is the source term of additional water and C is the loss term. For a simple line source with no vertical or lateral advection, the equation may be rewritten to describe changes in the direction of the wind, as follows:

$$\frac{\delta\chi}{\delta t} = -u\frac{\delta\chi}{\delta x} + \frac{\delta}{\delta y}K_y\left(\frac{\delta\chi}{\delta y}\right) + \frac{\delta}{\delta z}K_z\left(\frac{\delta\chi}{\delta z}\right) + E + C \tag{4a}$$

where K_i are diffusion coefficients which are a function of distance from the source (invariant with height), and x,y and z are orthogonal coordinates.

A solution [6,7] to equation 4a is:

$$\chi(x,y,o) = \frac{Q}{\sqrt{2\Pi}\, u\sigma_z}\left\{\operatorname{erf}\frac{(y + y_o)}{(\sqrt{2}\,\sigma_y)} - \operatorname{erf}\frac{(y - y_o)}{(\sqrt{2}\,\sigma_y)}\right\} \tag{4b}$$

at the surface (z = 0). In this equation, Q is the source strength, determined from equation 3, erf is the error function, y_o is the half width of the line source, and σ is the dispersion parameter in the direction of its subscript. This equation describes the source as a series of lines perpendicular to the wind, along which the evaporative process from the pond takes place.

CALCULATIONS

The form of data available for the calculations often determines the methodology used to perform the calculations. This section discusses the development of the methodology and states the assumptions included in the calculations.

Data on cooling pond surface temperatures are in the form of an average temperature for a unit area of the pond surface. Usually the unit area is a square grid equal to one tenth of the total area. In diffusion meteorology, the source strength of a unit area is represented by having the total strength concentrated either at a point in the center of the unit area, or along a line equal in length to the side of the unit area. Point sources tend to result in individual plumes originating at the point, when the dispersion equations are applied. Line sources, on the other hand, have edge effects where the individual line segments join.[6] The latter difficulty is more tractable for simulating fog than is the former. So in equation 4b, the source strength, Q, is a line source. The concentration per meter of line source is determined by summing the evaporation throughout the unit area for one-meter wide strips running the length of the area.

The gradient of the moisture, represented by the term $(q_1 - q_2)$ in equation 3, changes for a parcel of air traversing the pond. The change is a function of

a) Changes in q_1 as the parcel of air moves over subsequent unit areas of the pond surface, each area having its own average temperature, and
b) Changes in q_2 as the air amasses more moisture during its traverse.

Changes in q_1 are directly calculated, based upon the pond surface temperature. Changes in q_2 are assumed to be a function of traverse time, and a weighting factor, as discussed under verification, is applied to compensate for the physical change in the vertical transport gradient.[8] The weighting factor was initially calculated, but later changed based upon the empirical results of the verification of the program for an actual cooling pond.

In addition to the representation of the pond evaporation by a series of line sources, the following assumptions were applied to the calculations:

Eight wind directions were chosen to perform fog simulations, to determine the resulting fog patterns over the pond and adjacent land. For cardinal points of the compass, the wind blows normal to the selected line sources, which are chosen to be parallel with the appropriate side of the unit area grid square. For the four intermediate points of the compass (NE, SE, SW and NW), the wind blows at a 45-degree angle to the line source, and a correction was made in the width of the line sources to approximate a 45-degree projection. Since the basic unit line source is one meter in length, to represent Q in terms of grams of water per meter, the projected width becomes 0.707 meters (multiplying by cos 45°) and, to conserve mass, the effective source strength becomes

$$\frac{Q}{\cos 45°} = \frac{Q}{0.707} .$$

Another assumption is that the air must achieve 100 percent relative humidity before condensation can occur. The air must remain at 100 percent relative humidity while liquid condensed water exists in the air mass.

The third assumption is that sensible heat transfer from the surface of the pond can be represented by a corresponding change in atmospheric stability (the temperature gradient in the vertical), and that the stability once representative of the intruding air mass, remains constant thereafter while the air traverses the pond. In effect, this replaces a smooth transition with a step function. The approximation of the stepped function to the smooth curve was assessed during the verification program.

COMPUTER PROGRAM

Calculations to simulate fog from a cooling pond were programmed for use on a general purpose computer. The computer runs provided the quantified data upon which the conclusions of the study were based. For each initial condition of atmosphere and pond temperatures studied, the computer output specified the result in terms of a distribution of liquid water content per cubic meter. Positive values were interpreted as fog of a specified visibility through equation 1. Negative values were interpreted as no fog, with the air having less than sufficient water to achieve saturation and condensation.

The computer simulation system was designed, written and implemented to incorporate as much of the latest computer technology as was currently available. The system as depicted in Figure 1 includes two FORTRAN programs, both of which are compatible with most computer hardware systems supporting FORTRAN IV. For the purpose of this project and because of the proximity of the computer system, an IBM 1130 Central Processing Unit (CPU) (1442 card read/punch; 1132 line printer and 2315 mass storage) was used.

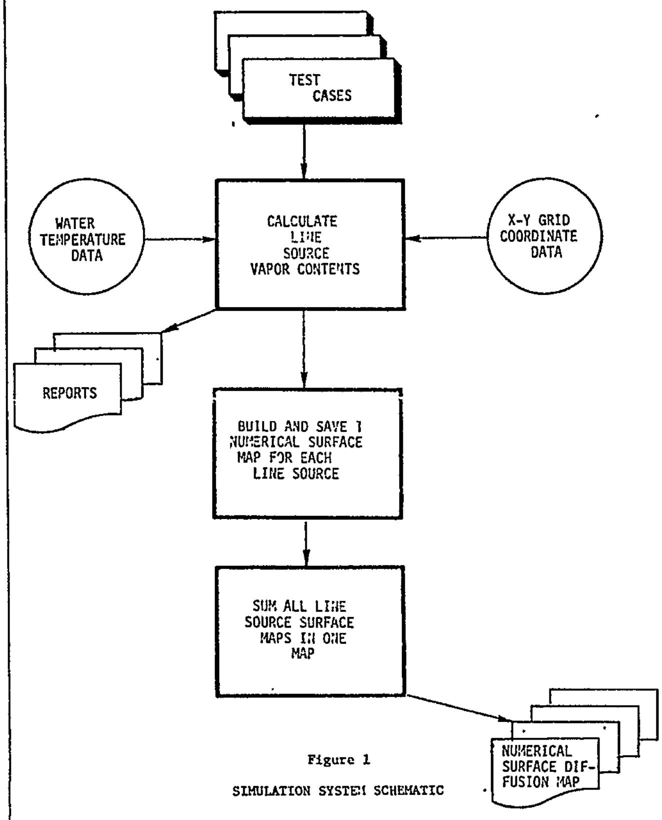


Figure 1

SIMULATION SYSTEM SCHEMATIC

Input to the system consisted of a series of parameters, each card simulating a "real world" occurrence. The parameters used consisted of:

1. Configuration of the cooling pond.
2. Water temperature.
3. Atmospheric conditions, consisting of air temperature, relative humidity and stability class.
4. Wind speed and direction.

From interpolation of these parameters, each line source vapor content was calculated. This method proved very successful in that many pond configurations and conditions could be simulated concurrently without the necessity of "program maintenance." Output from this program is a printed report showing both intermediate and final computations as well as the conditions selected. A computed data set is passed to the Multi Finite Line Source (MFLS) module.

The MFLS program creates one numerical surface map per line source. As test case in this exercise may consist of many line sources, one for each segment of the lake. Each of the maps is saved on a mass storage device until the entire test case has been completed. At this point each of the maps is merged and summed, and one map is produced on the line printer. The pond is drawn on the map based on a previously defined gridding system, and the isopleths are drawn accordingly. A line printer was used for the numerical surface maps instead of a plotter only because of the lack of easy availability to a large flat-bed or drum plotter. This conversion from line printer to plotter can be done quite easily since all the gridding is readily available.

VERIFICATION

The development of the simulation program was founded on physical processes described by microscale equations. Evaluation of individual cases of fogging requires use of data and assumptions which are on a mesoscale basis. The purpose of the verification program was to check on the accuracy of the assumptions and the scalar changes.

Observational data were supplied by the Commonwealth Edison Company. The data were the results of an observational program conducted at the Dresden Nuclear Power Station cooling pond and consisted of wind speed and direction, atmospheric dry and wet bulb temperatures at the surface and aloft, pond surface temperatures at the inlet and outlet of the pond and at the north and south sides of the county line bridge. Other information supplied included observed visibility, plant loading, spray operation and plant inlet and outlet water temperatures. Figure 2 shows the pond and the observing stations.

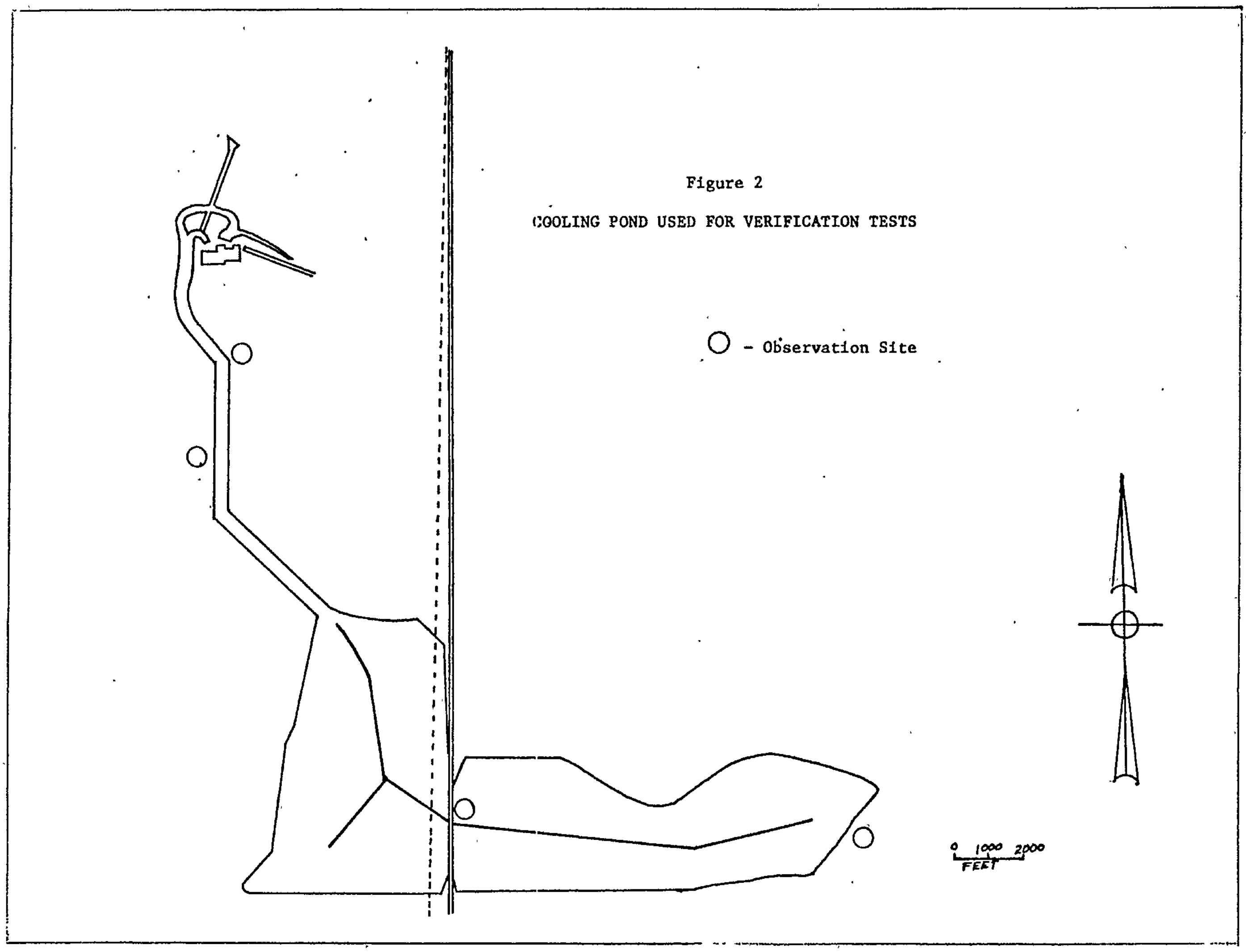


Figure 2

COOLING POND USED FOR VERIFICATION TESTS

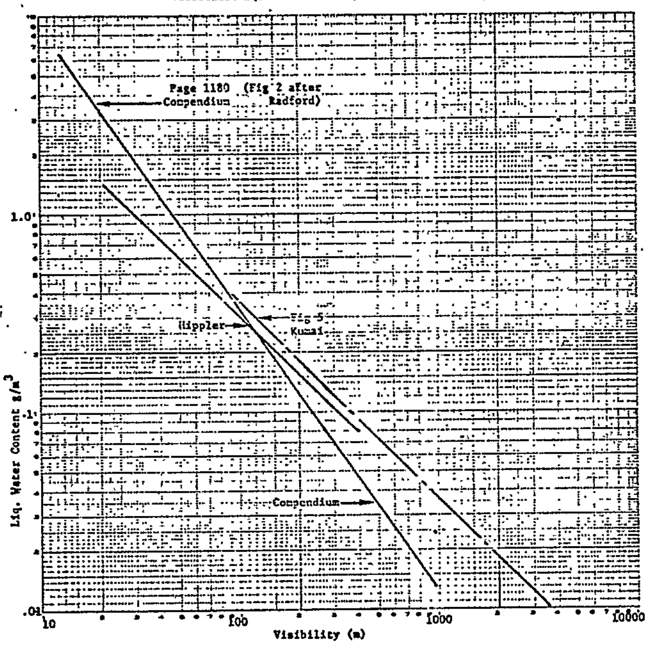
The model output is essentially mass of liquid (condensed) water per unit volume of air. This had to be related to an observed visibility range. These two parameters are related by equation 1, reproduced here for convenience:

$$w = \frac{c}{V} k r \qquad \text{(cgs units)} \qquad (1)$$

Figure 3 shows a log-log plot of the relationship between the visibility and the liquid water content as used for the study and as reported by Kumai.[2] With this plot relating the computer output to the observed visibility, nineteen cases were selected for testing from a three-month observing period. The cases were selected on a basis of first, visibility conditions of 1/4 mile or less to be duplicated (except for four "no-fog" cases), and, second, cases for which there was a representative visibility. Some cases of fog were patchy with widely varying visibility, and were not chosen for test cases because of the difficulty of "interpreting" a representative visibility.

FIGURE 3

VISIBILITY EQUIVALENT OF LIQUID WATER CONTENT



A simple regression equation served to relate predicted liquid water content to observed liquid water content (calculated from the observed visibility). Figure 4 shows that for visibilities less than 15 meters (water equivalent of about 1.9 grams per cubic meter) the simulation program underpredicts the restriction to visibility, and for visibilities greater than 15 meters the simulation program overpredicts the restriction to visibility. For an observed visibility of 100 meters, the simulation program would predict 70 meters, and for an observed visibility of 30 meters, the program would predict 27 meters.

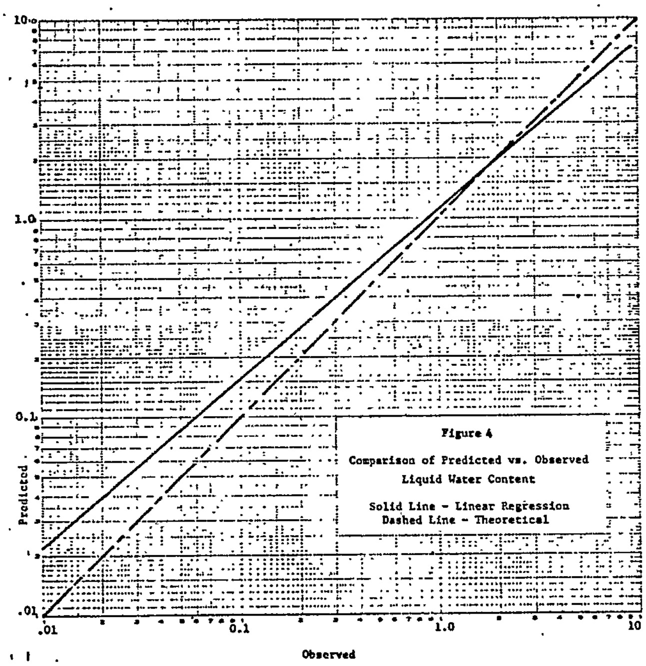


Figure 4

Comparison of Predicted vs. Observed Liquid Water Content

Solid Line - Linear Regression
Dashed Line - Theoretical

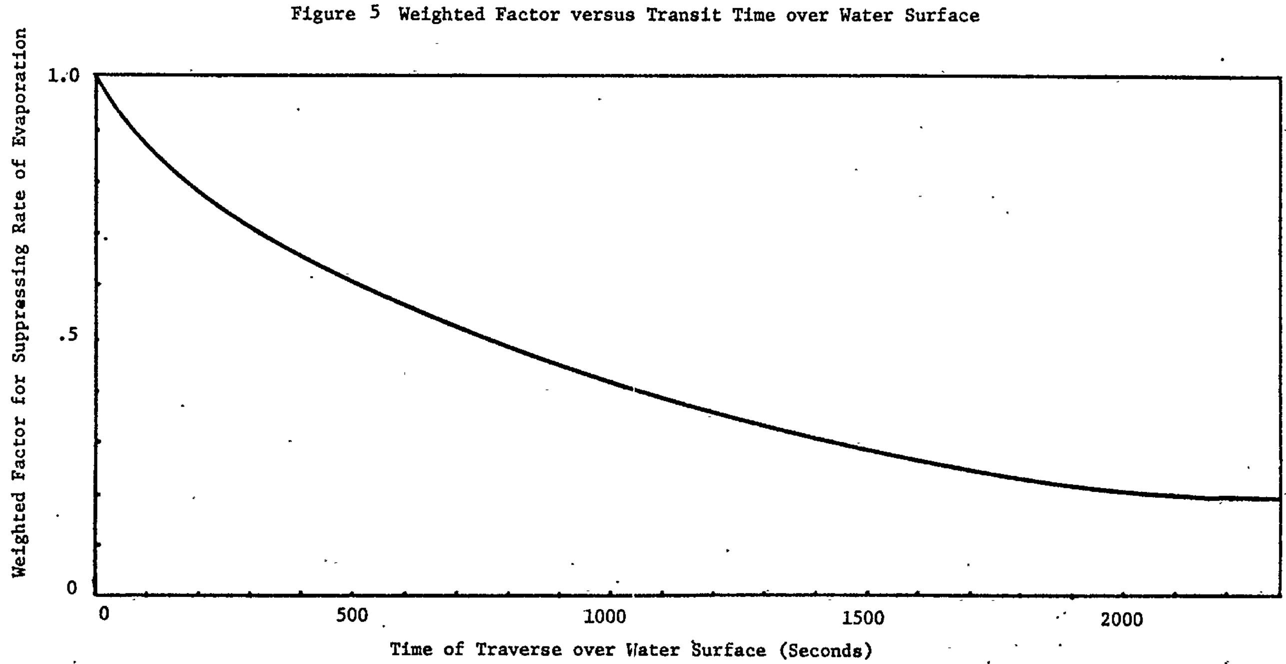
The verification program provided a basis for analysis of the variation of equation 3 with position over the pond. As the atmosphere travels over the pond, the term ($q_1 - q_2$) decreases with time due to the following:

a. The specific humidity of the air, q_2, initially is a function of the dew point, and is less than the saturation specific humidity. As the air receives water vapor from the pond, saturation is reached, increasing the value of q_2.
b. As further moisture is received by the air after it has reached saturation, the water vapor condenses into liquid water, releasing the latent heat during condensation of the water vapor. This further increases q_2.
c. As fog is formed, the radiation from the pond is reflected and absorbed by the water droplets, further increasing the air temperature and hence, q_2.
d. Convection of heat from the pond surface to the atmosphere still further increases q_2.

As the above four mechanisms cause an increase in q_2, the term $q_1 - q_2$ decreases and hence the evaporation into a parcel of air traversing the pond decreases. The first two mechanisms are quantifiable and were used to determine the weighting factor for adjusting evaporation rate with traverse time. Radiation effects were not computed, and the vertical dispersion was assumed invariant with height. Thus the initial "weighted factor" did not take mechanisms (c) and (d) into account. During the verification program, it was determined the "weighted factor" did not sufficiently suppress the evaporation rate with time, probably due to the above considerations. Therefore, this factor was adjusted and the program rerun for six selected cases.

Figure 5 shows the resulting weighting factor as a function of traverse time over a water surface. The values of this curve are a function of the value of k selected for equation 1. Had a larger value for k been chosen, less suppression of evaporation rate would have been needed. Thus, the physical significance of this curve is in its shape not its absolute values.

Figure 5 Weighted Factor versus Transit Time over Water Surface



RESULTS

The model has been applied to proposed designs for cooling ponds, using design pond temperatures. A map of the pond and the visibility patterns are drawn based upon the computer printout. A mapping of the isopleths of visibility reveals the extent of fog of varying density over the pond and the adjoining land area. The frequency of occurrence of the mapped fog patterns is determined from climatological records for the region, showing the history of occurrence of the atmospheric temperature, humidity and wind direction required to produce the given fog pattern.

The fog as simulated by the program reflects reasonably well the observed fog. For example, at low humidities the fog dissipates within relatively short distances after leaving the pond - at 100 meters or less. Whereas at higher humidities it tends to persist to greater distances from the pond and the visibility restrictions taper off more gradually. The denser fog is associated with the warmer sections of the pond. Increased wind speed tends to carry the fog farther from the pond, but results in lesser restrictions to visibility over a large part of the fog bank.

The simulated fog is occasionally different from observed fog, principally in the lack of the cellular makeup of fog. In real fog, one can note that there are variations of visibility on a patchy basis. The simulation predicts lesser restrictions to visibility as the edge of the fog boundary is approached, but does not predict asymmetrical or patchy conditions. The observed cases of fog with widely varying visibilities (in both time and space) were not reproducible by the simulation program and were therefore not used in the verification tests.

The simulation program can assist greatly in quantifying visibility restrictions, spatial extent of fogging and frequency of occurrence of fog associated with specific cooling pond characteristics. It is therefore useful in design considerations for a cooling pond and in reporting the environmental effect of a cooling pond.

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