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Atmospheric Turbulence and Diffusion Laboratory

Oak Ridge, Tennessee

COOLING TOWER PLUME RISE AND CONDENSATION

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1. INTRODUCTION

Recent regulations discourage the use of river or lake water for direct cooling in industrial processes. The trend is towards the increased use of evaporative cooling towers, in which hot water is cooled by the evaporation of part of the water into a passing air stream. The vertical flow of air through the tower can be driven by natural buoyancy forces or by fans. In order to estimate the effects on the environment of heat and moisture discharges from proposed cooling towers, it is necessary to develop theoretical or empirical models of these physical processes and verify them with observations. It is clear from the few environmental impact statements that we have seen (references 1 and 2 are good examples) that there currently are no standard methods for estimating plume rise and cloud formation from cooling towers. Furthermore, observations of cooling tower plumes are very limited. In this paper, methods of estimating cooling tower plume rise and the possibility of condensation will be outlined.

Our ultimate goal is to reduce the environmental impact of plumes from cooling towers as much as possible. The environmental impact can be described by several criteria, including increases in local and regional temperature, cloudiness, fog, and rainfall. Local surface effects depend strongly on plume rise. Regional temperature and moisture increases depend on the non-linear interaction between the heat and moisture in the plume and in the environment. As suggested by Hanna and Swisher⁽³⁾, the regional problem can be analyzed using mesoscale or synoptic-scale computer models of the atmosphere. The Gaussian plume model outlined by Slade⁽⁴⁾ may not be practical for estimating dispersion on regional scales (10 km or greater).

2. PLUME RISE

In this section problems involving total plume rise and the effects of tower configuration are discussed. In order to provide a comprehensive list of useful equations in the space available, lengthy derivations of many of the formulas will be omitted. Complete derivations are given in previous reports by Hanna⁽⁵⁾,⁽⁶⁾ and Briggs⁽⁷⁾.

2.1 Basic Plume Rise Formulas

According to Briggs⁽⁷⁾, the final rise H of dry plumes dominated by buoyancy in a stable atmosphere can be approximated by the equations:

$$H = 5.0 F_o^{1/4} s^{-3/8} \quad (\text{Calm}) \quad (1)$$

$$H = 2.9 (F_o/U_s)^{1/3} \quad (\text{Windy}), \quad (2)$$

where U is the wind speed, s is the stability parameter $(g/T_p)(\partial\theta_e/\partial z)$, and F_o is the initial sensible heat flux

$$F_o = (g/T_p) w_o R_o^2 (T_{po} - T_{eo}).$$

The factor π is omitted from all flux formulations. The parameters g , T , θ , w , and R are the acceleration of gravity, the temperature, the potential temperature, the vertical speed of the plume, and the plume radius, respectively. The subscripts p, e, o, s represent plume, environment, initial, and saturation variables, respectively. In these equations, plume rise depends only on the initial energy flux from the tower and the wind speed and stability of the environment. Equations (1) and (2) have been verified by observations of plume rise from conventional smoke stacks over many orders of magnitude of initial heat flux F_o .

Unlike most conventional smoke stack plumes, the cooling tower plume carries more latent heat than sensible heat. For the range of typical cooling tower parameters listed in Table 1, about 90% of the energy leaving the tower is in the form of latent heat. If this latent heat is not released to the atmosphere through condensation, then plume rise can be calculated using the sensible heat flux F_o in equations (1) or (2). In order to account for the difference in molecular weight between air and water vapor, the virtual temperature T_v should be used rather than actual temperature T . The resulting plume rise calculations differ by less than 10%.

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TABLE 1

Buoyancy due to molecular weight differences, and to potential latent heat release, divided by buoyancy due to initial temperature differences. Typical cooling tower plumes and environment initial temperature and environment relative humidities RH are considered. The plume is initially saturated.

T_{po}	T_{eo}	$\frac{.61(m_{po} - m_{eo})T_{po}}{(T_{po} - T_{eo})}$		$\frac{L(m_{po} - m_{eo})}{c_p(T_{po} - T_{eo})}$	
		100%RH	60%RH	100%RH	60%RH
305°K	275°K	.15	.16	2.32	2.48
315	285	.26	.29	3.91	4.24
305	285	.19	.22	2.88	3.37
315	295	.31	.39	4.63	5.68
305	295	.24	.36	3.60	5.43

If all the latent heat is released and all the resulting liquid water drops from the plume, then the total heat flux F_o is the sum of the sensible heat flux and the latent heat flux:

$$F_o = w_o R_o^2 g \left(\frac{T_{po} - T_{eo}}{T_{po}} + \frac{L}{c_p T_{po}} (m_{po} - m_{eo}) \right) \quad (3)$$

where L is the latent heat of condensation, c_p is the specific heat of air at constant pressure, and m is the water vapor mixing ratio. The release of latent heat thus can increase the heat flux F_o several times and can theoretically increase plume rise by 50 to 80% for the cases considered in Table 1. If only a fraction of the initial latent heat flux is released, then the second term in equation (3) must be multiplied by this fraction in order to more accurately estimate plume rise. Techniques for calculating the fraction of latent heat released are suggested in Section 3.

The plume rise calculated using a numerical cloud growth model (5) was compared with the rise predicted using equations (1) and (2) for a variety of initial and environment conditions. For dry plumes, agreement was $\pm 10\%$ and for cases in which condensation occurred, agreement was $\pm 50\%$. Consequently, it is believed that the simple equations (1) and (2) can be used to estimate plume rise within an error of $\pm 50\%$, even when a cloud forms in the plume.

2.2 Influence of Initial Radius on Plume Rise

If the energy flux, F_o , volume flux, $V_o = w_o R_o^2$, and environmental conditions are constant, then the question arises of whether plume rise can be increased by varying the cooling tower radius. Equations (1) and (2) are derived by assuming point sources of heat but are well proven by observations. If the full set of governing equations for plume rise are integrated, then factors such as initial source radius can be shown to have minor effects.

Since the relative rate at which environment air is entrained into the plume is inversely proportional to plume radius, it can be argued that the plume from a wide source will lose its buoyancy more slowly than a similar plume from a narrow source. On the basis of laboratory simulations in a calm environment, Brown and Sneck(8) state that increases in source radius can increase plume rise by several percent. However, integrations of the equations of motion(6) show that Brown and Sneck's conclusion is valid only for values of the dimensionless parameters $s R_o/b_o$ less than unity and $w_o^2 s/2 b_o^2$ less than two, where $b_o = F_o/V_o$. This usually occurs for small, buoyancy dominated energy sources (F_o less than about 10 megawatts). Since Brown and Sneck's model source is characterized by $s R_o/b_o$ less than .1, their observations validate the theory. However, for the energy fluxes typical of large hyperbolic cooling towers (100 or more megawatts per unit), it is predicted that increases in tower radius will decrease plume rise slightly. A good general rule of thumb is that when the ratio of expected plume rise to source radius drops below about ten, then increases in source radius (at constant volume and heat flux) will not increase total plume rise.

2.3 Downwash of Plume

Even if it were theoretically possible to increase plume rise by increasing the size of the tower opening, the resulting low efflux speed, w_0 , could result in the downwash of the plume behind the tower during windy conditions. Briggs⁽⁷⁾ suggests that downwash of the plume from a narrow, straight-sided stack will occur if the ratio w_0/U is less than about 1.5, for initial stack Froude numbers ($Fr_0 = w_0^2/2 R_0 b_0$) greater than about five. Overcamp and Hault⁽⁸⁾ on the basis of laboratory simulations and theoretical work, suggest that the critical value of w_0/U decreases to .5 at Fr_0 equal to .25 and decreases further to .2 at Fr_0 equal to .01. The Froude number Fr_0 ranges from about .5 to 1.5 for the typical data in Table 1, and for efflux speed and radius equal to about 5 m/sec and 30 m, respectively. Since the Froude number for most large cooling towers is on the order of unity, this theory predicts that downwash is likely to occur if the wind speed U is greater than the efflux speed w_0 . However, downwash is not observed, for example, at the large Keystone hyperbolic cooling towers, where the environment wind speed, U , often exceeds the efflux speed, 5 m/sec. The inhibition of downwash is probably partly due to the tower's hyperbolic shape, which displaces the low pressure zone downwards from the lip of the tower.

Downwash has been observed at banks of mechanical draft towers, where the bulky shapes of the towers present more of an obstacle to the airflow. The probability of downwash can be decreased by separating the individual towers, increasing the efflux speed, and encouraging flaired geometrical shapes. If the possibility of downwash can be eliminated, then problems associated with rain-out and fogging at the ground near the towers can be reduced.

2.4 Multiple Sources

The plume rise theory outlined above applies only to single, isolated, sources. At some large power plants, the problem exists of calculating the plume rise from a line of about ten mechanical draft cooling towers. The total rise of all the plumes is probably greater than the rise calculated using the heat flux from a single tower but less than the rise calculated using the combined flux from all the towers. Based on an unpublished analysis of TVA data, Briggs suggests that the total plume rise is influenced by the spacing of the towers and the angle between the wind direction and the line of the towers. He defines a "spacing factor," S , as the ratio of the crosswind component of the spacing of the towers to the plume rise expected from a single tower. The closer the towers, the more the individual plumes will interact. The rough rule that he suggests is that for S less than .1, the plume rise in windy conditions from two, three, and four towers will be 20%, 30%, and 40%, respectively, greater than the rise calculated for a single tower. For S greater than .25, interaction of the plumes can be ignored. Unfortunately, there are currently no published data on plume rise either from more than four multiple sources or from any banks of cooling towers to check these suggestions. There is a need for basic observations of cooling tower plumes.

On the basis of the discussions with respect to the problems of downwash and plume rise from multiple sources, it is clear that the use of a single hyperbolic tower will result in greater plume rise than the use of banks of mechanical draft towers, for a given heat flux. A single hyperbolic tower is not as susceptible to downwash as a bank of smaller towers, and its single plume rises higher than their combined plumes. Also, large hyperbolic towers have the added benefit of being taller than mechanical draft towers.

3. CONDENSATION IN THE PLUME

Qualitatively, condensation occurs in a plume if the flux of water from the cooling tower is sufficient to saturate the initial volume flux plus the flux of air entrained into the plume as it rises. It is important to know the characteristics of the entrained air since the flux of entrained air in the plume is usually at least an order of magnitude greater than the initial volume flux, by the time the plume nears its level of maximum rise.

The initial flux of water Q_0 (in mass per unit time) is defined by the equation:

$$Q_0 = \rho_0 V_0 (m_{p0} + \sigma_{p0}), \quad (4)$$

where ρ_0 and σ_{p0} are the initial air density and liquid water mixing ratio (gm water per gm of air). It is assumed that vertical speed, concentration of water vapor, and other variables are constant across a given plume cross-section. The flux of water Q_s at level z that would saturate the plume is given by the relation:

$$Q_s(z) = \rho(z) \left[V_0 m_{ps}(z) + \left(V(z) - V_0 \right) \left(m_{ps}(z) - \bar{m}_e(z) \right) \right], \quad (5)$$

where \bar{m}_e is the average mixing ratio of the air entrained into the plume, defined by

$$\bar{m}_e(z) = \left[\int_0^z m_e(\eta) \left(\partial V(\eta) / \partial \eta \right) d\eta \right] / \left[V(z) - V_0 \right]. \quad (6)$$

The term $(m_{ps} - \bar{m}_e)$ is sometimes called the "saturation deficit." Saturation is more likely to be achieved in an environment where the saturation deficit is small; e.g. a cold environment or a warm humid environment. Because the water vapor mixing ratio generally decreases with height, the average mixing ratio \bar{m}_e in the plume at level z is generally greater than the mixing ratio m_e in the local environment. It is then possible for Q_s to drop below zero at some height as T_p approaches T_e , even if the plume initially contains no excess water. In this case, condensation will occur at the level of natural cloud formation.

The ratio $(Q_0 - Q_s(z))/Q_0$ is defined as the fraction, A , of the initial water flux Q_0 that is condensed at any level. If there is an initial liquid water flux, $\rho_0 \sigma_{po} V_0$, the fraction, B , of this flux remaining as liquid water in the plume at level z can be estimated from the equation

$$B = -AQ_0 / \rho_0 V_0 \sigma_{po} \quad (Q_s > Q_0) . \quad (7)$$

When B increases to unity, all the initial liquid water has evaporated.

3.1 Level of First Condensation

The fraction A of the initial water flux that is condensed is thus equal to the ratio

$$A = 1 - \frac{\rho(z)}{\rho_0} \frac{V(z)}{V_0} \frac{\left[m_{ps}(z) - \left(1 - \frac{V_0}{V(z)} \right) \bar{m}_e(z) \right]}{(m_{po} + \sigma_{po})} . \quad (8)$$

It is seen that A is a function of the initial plume mixing ratio, the vertical variation of plume and environment mixing ratio, and the dimensionless ratios $\rho(z)/\rho_0$ and $V(z)/V_0$. For heights less than two or three kilometers, the ratio $\rho(z)/\rho_0$ can be approximated by the simple expression $\exp(-gz/R_d\bar{T})$, where R_d is the gas constant for dry air. The saturation mixing ratio m_{ps} is a function of height and temperature and can be approximated by the analytical expression:

$$m_{ps} = m_{eso} e^{\frac{-gz}{R_d\bar{T}}} e^{\frac{L}{R_v\bar{T}^2} (T_e - T_{eo})} e^{\frac{L}{R_v\bar{T}^2} (T_p - T_e)} , \quad (9)$$

where R_v is the gas constant for water vapor. The temperature difference $(T_e - T_{eo})$ is known from the vertical distribution of environment temperature and the temperature difference $(T_p - T_e)$ is obtained from the definition

$$(T_p - T_e) = (T_{po} - T_{eo}) \frac{F(z)}{F_0} \frac{V_0}{V(z)} . \quad (10)$$

The ratios $F(z)/F_0$ and $V(z)/V_0$ can be calculated using Briggs' (7) theory of plume rise. Detailed derivations of the following analytical expressions can be found in reference 6:

$$\frac{V(z)}{V_0} = \left(1 + .5 \frac{z}{R_0} \left(\frac{U}{w_0} \right)^{1/2} \right)^2 \quad \text{Windy} \quad (11)$$

$$\frac{V(z)}{V_0} = \left(1 + .2 \left(\frac{15}{8Fr_0} \right)^{1/5} \frac{z}{R_0} \right)^{5/3} \quad \text{Calm} \quad (12)$$

$$\frac{F(z)}{F_0} = 1 - \frac{s}{b_0} \left(\frac{w_0}{U} \right)^{1/2} \frac{R_c}{1.5} \left\{ \left(1 + .5 \frac{z}{R_0} \left(\frac{U}{w_0} \right)^{1/2} \right)^3 - 1 \right\} \quad \text{Windy} \quad (13)$$

$$\frac{F(z)}{F_0} = 1 - \frac{15}{8} \frac{sR_0}{b_0} \left(\frac{15}{8Fr_0} \right)^{-1/5} \left\{ \left(1 + .2 \left(\frac{15}{8Fr_0} \right)^{1/5} \frac{z}{R_0} \right)^{8/3} - 1 \right\} \quad \text{Calm} \quad (14)$$

The ratios of volume fluxes $V(z)/V_0$ are plotted as a function of z/R_0 for various values of U/w_0 and Fr_0 in Figure 1.

Using the above formulas, it is possible to calculate the fraction A of the initial water flux that is condensed at any level z , based on the initial plume conditions and the vertical variation of environment temperature and wind speed. As Morton⁽⁹⁾ concluded from his analysis of moist plume rise during calm conditions, plume rise is highly sensitive to slight variations in environmental mixing ratio. There is a thin line between no cloud development and explosive cloud development.

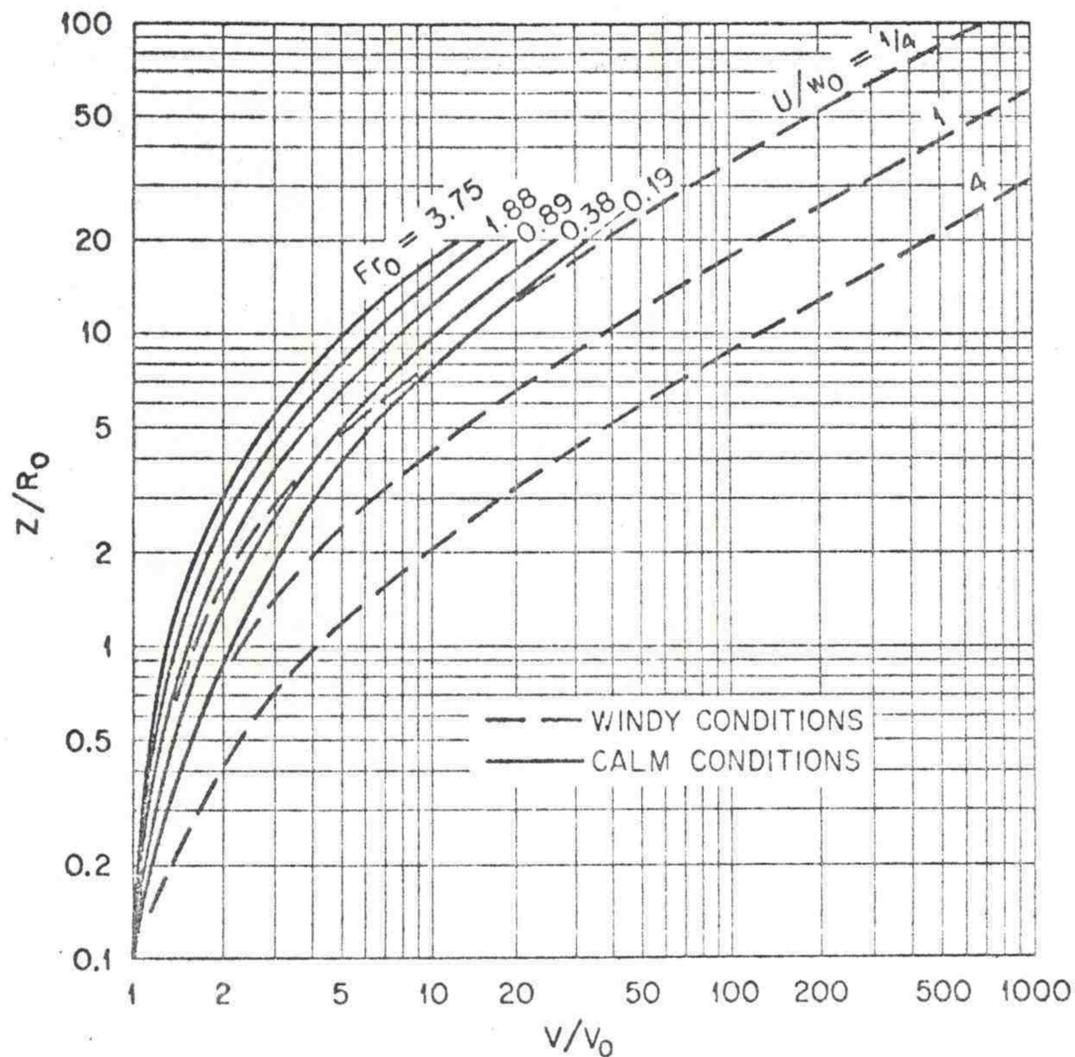


Figure 1. The ratio of the volume flux V to initial volume flux V_0 , as a function of the ratio of height z to initial radius R_0 , for windy conditions at various values of U/w_0 , and calm conditions at various values of $Fr_0 = w_0^2/2R_0b_0$.

As an example of the application of these techniques, consider a plume in a well-mixed atmosphere at great heights, such that potential temperature and mixing ratio are constant with height ($\theta_e = \theta_{e0}$ and $m_e = m_{e0}$) and plume temperature equals environment temperature. Under these conditions, the plume saturation mixing ratio m_{ps} can be approximated by $m_{eos} \exp(-4.5 gz/R_d \bar{T})$. Furthermore, assume that the scale height of the atmosphere, $R_d \bar{T}/g$, is 8000 m, and the initial liquid water content, σ_{p0} , is zero. Then equation (8) becomes:

$$A(z) = 1 - e^{\frac{-z}{8000m} \left(1 + .5 \frac{z}{R_0} \left(\frac{U}{w_0} \right)^{1/2} \right)^2} \frac{\left[e^{\frac{-z}{1800m} - RH_0 \left(1 - 1 / \left(1 + .5 \frac{z}{R_0} \left(\frac{U}{w_0} \right)^{1/2} \right)^2 \right)} \right]}{m_{p0}/m_{eos}} \quad (15)$$

where RH_0 equals m_{e0}/m_{eos} . In a specific case, for example, $R_0 = 30$ m, $U/w_0 = 4.0$, $m_{p0}/m_{eos} = 3.2$, and $RH_0 = .8$. The first level of condensation ($A(z)=0$) is at 370 m, and the level at which a quantity of water equal to the initial water flux condenses ($A(z)=1$) is at 410m. This is the height at which an initially dry plume would begin to condense.

After working a few examples, one find that the above condensation criterion is sensitive to slight variations in the variables U/w_0 , RH_0 , and m_{p0}/m_{eos} . However, we know from many years of experience that the analogous problem of the prediction of the formation of cloud layers is also very difficult.

3.2 Iterative Technique for Estimating Plume Rise

It was mentioned in Section 2 that the plume rise equations (1) and (2) are adequate for calculating cooling tower plume rise, provided that the initial latent heat flux is accounted for when calculating the total initial energy flux F_0 . Now that we have developed methods for estimating the fraction of the initial water flux that is condensed, it is possible to estimate the latent heat flux at the height, H , of final plume rise. The first estimate of plume rise, H_1 , is calculated assuming that no vapor has condensed. Then the fraction A_1 of the initial water flux condensed at level H_1 is calculated. The value, A_1 , is then multiplied by the total possible latent heat flux and the new heat flux is used to calculate a new estimate of plume rise H_2 . This procedure is repeated until plume rise, H , and fraction of initial water condensed, $A(H)$, approach constants.

4. ADDITIONAL REMARKS

It is seen that cooling tower plume rise can be easily calculated for either uncondensed or completely condensed plumes. Due to the sensitivity of the condensation processes to slight changes in, for example, environment mixing ratio, cooling tower plume rise in borderline cases can not be calculated with so much confidence. It is because of this sensitivity that observation programs of cooling tower plumes will require much attention to detail.

In writing environmental impact statements, it is necessary to determine the diffusion of water vapor or drops to the ground from the elevated cooling tower plume. The usual assumption is that water vapor diffuses in the same manner as an inert gas. Consequently the Gaussian dispersion equation ⁽⁴⁾ may possibly be used, knowing the approximate wind speed and stability class. It is necessary to conduct a comprehensive observation program to determine the limitations of the simple Gaussian equation. If a thin elevated inversion layer is between the plume axis and the ground, dispersion of moisture to the ground may be inhibited. Nonlinear interactions between plume and environment heat and moisture may also prove to be important.

The techniques discussed in this paper provide a starting point for the analysis of the environmental impact of cooling tower plumes. Observations of the rise, condensation, and dispersion of cooling tower plumes are practically non-existent. Much more research needs to be done with respect to cooling tower behavior.

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