Calculating Realistic PM_{10} Emissions from Cooling Towers

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Emissions of particulate matter less than 10 micrometers in diameter (PM_{10}) from wet cooling towers may be calculated using the methodology presented in EPA's AP-42 [1], which assumes that all total dissolved solids (TDS) emitted in "drift" particles (liquid water entrained in the air stream and carried out of the tower through the induced draft fan stack) are PM_{10}. However, this assumption is overly conservative because it does not consider that, upon evaporation of the drift, many of the solid particles that remain are ***larger*** *than PM_{10}. Particles larger than 10 micrometers do not represent a health hazard and are* ***not*** *regulated under current air quality regulations. For example, for wet cooling towers with medium to high TDS levels, the AP-42 methodology predicts significantly higher PM_{10} emissions than would actually occur, even for towers equipped with very high efficiency drift eliminators (e.g., 0.0006% drift rate). Such over-prediction may result in unrealistically high PM_{10} modeled concentrations and/or the need to purchase expensive Emission Reduction Credits (ERCs) in PM_{10} non-attainment areas. Since these towers have fairly low emission points (10 to 15 m above ground), over-predicting PM_{10} emission rates can also result in exceeding federal Prevention of Significant Deterioration (PSD) significance levels at a project's fenceline. This paper presents a method for computing realistic PM_{10} emissions from cooling towers with medium to high TDS levels by enabling the engineer to determine the PM_{10} mass fraction of the total amount of particulate emitted by a cooling tower.*

INTRODUCTION

Cooling towers are heat exchangers used to dissipate large heat loads to the atmosphere. Wet, or evaporative, cooling towers rely on the latent heat of water evaporation to exchange thermal energy between the process and the air passing through the cooling tower. The cooling water may be an integral part of the process or may provide cooling via heat exchangers, for example, steam condensers. Wet cooling towers provide direct contact between the cooling water and air passing through the tower, and as part of normal operation, a very small amount of the circulating water may be entrained in the air stream and be carried out of the tower as "drift" droplets. Because the drift droplets contain the same chemical impurities as the water circulating through the tower, the particulate matter within the drift droplets may be classified as an emission. The magnitude of the drift loss is influenced by the number and size of droplets produced within the tower, which are determined by fill design, tower design, the air and water patterns, and design of the drift eliminators.

AP-42 METHOD OF CALCULATING DRIFT PARTICULATE

EPA's AP-421 provides available particulate emission factors for wet cooling towers, however, these values only have an emission factor rating of "E" (the lowest level of confidence acceptable). They are also rather high, compared to typical present-day manufacturers' guaranteed drift rates, which are on the order of 0.0006%. (Drift emissions are typically expressed as a percentage of the cooling tower water circulation rate). AP-42 states that "a *conservatively high* PM_{10} emission factor can be obtained by: (a) multiplying the total liquid drift factor by the TDS fraction in the circulating water, and (b) assuming that once the water evaporates, all remaining solid particles are within the PM10 range." (Italics per EPA).

If TDS data for the cooling tower are not available, a source-specific content can be estimated by obtaining the TDS for the make-up water and multiplying it by the cooling tower cycles of concentration. (The cycles of concentration is the ratio of a measured parameter for the cooling tower water [such as conductivity, calcium, chlorides, or phosphate] to that parameter for the make-up water.)

Using AP-42 guidance, the total particulate emissions (PM), after the pure water has evaporated, can be expressed as:

$$PM = \text{Water Circulation Rate x Drift Rate x TDS} \quad (1)$$

For example, for a typical power plant wet cooling tower with a water circulation rate of 146,000 gallons per minute (gpm), drift rate of 0.0006%, and TDS of 7,700 parts per million by weight (ppmw):

PM = 146,000 gpm x 8.34 lb water/gal x 0.0006/100 x 7,700 lb solids/10^6 lb water x 60 min/hr = 3.38 lb/hr

On an annual basis, this is equivalent to almost 15 tons per year (tpy). Even for a state-of-the-art drift eliminator system, this is not a small number, especially if assumed to all be equal to PM_{10}, a regulated criteria pollutant. However, as the following analysis demonstrates, only a very small fraction is actually PM_{10}.

COMPUTING THE PM_{10} FRACTION

Based on a representative drift droplet size distribution and TDS in the water, the amount of solid mass in each drop size can be calculated. That is, for a given initial droplet size, assuming that the mass of dissolved solids condenses to a spherical particle after all the water evaporates, and assuming the density of the TDS is equivalent to a representative salt (e.g., sodium chloride), the diameter of the final solid particle can be calculated. Thus, using the drift droplet size distribution, the percentage of drift mass containing particles small enough to produce PM_{10} can be calculated. This method is conservative as the final particle is assumed to be perfectly spherical, hence, as small a particle as can exist.

The droplet size distribution of the drift emitted from the tower is critical to performing the analysis. Brentwood Industries, a drift eliminator manufacturer, was contacted and agreed to provide drift eliminator test data from a test conducted by Environmental Systems Corporation (ESC) at the Electric Power Research Institute (EPRI) test facility in Houston, Texas, in 1988. The particle size distribution is included in the first and last columns of Tables 1 and 2. The data consist of water droplet size distributions for a drift eliminator that achieved a tested drift rate of 0.0003%. As we are using a 0.0006% drift rate, it is reasonable to expect that the 0.0003% drift rate would produce smaller droplets, therefore, this size distribution data can be assumed to be *conservative* for predicting the fraction of PM_{10} in the total cooling tower PM emissions.

In calculating PM_{10} emissions, the following assumptions were made:

- Each water droplet was assumed to evaporate shortly after being emitted into ambient air, into a single, solid, spherical particle.
- Drift water droplets have a density (ρ_w) of water; 1.0 g/cm^3 or 1.0 * 10^{-6} µg/µm^3.
- The solid particles were assumed to have the same density (ρ_{TDS}) as sodium chloride, (i.e., 2.2 g/cm^3).

Using the formula for the volume of a sphere, $V=4\pi r^3/3$, and the density of pure water, $\rho_w=1.0$ g/cm^3, the following equations can be used to derive the solid particulate diameter, D_p, as a function of the TDS, the density of the solids, and the initial drift droplet diameter, D_d:

$$\text{Volume of drift droplet} = (4/3)\pi(D_d/2)^3 \quad (2)$$

$$\text{Mass of solids in drift droplet} = (TDS)(\rho_w)(\text{Volume of drift droplet}) \quad (3)$$

substituting,

$$\text{Mass of solids in drift} = (TDS)(\rho_w)(4/3)\pi(D_d/2)^3 \quad (4)$$

Assuming the solids remain and coalesce after the water evaporates, the mass of solids can also be expressed as:

$$\text{Mass of solids} = (\rho_{TDS})\,(\text{solid particle volume}) = (\rho_{TDS})\,(4/3)\pi(D_p/2)^3 \quad (5)$$

Equations 4 and 5 are equivalent:

$$(\rho_{TDS})\,(4/3)\pi(D_p/2)^3 = (TDS)\,(\rho_w)(4/3)\pi(D_d/2)^3 \quad (6)$$

Solving for D_p:

$$D_p = D_d\,[(TDS)(\rho_w/\rho_{TDS})]^{1/3} \quad (7)$$

Where:
TDS is in units of ppmw
D_p = diameter of solid particle, micrometers (µ*m*)
D_d = diameter of drift droplet, µm

Using Formulas 2 through 7 and the particle size distribution test data, Table 1 can be constructed for drift from a wet cooling tower having the same characteristics as our example: 7,700 ppmw TDS and a 0.0006% drift rate. The first and last columns of this table are the particle size distribution derived from test results provided by Brentwood Industries. Using straight-line interpolation for a solid particle size 10 µm in diameter, we conclude that approximately 14.9% of the mass emissions are equal to, or smaller than, PM_{10}. The balance of the solid material are particulates greater than 10 µm. Hence, PM_{10} emissions from this tower would be equal to PM emissions x 0.149, or 3.38 lb/hr x 0.149 = 0.50 lb/hr. The process is repeated in Table 2, with all parameters equal except that the TDS is 11,000 ppmw. The result is that approximately 5.11% are smaller at 11,000 ppm. Thus, while total PM emissions are larger by virtue of a higher TDS, overall PM_{10} emissions are actually *lower*, because more of the solid particles are larger than 10 µm.

The percentage of PM_{10}/PM was calculated for cooling tower TDS values from 1,000 to 12,000 ppmw and the results are plotted in Figure 1. Using these data, Figure 2 presents predicted PM_{10} emission rates for the 146,000 gpm example tower. As shown in this Figure, the PM emission rate increases in a straight line as TDS increases, however, the PM_{10} emission rate increases to a maximum at around a TDS of 4,000 ppmw, and then *begins to decline*. The reason is that at higher TDS, the drift droplets contain more solids

Table 1. Resultant solid particulate size distribution (TDS = 7,700 ppmw).

EPRI Droplet Diameter (μm)	Droplet Volume (μm^3) [2][1]	Droplet Mass (μg) [3]	Particle Mass (Solids) (μg) [4]	Solid Particle Volume (μm^3)	Solid Particle Diameter (μm) [7]	EPRI % Mass Smaller
10	524	5.24E-04	4.03E-06	1.83	1.518	0.000
20	4189	4.19E-03	3.23E-05	14.66	3.037	0.196
30	14137	1.41E-02	1.09E-04	49.48	4.555	0.226
40	33510	3.35E-02	2.58E-04	117.29	6.073	0.514
50	65450	6.54E-02	5.04E-04	229.07	7.591	1.816
60	113097	1.13E-01	8.71E-04	395.84	9.110	5.702
70	179594	1.80E-01	1.38E-03	628.58	10.628	21.348
90	381704	3.82E-01	2.94E-03	1335.96	13.665	49.812
110	696910	6.97E-01	5.37E-03	2439.18	16.701	70.509
130	1150347	1.15E+00	8.86E-03	4026.21	19.738	82.023
150	1767146	1.77E+00	1.36E-02	6185.01	22.774	88.012
180	3053628	3.05E+00	2.35E-02	10687.70	27.329	91.032
210	4849048	4.85E+00	3.73E-02	16971.67	31.884	92.468
240	7238229	7.24E+00	5.57E-02	25333.80	36.439	94.091
270	10305995	1.03E+01	7.94E-02	36070.98	40.994	94.689
300	14137167	1.41E+01	1.09E-01	49480.08	45.549	96.288
350	22449298	2.24E+01	1.73E-01	78572.54	53.140	97.011
400	33510322	3.35E+01	2.58E-01	117286.13	60.732	98.340
450	47712938	4.77E+01	3.67E-01	166995.28	68.323	99.071
500	65449847	6.54E+01	5.04E-01	229074.46	75.915	99.071
600	113097336	1.13E+02	8.71E-01	395840.67	91.098	100.000

[1] Bracketed numbers refer to equation number in text.

Table 2. Resultant solid particulate size distribution (TDS = 11,000 ppmw).

EPRI Droplet Diameter (μm)	Droplet Volume (μm^3) [2][1]	Droplet Mass (μg) [3]	Particle Mass (Solids) (μg) [4]	Solid Particle Volume (μm^3)	Solid Particle Diameter (μm) [7]	EPRI % Mass Smaller
10	524	5.24E-04	5.76E-06	2.62	1.710	0.000
20	4189	4.19E-03	4.61E-05	20.94	3.420	0.196
30	14137	1.41E-02	1.56E-04	70.69	5.130	0.226
40	33510	3.35E-02	3.69E-04	167.55	6.840	0.514
50	65450	6.54E-02	7.20E-04	327.25	8.550	1.816
60	113097	1.13E-01	1.24E-03	565.49	10.260	5.702
70	179594	1.80E-01	1.98E-03	897.97	11.970	21.348
90	381704	3.82E-01	4.20E-03	1908.52	15.390	49.812
110	696910	6.97E-01	7.67E-03	3484.55	18.810	70.509
130	1150347	1.15E+00	1.27E-02	5751.73	22.230	82.023
150	1767146	1.77E+00	1.94E-02	8835.73	25.650	88.012
180	3053628	3.05E+00	3.36E-02	15268.14	30.780	91.032
210	4849048	4.85E+00	5.33E-02	24245.24	35.909	92.468
240	7238229	7.24E+00	7.96E-02	36191.15	41.039	94.091
270	10305995	1.03E+01	1.13E-01	51529.97	46.169	94.689
300	14137167	1.41E+01	1.56E-01	70685.83	51.299	96.288
350	22449298	2.24E+01	2.47E-01	112246.49	59.849	97.011
400	33510322	3.35E+01	3.69E-01	167551.61	68.399	98.340
450	47712938	4.77E+01	5.25E-01	238564.69	76.949	99.071
500	65449847	6.54E+01	7.20E-01	327249.23	85.499	99.071
600	113097336	1.13E+02	1.24E+00	565486.68	102.599	100.000

[1] Bracketed numbers refer to equation number in text.