Sizing of plume abatement coils

Plume abatement coils are used to reduce/prevent visible plumes of moisture exiting a wet cooling tower fan stack. Typically, this is done by mixing in dry, heated ambient air with the moist air stream exiting the drift eliminators. The cold ambient air passes over the "airside" of the coil and is heated by transferring heat from a hot fluid source flowing on the "tube side" of the coil. The article will present the methodology and equations required to budget size the overall plume abatement coil surface area required.

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Plume abatement coils can be used in both counter flow or cross flow cooling towers as shown in Figures 1 and 2. The plume abatement coils sit above the water distribution system and drift eliminators on the perimeter/sides of the tower. Dry air from ambient is drawn through the plume abatement coils and is mixed with the moist air exiting the drift eliminators. The resultant air mixture is then expelled from the cooling tower via the fan and fan stack.

The following is a basic method to size plume abatement coils used in wet cooling towers. It should be noted that the following method is accurate to only +/-10% and should only be used for scoping and/or budget calculations.

About the author

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Basic coil design and assumptions

A typical plume abatement coil is shown in Figures 3 and 4. As shown in Figures 1 or 2, ambient air enters the plume abatement coil and is heated via a hot fluid to a predetermined temperature needed to mix with the moist air and abate the plume. For this sizing calculation, the following assumptions have been made:

- The heat exchanger is a one-pass cross flow with both fluids unmixed.
- The process fluid is water from the hot water basin.
- The tube side fouling factor (f) is 0.00026 sqm K / W (0.0015 sqft hr F / Btu)
- The air to be heated is ambient air.
- Tube side pressure drop is between 0 and 240 N/sqm (0 and 5 lb/sqin)
- Process tube material is carbon steel with extended wrap on aluminum fins.
- Process tubes are 25.4 mm (1.0 inch) in diameter and between 0.89 mm (0.035 inch) and 2.77 mm (0.109 inch) thick.
- Extended fins are 15.88 mm (0.625 inch) high, 0.41 mm (0.016 inch) thick and have a spacing of 394 fins/m (10.0 fins/inch).
- Tubes are in a staggered pitch pattern with the transverse pitch (Pt) being 63.5 mm (2.50 inch) and the longitudinal pitch (Pl) being 55.0 mm (2.165 inch) as shown in Figure 5.

Coil thermal sizing

The method employed here to thermally size the coil will be the NTU Method as described in *Compact Heat Exchangers* (Reference 1) as well as in the *Fundamentals of Heat and Mass Transfer* (Reference 2) as applied to plume abatement coils. The following are the equations to determine the total surface area required to thermally size the coil.

The required duty of the coil(s) can be determined as follows:

$$Q_a = M_a\, cp_a\, (T_{ai} - T_{ao}) \qquad \text{(Eq. 1)}$$

Next, a heat balance is performed where $Q_a = Q_h$:

$$Q_a = Q_h = Q = M_h\, cp_h\, (T_{hi} - T_{ho}) \qquad \text{(Eq. 2)}$$

From here, we solve for M_h assuming a temperature difference between T_{hi} and T_{ho}:

$$M_h = Q / (cp_h\, (T_{hi} - T_{ho})) \qquad \text{(Eq. 3)}$$

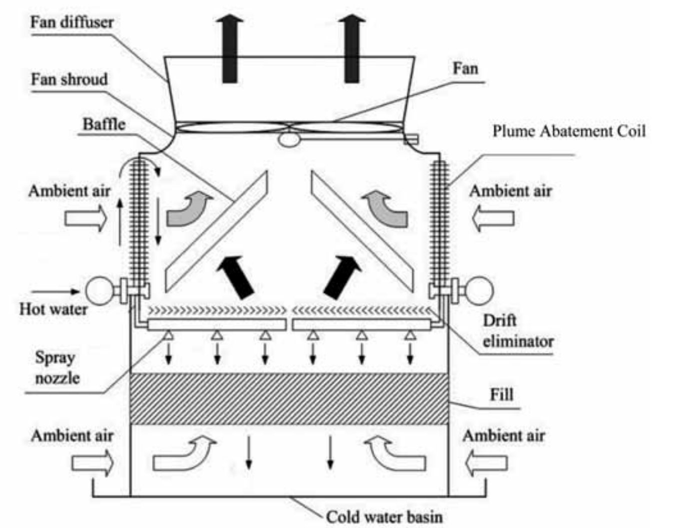

Figure 1. Counter flow cooling tower with plume abatement

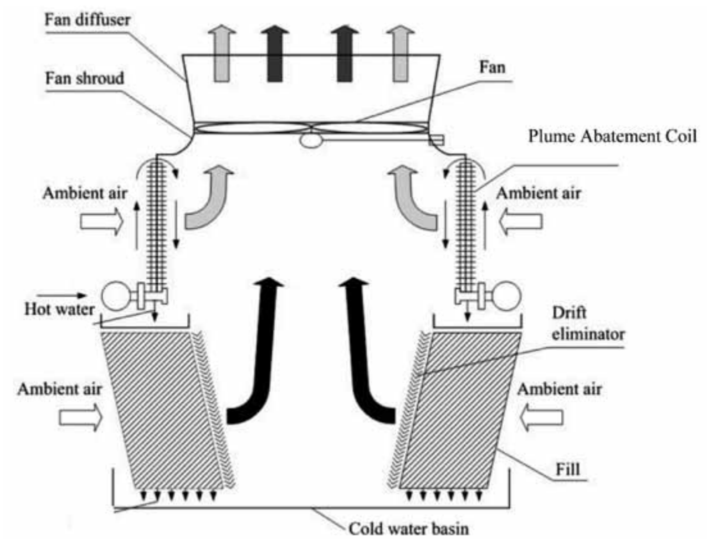

Figure 2. Cross flow cooling tower with plume abatement

Figure 3. Plume abatement coil

Hot Fluid	t (mm)	t (in)	U (J/hr sqm C)	U (Btu/hr sqft F)
Process Water	0.889	0.035	2,381,330	116.5
Process Water	1.245	0.049	2,360,890	115.5
Process Water	1.651	0.065	2,330,230	114.0
Process Water	2.108	0.083	2,309,790	113.0
Process Water	2.769	0.109	2,258,690	110.5

Table 1 – Overall heat transfer coefficient

Note: This step may take several iterations unless the mass flow of the hot fluid is known. If not, starting with a 2.1 C (3.8 F) difference between the inlet and outlet hot side fluid temperatures is a good first assumption.

We then calculate the heat capacity for both the hot fluid and ambient air as follows:

$$C_h = M_h\, cp_h = Q/(T_{hi} - T_{ho}) \quad \text{(Eq. 4)}$$
$$C_a = M_a\, cp_a = Q/(T_{ai} - T_{ao}) \quad \text{(Eq. 5)}$$

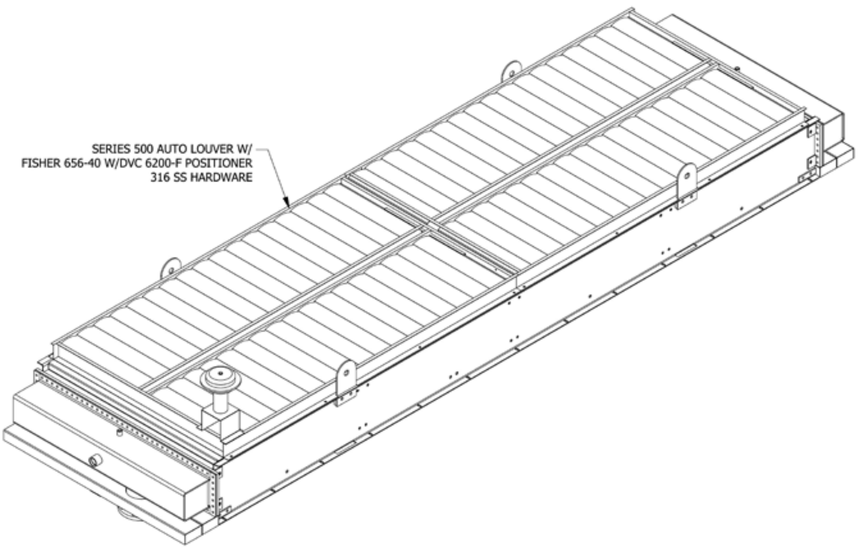

Figure 4. Plume abatement coil with louver

Then, the heat capacity ratio is determined as follows:

$$C_r = C_{min}/C_{max} \quad \text{(Eq. 6)}$$

Where:
C_{min} = The lower value of C_h or C_a
C_{max} = The higher value of C_h or C_a

The maximum heat transfer rate is calculated as follows:

$$Q_{max} = C_{min}(T_{hi} - T_{ai}) \quad \text{(Eq. 7)}$$

From here, heat transfer effectiveness is determined by:

$$E = Q/Q_{max} \quad \text{(Eq. 8)}$$

Now, we need to determine the value of NTU. This comes from plotting the following equation for a range of C_r and NTU:

$$E = 1 - \exp[(1/C_r)(NTU)^{0.22}\{\exp[-C_r(NTU)^{0.78}]-1\}] \quad \text{(Eq. 9)}$$

Figure 6 has been created from this equation for C_r between 0.1 and 1.0 and NTU between 0.0 and 5.0 Calculating the value for C_r and E from equations 6 and 8 above, one can determine the value of NTU from Figure 6.
Next, an estimate of the overall heat transfer coefficient (U) needs to be made. Based on this being process water on the tube side and air on the fin side, the range of accept-

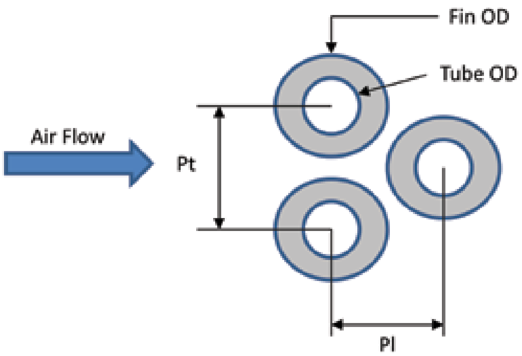

Figure 5. Plume abatement coil tube lay out

able U values is approximately between 2,248,500 and 2,453,000 J/hr sqm C (110 to 120 Btu/hr sqft F) depending on the tube wall thickness. For the tube OD, tube pitch, fin density, fin material and hot fluid assumed above, the overall heat transfer coefficient for this set of calculations can be found in Table 1 as a function of tube wall thickness. Now, we can determine the approximate overall bare tube surface area required as follows:

$$A = NTU\ C_{min}/U \qquad \text{(Eq. 10)}$$

Next, we need to determine the number of tube rows in the coil. This can be determined by the following equation (Reference 3):

$$N_z = [(T_{hi}-T_{ho})/(T_{hi}-T_{ci})](U_c/U) \qquad \text{(Eq. 11)}$$

Where:
U_c = 2,044,061 J/hr sqm C (100 Btu/hr sqft F)

N_z	Number of Rows (N)
0 to 0.4	4
0.4 to 0.5	5
0.5 to 0.7	6

Table 2 – Number of required tube rows

And, the number rows can be assumed to be per Table 2. The number of tubes is calculated as follows:

$$N_t = A/A_t = A / [(pi)(OD/w)(L)] \qquad \text{(Eq. 12)}$$

Where:
w = 1,000 mm (12 in)

Based on the number of tube rows determined by equation 11 and Table 2, the number of tubes per row can be calculated as follows:

$$N_r = N_t/N \qquad \text{(Eq. 13)}$$

From here, the overall width of the heat exchanger surface can be determine as follows:

$$W = N_r(Pt/w) \qquad \text{(Eq. 14)}$$

Now, the value given in equation 14 is for the overall width of the exchanger. Given this is for a plume abatement application, the overall heat transfer surface is typically broken down into smaller sections for easier manufacturing, transport and installation. The approximate width of an individual bundle can be determined as follows:

$$W_b = (W/N_s) + G \qquad \text{(Eq. 15)}$$

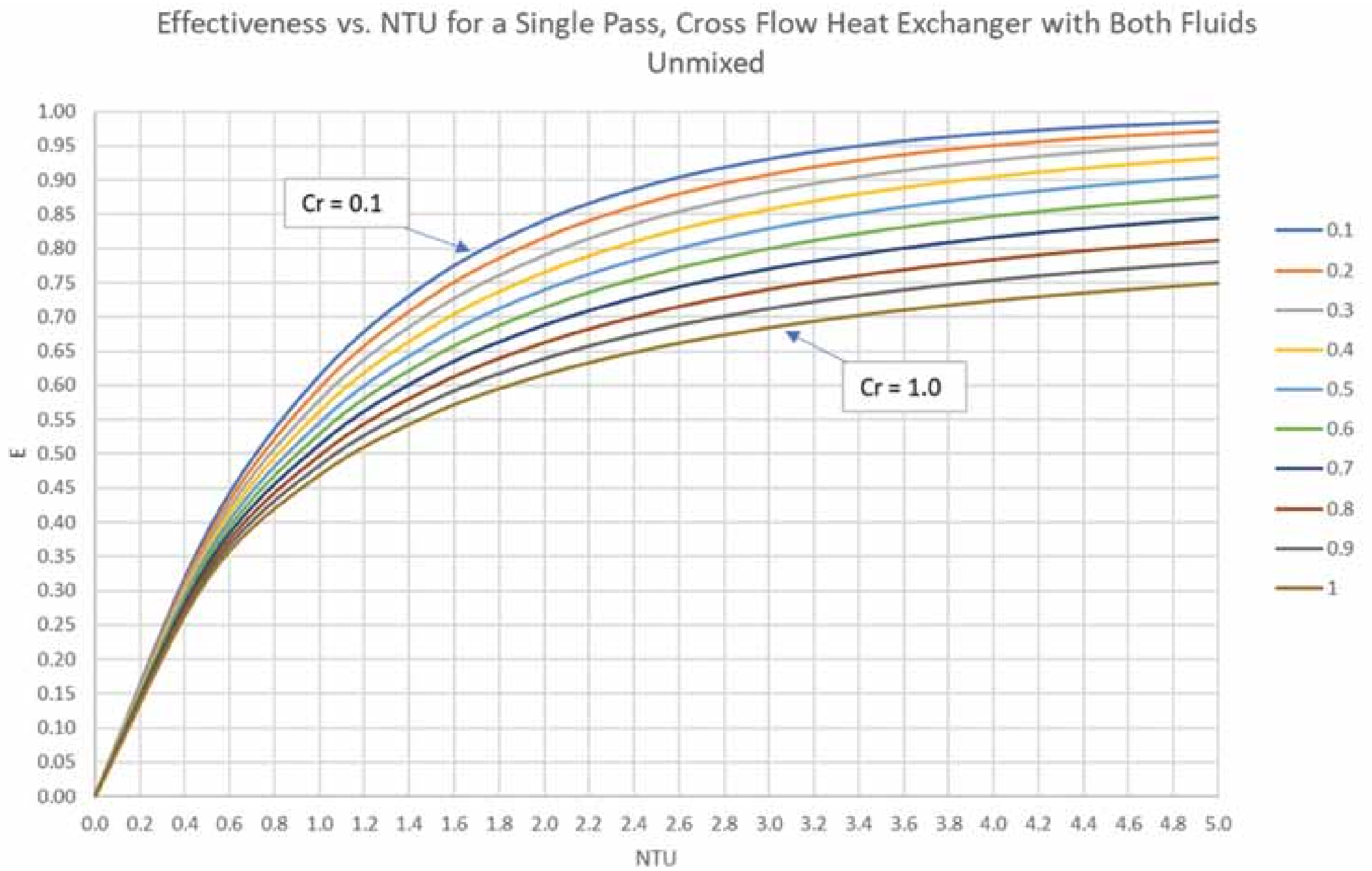

Figure 6. Effectiveness (E) versus NTU for CR range of 0.1 to 1.0

Where:
$G = 0.1524$ m (0.50 ft)

Equations 12 through 15 inclusive can be iterated for different values of L and N_s to find an acceptable tube length (L), bundle width (W_b) and number of bundles (N_s) for the application.

Conclusion

The above method, while simple, provides the user with a quick and reasonably accurate way to thermally size a set of plume abatement coils given a defined set of conditions. The author hopes users of this calculation method find it useful for budget designs. Future articles are being considered for additional tube sizes (OD), pitches (Pt & Pl), tube side fouling factors (f) as well as a calculation of air side and tube side pressure drops.

References

1. W. M. Kays, A. L. London: Compact Heat Exchangers, Third Edition, McGraw-Hill Book Company, New York, 1984
2. F. P. Incropera, D. P. De Witt: Fundamentals of Heat and Mass Transfer, Third Edition, John Wiley and Sons, New York, 1990
3. The Basics of Air-Cooled Heat Exchangers, Hudson Products Corporation, Texas, 2007

Sample calculation

Size a plume abatement coil for the following conditions:

$T_{ai} = 5.0$ C (41.0 F)

$T_{ao} = 15.6$ C (60.0 F)

$M_a = 1{,}216{,}966$ kg/hr (2,682,194 lb/hr)

$cp_a = 1013.1$ J/kg C (0.242 Btu/lb F)

$Th_i = 23.9$ C (75.0 F)

$Th_o = 21.8$ C (71.2 F)

$cp_h = 4{,}245.2$ J/kg C (1.014 Btu/lb F)

OD = 25.4 mm (1.00 in)

t = 0.89 mm (0.035 in)

Pt = 63.5 mm (2.50 in)

L = 6.93 m (22.75 ft)

U = 2,381,330 J/hr sqm C (116.5 Btu hr sqft F)

$N_s = 8$ bundles

Solve for the required heat duty as expressed in equation 1:

$Q_a = M_a\, cp_a\, (T_{ai} - T_{ao})$

$Q_a = (1{,}216{,}966 \text{ kg/hr})(1013.1 \text{ J/kg C})(15.6 \text{ C} - 5.0 \text{ C})$

$Q_a = 13{,}035{,}173{,}549$ J/hr

Solve for the hot side mass flow as expressed in equation 3 assuming a 2.1 C difference between the hot fluid inlet and outlet temperatures:

$M_h = Q / (cp_h\, (T_{hi} - T_{ho}))$

$M_h = 13{,}035{,}173{,}549 \text{ J/hr} / (4{,}245.2 \text{ J/kg C } (23.9 \text{ C} - 21.8 \text{ C}))$

$M_h = 1{,}454{,}492$ kg/hr

Calculate the heat capacity for both the hot fluid and air per equations 4 and 5:

$C_h = M_h\, cp_h = Q/(T_{hi} - T_{ho})$

$C_h = 13{,}035{,}173{,}549 \text{ J/hr} /(23.9 \text{ C} - 21.8 \text{ C})$

$C_h = 6{,}174{,}555{,}892$ J/hr C

$C_a = M_a\, cp_a = Q / (T_{ai} - T_{ao})$

$C_a = 13{,}035{,}173{,}549 \text{ J/hr} / (15.6 \text{ C} - 5.0 \text{ C})$

$C_a = 1{,}232{,}964{,}392$ J/hr C

Calculate the heat capacity ratio per equation 6 with $C_{min} = C_a$ and $C_{max} = C_h$:

$C_r = C_{min}/C_{max}$

$C_r = 1{,}232{,}964{,}392 \text{ J/hr C} / 6{,}178{,}079{,}644 \text{ J/hr C}$

$C_r = 0.200$

Calculate the maximum heat transfer rate per equation 7:

$Q_{max} = C_{min}(T_{hi} - T_{ai})$

$Q_{max} = 1{,}232{,}964{,}392 \text{ J/hr C } (23.9 \text{ C} - 5.0 \text{ C})$

$Q_{max} = 23{,}289{,}327{,}412$ J/hr

Calculate the heat transfer effectiveness per equation 8:

$E = Q/Q_{max}$

$E = 13{,}035{,}173{,}549 \text{ J/hr} / 23{,}289{,}327{,}412 \text{ J/hr}$

$E = 0.560$

Determining the value of NTU per Figure 6 with E = 0.560 and $C_r = 0.200$ you get an NTU value of 0.90. Now, from equation 10 we can calculate the bare tube surface area using the overall heat transfer coefficient provided in Table 1:

$A = NTU\, C_{min}/U$

$A = (0.90)(1{,}232{,}964{,}392 \text{ J/hr C} / 2{,}381{,}331 \text{ J/hr sqm C})$

A = 466.0 sqm

Determine the number of tube rows in the bundle from equation 11 and Table 2:

$N_z = [(T_{hi}-T_{ho})/(T_{hi}-T_{ci})](U_c/U)$

$N_z = [(23.9 \text{ C} - 21.8 \text{ C})/(23.9 \text{ C} - 5.0 \text{ C})](2{,}044{,}061/2{,}381{,}331 \text{ J/hr sqm C})$

$N_z = 0.096$

From Table 2, N = 4 rows.

The total number of tubes in the bundle can now be determined by equation 12:

$N_t = A / [(pi)(OD/w)(L)]$

$N_t = 466.0 \text{ sqm} / [(3.1416)(25.4 \text{ mm}/1000 \text{ mm}/1 \text{ m})(6.93 \text{ m})]$

$N_t = 842.1$ tubes rounded down to 842 tubes

Based on the number of rows being 4, the number of tubes per row of the exchanger can be determined by equation 13:

$N_r = N_t/N$

$N_r = 842 / 4$

$N_r = 210.5$ rounded up to 211 tubes.

From here, the overall width of the heat exchanger surface can be determined by equation 14 as follows:

$W = N_r\, (P_t/w)$

$W = 211 \,(63.5 \text{ mm} / 1000 \text{ mm/m})$

W = 13.4 m

The approximate width of an individual bundle can be determined from equation 15 as follows:

$W_b = (W/N_s) + G$

$W_b = (13.4 \text{ m}/8 \text{ bundles}) + 0.1524 \text{ m}$

$W_b = 1.82$ m / bundle