Effect of Diffusiophoresis and Thermophoresis on the Overall Particle Collection Efficiency of Spray Droplet Scrubbers

Michael J. Pilat and Anil Prem
University of Washington

The overall particle collection efficiencies of spray scrubbers using monodisperse droplets of 100, 500, and 1000 microns diameter were calculated for the cases of evaporating and condensing droplets. The properties of the gas at the inlet to the spray scrubber were maintained constant at 150°F, 100% relative humidity, and 1 atmosphere pressure. At the liquid entrance to the spray scrubber, the water droplet temperature was 50°F for the condensing case and 180°F for the evaporating case. The liquid to gas flow rate ratio for all the calculations was held constant at 4 gal/1000 acf. The gas velocity in the co-current spray tower was 1 ft/sec in the downwind direction. The calculation results show that for the particles in the 0.01 to 10 μm diameter range, the overall spray scrubber particle collection efficiency is greater with the cooler 50°F water (condensing case) than with the warmer 180°F water (evaporating case). The effect of diffusiophoresis and thermophoresis is noticeable for all the water droplet sizes considered, but is more significant for the larger water droplets. This greater effect for the larger water droplets compared to the smaller droplets is due to the longer existence of the temperature and water vapor concentration gradients between the water droplets and the surrounding gas.

Nomenclature

A	Surface area across which heat and mass transfer takes place
C_d	Vapor concentration at the droplet surface
C_g	Vapor concentration in gas
C_{gi}	Gas vapor concentration at section inlet
C_{go}	Gas vapor concentration at section outlet
C_p	Specific heat of gas
ΔC_g	Change in gas vapor concentration in section dz
dz	Section height of tower across which simultaneous heat and mass transfer calculations are done
D	Droplet diameter
D_v	Diffusion coefficient of water vapor molecules
E	Single droplet collection efficiency
f	Fraction of gas swept by the droplets
F_G	Gas flow rate
F_L	Liquid flow rate
h_g	Mass transfer coefficient
H	Distance droplet travels with respect to gas
K	Thermal conductivity of gas
k_g	Heat transfer coéfficient
L	Latent heat of vaporization
m_i	Mass of water droplets at section inlet
m_o	Mass of water droplets at section outlet
dm/dt	Mass transfer rate
N	No. of droplets coming out of nozzle per second
N_o	Overall collection efficiency for a given droplet and particle size
N_L	No. of droplets per unit length of tower
$\mathbf{P_r}$	Prandtl's number
dq_1/dt	Sensible heat transfer rate
dq_2/dt	Latent heat transfer rate
dq/dt	Total heat transfer rate
$\mathbf{Re}$	Reynolds number of the droplet
$\mathbf{Sc}$	Schmidt's number for water vapor
T_d	Droplet temperature
T_{di}	Drop temperature at section inlet
T_{do}	Drop temperature at section outlet
T_g	Gas temperature
ΔT_d	Change of droplet temperature in section dz
ΔT_g	Change of gas temperature in section dz
T_i	Gas temperature at section inlet
T_o	Gas temperature at section outlet
U_d	Drop velocity with respect to the scrubber tower wall
U_g	Gas velocity

Greek Letters

ρ_g	Gas density
μ_g	Gas viscosity

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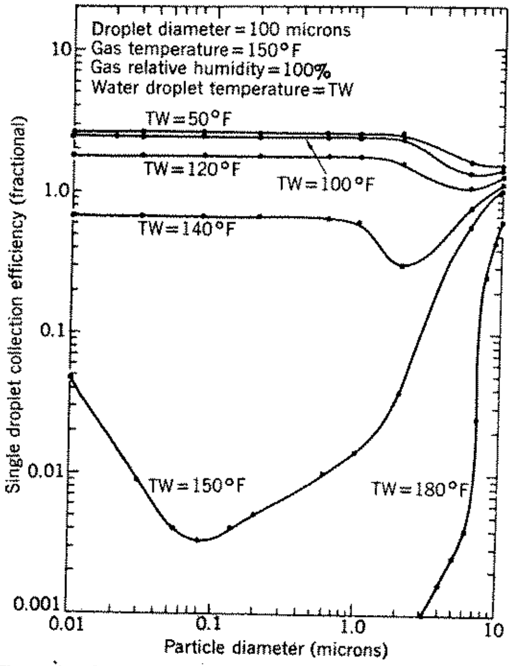

Figure 1. Calculated particle collection efficiencies of a single 100 μm diameter droplet at 30 cm/sec velocity, 150°F air temperature, and various water droplet temperatures.

Conventional wet scrubbers such as spray towers, venturi scrubbers, sieve plate scrubbers, etc. usually have lower particle collection efficiencies in the 0.01 to 2.0 μm diameter range. This lower particle collection efficiency in fine particle size range is because conventional wet scrubbers utilize the particle collection mechanisms of primarily inertial impaction (large particle collection) and secondarily Brownian diffusion (small particle collection). In order to increase the fine particle collection efficiency of conventional wet scrubbers depending upon the inertial impaction mechanism, it is necessary to increase the energy input (i.e. increase the gas pressure drop across a venturi scrubber). For the high efficiency collection of submicron particles at moderate gas and liquid pressure drops, one must apply some particle collection force that is not dependent upon increasing the relative velocity difference between the water droplets and the gas. Such particle collection forces include diffusiophoresis and thermophoresis. These forces exist when there is a temperature and/or water vapor pressure gradient between the water droplets and the gas. This paper presents the computation method and calculation results for the overall particle collection efficiencies of a spray droplet scrubber including the particle collection mechanisms of inertial impaction, Brownian diffusion, diffusiophoresis, and thermophoresis.

Sparks and Pilat[1] reported calculated particle collection efficiencies for single droplets considering inertial impaction, Brownian diffusion and diffusiophoresis and showed that positive diffusiophoresis (condensation) could substantially improve the collection efficiency. Slinn and Hales[2] reported that thermophoresis was an important collection mechanism for submicron particles in below-cloud scavenging. Based on extensive theoretical and experimental work on sieve plate scrubbers, Calvert, *et al.*[3] reported that when diffusiophoresis and thermophoresis are present in a sieve plate scrubber, they significantly affect the particle collection efficiency.

Particle Collection Efficiency of Single Droplets

The single droplet collection efficiencies for particles were calculated using a Runge-Kutta numerical solution for the particle equation of motion. The collection mechanisms considered were inertial impaction, Brownian diffusion, diffusiophoresis and thermophoresis. Pilat and Prem[4] presented the complete mathematics for these calculations of the particle collection efficiency of single droplets including these forces.

The single droplet collection efficiencies were calculated for 100, 500, and 1000 μm diameter droplets with droplet sedimentation velocities of 30, 210, and 385 cm/sec, respectively. For all calculations, the inlet gas conditions were held constant at 150°F and 100% relative humidity. The external forces of Brownian diffusion, diffusiophoresis and thermophoresis are the result of gradients of aerosol particle concentration, water vapor concentration, and gas temperature. These gradients were assumed to be linear and to exist only within the boundary layer surrounding the water droplet. The linear gradients were assumed to be symmetrical around the droplet and thus the external forces acted radially towards or away from the droplet center. The thickness of the boundary layer surrounding the droplet is dependent upon the gas velocity, diameter of the droplet, properties of gas and diffusing species, and the temperature of the droplet. From the calculations it was found that the boundary layer thicknesses due to diffusiophoresis and thermophoresis were nearly equal in magnitude. For a droplet temperature of 50°F, the boundary layer thicknesses due to diffusiophoresis and thermophoresis for the 100, 500, and 1000 μm diameter droplets were about 37, 88, and 110 μm, respectively.

Calculated particle collection efficiencies of single droplet of 100, 500, and 1000 microns diameter are shown in Figures 1–3. Curves for water droplet temperatures of 50°, 100°, 120°, 140°, 150°, and 180°F are presented in each figure. The results indicate that the phoretic forces of diffusiophoresis and thermophoresis do affect particle collection efficiencies of single droplets. The particle collection efficiencies were increased when these phoretic forces were positive (condensing case) and decreased when the phoretic forces were negative (evaporating case).

From Figures 1–3 it can be seen that the smaller the water droplets, the greater the influence of diffusiophoresis and

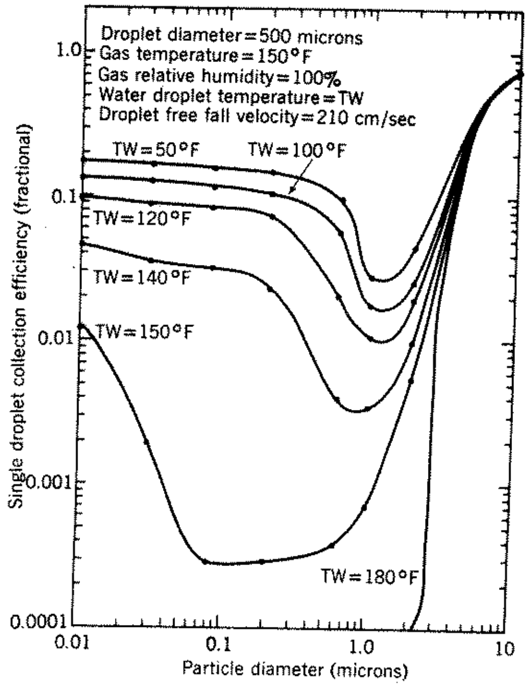

Figure 2. Calculated particle collection efficiencies of a single 500 μm diameter droplet at 210 cm/sec velocity, 150°F air temperature, and various droplet temperatures.

Table I. Spray tower calculation parameters for 100 micron droplets.

Length of tower drop travels in section, z (cm)	Height of section, Δz (cm)	Distance droplet travels with respect to gas, H (cm)	Fraction of gas swept by droplets, f
0.0 to 0.1	0.1	0.0515	0.00414
0.1 to 0.25	0.15	0.0773	0.00621
0.25 to 0.5	0.25	0.1288	0.01035
0.5 to 1.0	0.5	0.2576	0.02069
1.0 to 11	10.0	5.1529	0.41385
11 to 111	100	51.5287	4.13852
111 to 304.8	193.8	99.8626	8.02046

thermophoresis on the particle collection efficiencies. This is caused by the lower water droplet sedimentation velocities of the smaller droplets. With the lower droplet sedimentation velocities, the aerosol particles remain longer in the boundary layer surrounding the droplets (where the phoretic forces are present). The result is that the forces of thermophoresis and diffusiophoresis act on the particles for a longer time, thereby having a greater effect on the particle collection efficiencies.

Particle Collection Efficiency of Spray Tower

Calculation Procedure

The overall particle collection efficiencies of a co-current spray scrubber were calculated for both the condensing (water entered at 50°F) and the evaporating case (water entered at 180°F) with gases entering at 150°F and 100% saturated with water vapor. The liquid to gas flow rate ratio for all the calculations was 4 gal/1000 acf. The liquid and gas both entered in the top of the spray tower. The gas velocity was 1 ft/sec in the downward directions. The height at the section Z where the water spray contacted the gases was 10 ft.

The overall particle collection efficiency was calculated by using the Kleinschmidt[5] equation:

$$N_0 = 1 - e^{-fE} \tag{1}$$

where N_0 is the overall collection efficiency for a given particle and droplet size, E the particle collection efficiency of a single droplet, and f the fraction of the gas swept by the drops.

$$f = \frac{6.12 \times 10^4 H \cdot F_L}{DF_G} \tag{2}$$

where H is the distance the droplet travels with respect to gas (ft), F_L the liquid flow rate (gal/min), F_G the gas flow rate (cfm) and D the droplet diameter in μm.

With a temperature and water vapor concentration existing between the water droplets and the gas at the spray tower inlet in both the condensing and evaporating cases, there is heat and mass transfer between the droplets and the gas occurring down the tower. These resulting changes in the water droplet temperature, gas temperature, and water vapor concentration in gas were taken into account when calculating the overall particle collection efficiency of the spray tower. This was done by dividing the spray tower into a number of sections (Δz) in relation to the height and calculating the overall particle collection efficiency for each scrubber section for a given water droplet size, particle size, liquid/gas flow rate ratio, gas and liquid temperatures, and water vapor concentration in the gas. The number of tower sections used depended on the magnitude of the water vapor concentration and the temperature gradients down the tower. These gradients were obtained by performing simultaneous heat and mass transfer calculation down the tower (the results are presented in Figures 4 through 7).

The fraction of gas swept by the water droplets f is a function of H, F_L/F_G and D as is shown by Eq. 2. The liquid to gas flow rate ratio F_L/F_G was constant at 4 gal/1000 acf for our calculations. The droplet diameter D is nearly constant as the droplet diameter change due to evaporation or condensation is negligible (less than 10% change in diameter). Thus f is only a function of H, the distance the droplet travels with respect to the gas. H is a function of the gas velocity, droplet sedimentation velocity, and the height of the tower section. Because the gas velocity and the droplet sedimentation velocities are constant, H is only a function of the height of the tower section under consideration.

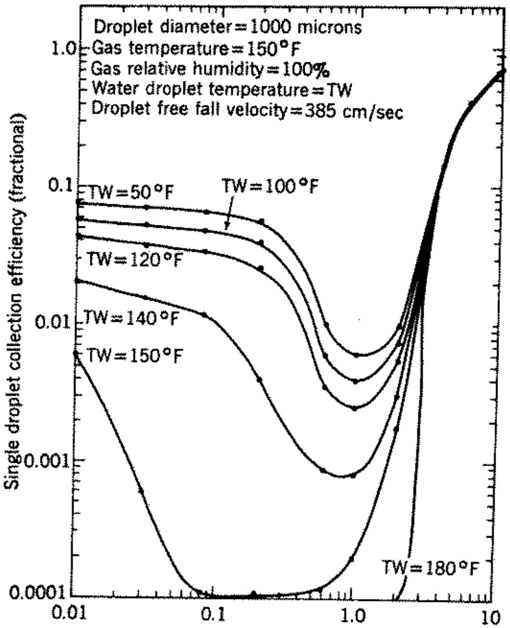

Figure 3. Calculated particle collection efficiencies of a single 1000 μm diameter droplet at 385 cm/sec velocity, 150°F air temperature, and various droplet temperatures.

For 100 μm diameter water droplets at 50°F at the spray tower top, Table I presents the magnitudes of the section height, Δz; distance section is from the tower top, z; distance the droplet travels with respect to the gas in that section, H; and the fraction of gas swept in that section, f.

For a given droplet and particle size, the overall collection efficiency for a section Δz was calculated as follows. From the heat and mass transfer calculations, the mean temperatures of water droplet and gas and the water vapor concentration of the gas were obtained providing the mean temperature and water vapor concentration gradients, between the droplet and the gas for the section dz being considered. These values of ΔP and ΔT can be obtained from Figures 4 through 7. Knowing the temperature and water vapor concentration gradients between the droplet and the gas, the single droplet collection efficiency for a given particle and droplet size was obtained, from the single droplet collection efficiency curves (Figures 1 through 3).

It should be noted that the single droplet collection efficiency curves are drawn for a constant gas temperature of 150°F whereas the gas temperature changes down the tower.

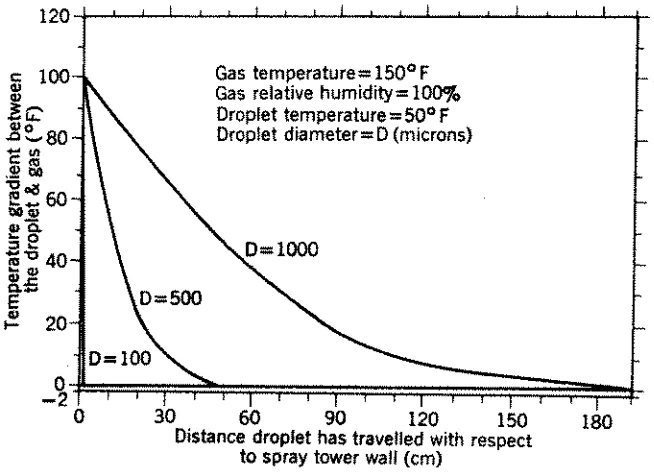

Figure 4. Temperature gradient between water droplet and gas down the scrubber for condensing case.

The change in gas temperature is only dependent on the temperature of water droplets at inlet in our calculations. The maximum change in gas temperature would occur when the temperature of the water droplets at inlet to the scrubber is 50°F. Based on the calculations it was found that the maximum change in gas temperature was around 7.5°F (from 150 to 142.5°F). With a change in gas temperature, the gas properties such as density and viscosity will change, thereby affecting the magnitude of the single droplet collection efficiency. In order to determine what effect this maximum 7.5°F change in gas temperature would have on the single droplet collection efficiencies, calculations were done for 0.1 and 1.0 μm diameter particles considering a 100 μm diameter droplet at gas temperatures of 150° and 157.5°F (the phoretic forces were assumed to be zero). For the 0.1 μm diameter droplet, the single droplet collection efficiency increased from 0.014911 to 0.015102 when the gas temperature was increased from 150° and 157.5°F. For the 0.1 μm diameter particle, the single droplet collection efficiency remained constant at 0.003604 for both gas temperatures. Based on the results, it was assumed that the change in gas properties down the tower due to change in gas temperatures is insignificant. Even though Figures 1 through 3 were based on a gas temperature of 150°F, a little change in the gas temperature would not alter the curves significantly (less than 1.5% change in single droplet collection efficiency).

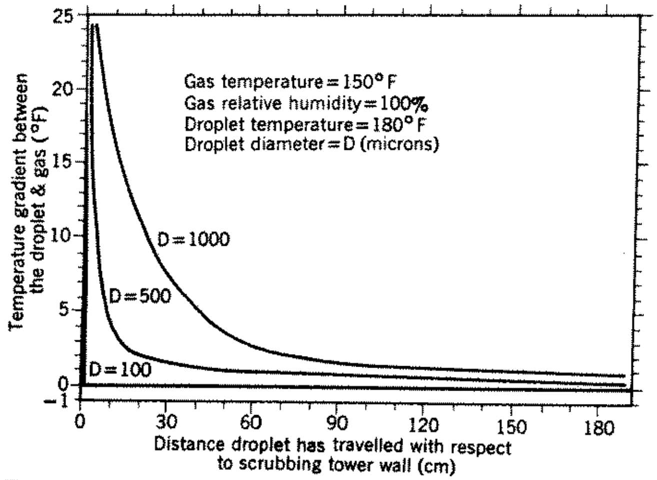

Figure 5. Temperature gradient between water droplet and gas down the scrubber for evaporating case.

Knowing the single droplet collection efficiencies, liquid and gas flow rates, droplet diameters, and the distance droplet travels with respect to gas in the section Δz, the overall collection efficiency for each tower section was calculated using Eq. 1 and 2.

Temperature and Water Vapor Concentration Profiles in Spray Tower

Calculation Assumptions. The temperature and water vapor concentration profiles down the spray tower were obtained by performing simultaneous heat and mass transfer balance between the water droplets and the gas. The major assumptions made were as follows:

1. Steady state operation.
2. Water droplets were evenly distributed across the spray tower.
3. Water droplets were monodisperse in size.
4. Water droplets attained their terminal sedimentation velocity upon release from the spray nozzles.
5. Water droplets did not hit the tower wall.
6. No coalescence between the water droplets.
7. No heat transfer through the spray tower walls.
8. The temperature and water vapor concentration were constant in each tower section, dz.

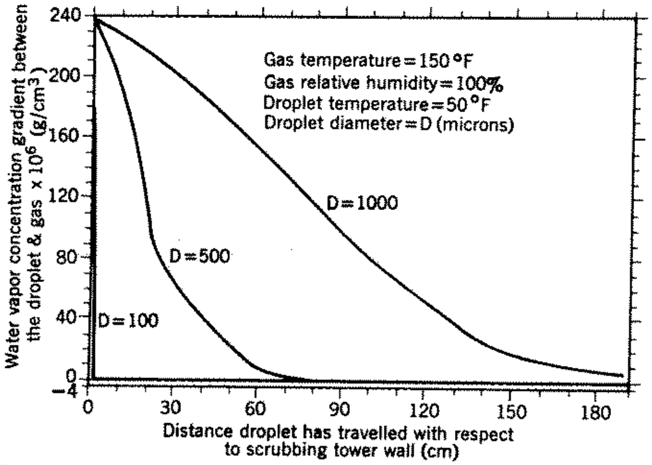

Figure 6. Water vapor concentration gradient between water droplet and gas down the scrubber for condensing case.

The temperature and water vapor concentration of the water droplets and the gas were obtained by dividing the tower into sections dz and performing simultaneous heat and mass transfer calculations. The heat and mass balance was done at the end of each tower section. The size of the tower section dz depended upon the magnitude of the temperature and water vapor gradients. In the top of the tower where the gradients were large, the tower sections were the smallest. In the calculations, the tower section height was 0.01 cm for the first 50 sections, 0.1 cm for the next 50 sections, and 0.25 cm for the remaining sections (total spray tower height was 10 ft or 304.8 cm).

Mass Transfer. The mass transfer dm/dt of water between the droplets and the gas in the tower section was given by

$$\frac{dm}{dt} = h_g A (C_d - C_g) \qquad (3)$$

where h_g is the mass transfer coefficient, A water droplet

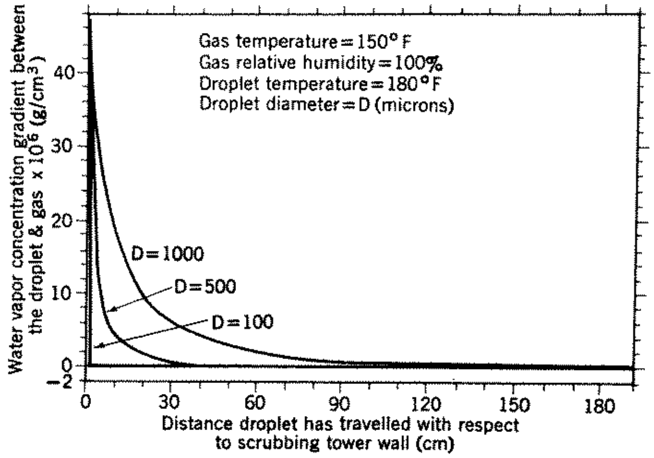

Figure 7. Water vapor concentration gradient between water droplet and gas down the scrubber for evaporating case.

surface area, C_d and C_a the water vapor concentrations at the droplet surface and in the bulk gas, respectively. Knowing the bulk gas temperature, the water droplet temperature, and the gas relative humidity, C_d and C_g were calculated. The droplet surface area A was calculated from the liquid flow rate.

$$A = N_L \pi D^2 \, \mathrm{d}z \tag{4}$$

where N_L is the number of droplets per unit length of tower.

$$N_L = N/U_d \tag{5}$$

where N is the number of droplets emitted per second from the nozzles and U_d is the droplet velocity with respect to the spray tower wall.

$$N = 6F_L/\pi D^3 \tag{6}$$

where F_L is the liquid flow rate.

The mass transfer coefficient was calculated by using the empirical equation given by Rowe, *et al.*[6] for the Sherwood number as a function of Reynolds number of the drop and Schmidts number. Substituting for h_g, equation (3) was reduced to

$$\frac{\mathrm{d}m}{\mathrm{d}t} = (D_v A/D)(C_d - C_g)[2 + 0.69\,\mathbf{Re}^{1/2}\mathbf{Sc}^{1/3}] \tag{7}$$

where D_v is the diffusion coefficient of water vapor molecules in cm^2/sec, D is the diameter of droplet in cm, A the surface area of droplets in section dz, C_d and C_g the concentrations of water vapor at drop surface and gas in g/cm^3. D_v was assumed to be constant in the boundary layer and its magnitude was dependent on the mean temperature of the droplet and gas. The Reynolds number of the drop **Re** and **Sc** the Schmidts number for water vapor are given by:

$$\mathbf{Re} = \frac{(U_d - U_g)D\rho_g}{\mu_g} \tag{8}$$

$$\mathbf{Sc} = \frac{\mu_g}{\rho_g D_v} \tag{9}$$

where U_d is the drop velocity with respect to the scrubber wall in cm/sec, U_g the gas velocity in cm/sec, ρ_g the density of gas in g/cm^3 and μ_g the viscosity of gas in g/cm-sec.

Heat Transfer. The total heat transfer rate dq/dt between the water droplets and the gas is the sum of the sensible heat transfer rate dq_2/dt and the latent heat transfer rate dq_1/dt.

$$\mathrm{d}q/\mathrm{d}t = \mathrm{d}q_2/\mathrm{d}t + \mathrm{d}q_1/\mathrm{d}t \tag{10}$$

The latent heat transfer is given by

$$\mathrm{d}q_1/\mathrm{d}t = L\frac{\mathrm{d}m}{\mathrm{d}t} \tag{11}$$

where L is the latent heat of vaporation. The sensible heat transfer rate between the droplets and the gas is given by

$$\mathrm{d}q_2/\mathrm{d}t = k_g A(T_d - T_g) \tag{12}$$

where k_g is the heat transfer coefficient, A the droplet surface area, and T_d and T_g are the droplet and gas temperatures, respectively. The droplet surface area was calculated from the droplet number concentration and droplet diameter using Eq. 6. The heat transfer coefficient k_g was calculated using an empirical equation reported by Rowe, *et al.*[6] for the Nusselt number as a function of the droplet Reynolds number and Prandlt number. Substituting for k_g, Eq. (12) was reduced to

$$\mathrm{d}q_2/\mathrm{d}t = (KA/D)(T_d - T_g)[2 + 0.69\,\mathbf{Re}^{1/2}\mathbf{Pr}^{1/3}] \tag{13}$$

where K is the thermal conductivity of the gas in cal/sec·cm^2·°C, **Pr** the Prandtl number is given by

$$\mathbf{Pr} = \mu_g C_p/K \tag{14}$$

where C_p is the heat capacity of the gas in cal/gm·°C.

Knowing the heat and mass transfer rates down the scrubber section dz, the change in the gas temperature and vapor concentration, drop temperature and vapor concentration, and droplet size in the section dz were calculated. This was done by performing heat and mass balances at the end of section dz (the procedures for these calculations are presented in the following sections).

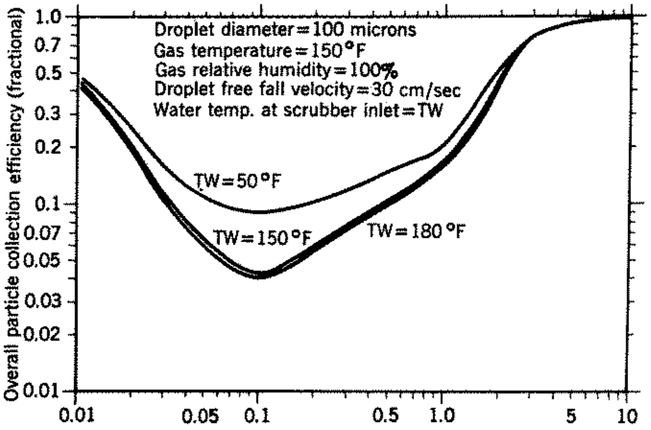

Figure 8. Calculated overall particle collection efficiencies for 100 μm diameter droplet.

Changes in Gas Temperature. The changes in the gas temperature down the section were obtained by a heat balance on the section

$$\mathrm{d}q_2/\mathrm{d}t = (\text{gas flow rate})\ C_p \cdot \Delta T_g \tag{15}$$

T_0, the temperature of the gas at the outlet of section dz, is given by

$$T_0 = T_i + \Delta T_g \tag{16}$$

where T_i is the gas temperature at the top (inlet) of the section dz and ΔT_g is the change in the gas temperature from the inlet to outlet of the section.

Change in Water Vapor Concentration of Gas. A water vapor balance for the gas at the outlet of a tower section provides

$$dm/dt = (\text{gas flow rate})\ \Delta C_g \qquad (17)$$

C_{go}, the water vapor concentration at the section outlet is given by

$$C_{go} = C_{gi} + \Delta C_g \qquad (18)$$

where C_{gi} is the water vapor concentration of the inlet to the section and ΔC_g is the change in the water vapor concentration for the inlet to the outlet of the section.

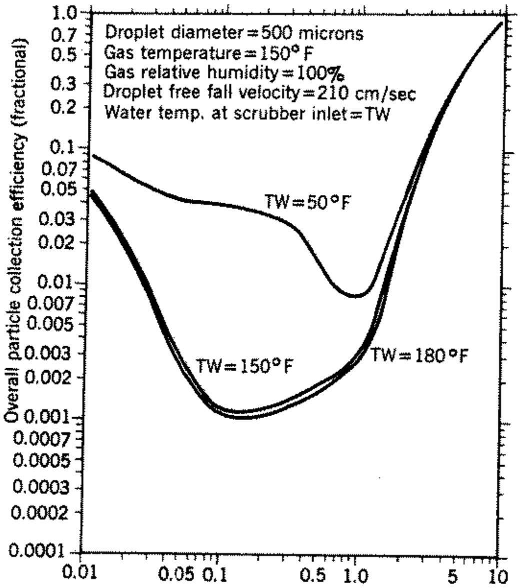

Figure 9. Calculated overall particle collection efficiencies for 500 μm diameter droplet.

Change in the Water Droplet Temperature. The water droplet temperature at the section outlet, T_{do} is provided by

$$dq/dt = (\text{liquid flow rate})\ C_{p\,H_2O} \Delta T_d \qquad (19)$$

$$T_{do} = T_{di} + \Delta T_d \qquad (20)$$

Change in Droplet Size. A mass balance on the water droplets provided the change in the droplet size

$$\begin{matrix}\text{Rate of mass} \\ \text{transfer per} \\ \text{droplet in} \\ \text{section } dz\end{matrix} = \left(\frac{dm}{dt}\right)\left(\frac{1}{\text{number of droplets in } dz}\right) \qquad (21)$$

The number of droplets in the section dz was calculated knowing the liquid and gas flow rates, droplet size, and droplet and gas velocities.

$$dm = \left(\frac{dm}{dt}\right)(\text{time droplet spends in section } dz) \qquad (22)$$

$$m_0 = m_i - dm \qquad (23)$$

The droplet diameter was calculated from the droplet mass at the end of each section dz.

Temperature and Vapor Concentration Gradient between the Droplets and Gas in a Scrubbing Tower

Figures 4 and 5 present the temperature gradient profiles down the spray tower between the droplet and gas for the condensing and evaporating cases, respectively. Figures 6 and 7 show the water vapor concentration gradient profiles across the scrubbing tower between the droplet and gas for condensing and evaporating cases respectively. For the condensing case, the droplet temperature at entrance was 50°F and for the evaporating case the temperature was 180°F. For all the calculations, the temperature and relative humidity of gas at the spray tower inlet was 150°F and 100%, respectively.

From the figures it can be seen that the droplet and the gas come to equilibrium rapidly (in about 2 cm) when the droplets are small (100 μm diameter). The time that the gas and droplet take to come into equilibrium is directly proportional to the size of the droplet and the temperature and vapor concentration difference between them. For constant liquid and gas flow rates, the smaller droplets have a larger surface area across which heat and mass transfer can take place, thereby smaller droplets come to equilibrium more rapidly. The larger droplets having a lower surface area to mass ratio take a longer time to come to equilibrium with the gas. The result of this is that when small droplets are used in a scrubbing tower the temperature and vapor concentration gradients exist only in the top part of the tower. When the larger 1000 μm diameter droplets are used in the tower, the temperature and vapor concentration gradients exist down a greater distance (about 5 ft or 150 cm).

Overall Particle Collection Efficiency

The calculated overall particle collection efficiencies for droplet diameters of 100, 500, and 1000 μm for both evaporating (droplet temperature at scrubber entrance—180°F) and condensing (droplet temperature at scrubber entrance—50°F) cases are shown in Figures 8 through 10, respectively. The particle diameter ranges from 0.01 to 10 μm diameter. The results indicate that the overall collection efficiency of the particle is affected by diffusiophoresis and thermophoresis. The overall collection efficiencies are higher when positive diffusiophoresis and thermophoresis are present in the scrubber (condensing case).

From Figures 8 through 10 it is seen that for the large particle sizes where the inertial impaction is the dominant particle

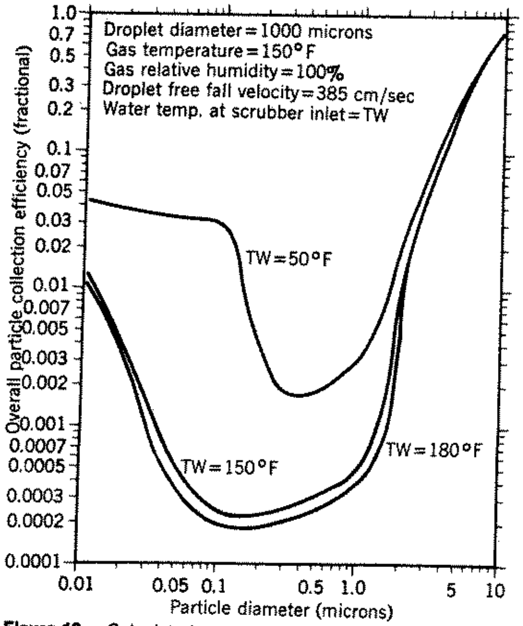

Figure 10. Calculated overall particle collection efficiencies for 1000 μm diameter droplet.

collection mechanism, the effect of diffusiophoresis and thermophoresis on overall collection efficiency is negligible. It is also seen that the effect of phoretic forces on overall collection efficiency becomes greater as the droplet size is increased. This is because for large droplets the rate of heat and mass transfer in the scrubber is slow resulting in the existence of the temperature and vapor pressure gradients between the droplets and gas for a substantial height of the tower. The result is that the phoretic forces are active for a longer duration when large droplets are used in the scrubber.

Comparing the single droplet and overall collection efficiency of the particles for 100, 500, and 1000 μm diameter droplets it is seen that if the single droplet collection efficiency for a particle is very high, it does not necessarily follow that the overall collection efficiency will also be high. For example, referring to Figure 2, the single droplet collection efficiency for a 0.01 μm diameter particle with a droplet diameter of 100 μm at 50°F is 2.7 whereas the overall particle collection efficiency is only 0.48. This is so because the phoretic forces are active only in a small portion of the scrubber, and in this portion of the tower the collection efficiency is very high. But once the droplets are in equilibrium with the gas the collection efficiency decreases sharply (to the case where the water temperature is 150°F).

Conclusions

Calculated overall collection efficiencies for 100, 500, and 1000 μm diameter droplets indicate that the overall collection efficiency can be significantly affected by diffusiophoresis and thermophoresis. It is seen that the overall particle collection efficiency for the 100 μm droplet is largest for all the particle sizes considered followed by the 500 μm diameter droplet. The overall collection efficiencies for a 1000 μm droplet are the smallest. The effect of diffusiophoresis and thermophoresis on the overall particle collection efficiency is most significant for the 1000 μm droplet followed by the 500 μm droplet, but for these larger droplets the overall particle collection efficiencies are small even when diffusiophoresis and thermophoresis are assisting with the particle collection. For example, with the 1000 μm diameter droplet, the calculated overall scrubber particle collection efficiencies for particles smaller than 2 μm diameter were in all cases less than 5%.

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Dr. Pilat is Associate Professor of Air Resources Engineering and Mr. Prem is a research engineer, both in the Department of Civil Engineering, University of Washington, Seattle, WA.