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Gas Absorption by Alkaline Solution in a Cyclone Scrubber: Experimental and Modeling Study

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Abstract

Experimental and modeling studies have been conducted on a CO_2 absorption in a cyclone scrubber operated at room temperature. The effects of parameters such as the initial concentration of alkali in the solution and the liquid – gas ratio on the CO_2 absorbed flux were experimentally and theoretically investigated. A theoretical study has been performed using a mathematical model based on the absorption in the liquid droplet with instantaneous reaction, in the inlet duct of the cyclone and in the cyclone itself. The results from the model were compared with experimental data and showed satisfactory agreement.

Keywords: CO_2 removal, mathematical model, wet cyclone scrubber

1. Introduction

The development of a low cost process for the removal of acid gases and dusts in flue gases of incinerators is desirable. A cyclone scrubber is considered to be one of the processes, which can absorb gases, separate particles, and decrease the gas temperature simultaneously. It is very important to understand the mechanism of gas absorption and particle separation in a cyclone scrubber for the proper design and the optimum operation of the process. A few researches on cyclones have been reported and mathematical models have been developed to understand the mechanism of the particle separation and the gas absorption in the cyclone (Johnstone and Silcox, 1947; Schrauwen and Thoenes, 1988; Mothes and Loffler, 1988; Patterson and Munz, 1996). Although these researches have been reported on cyclone systems, the performance and the absorption mechanism in the cyclone scrubber are still not clear.

As a preliminary study, the purposes of this study are to evaluate the performance and to analyze the mechanism of absorption by performing the experiment of CO_2 absorption with aqueous solution in a wet cyclone scrubber at room temperature. The solution was sprayed in the inlet duct of the cyclone. For the adequately rational design of a cyclone scrubber and for optimizing the absorption rate as a function of various parameters, this study presents a mathematical model based on absorption in the liquid droplet with an instantaneous reaction. The material balance between gas–liquid droplets in the inlet duct was used to study the absorption mechanism in the inlet duct of the cyclone, while the material balance between gas–liquid droplet and gas–liquid film on cyclone wall was used to study the absorption in the cyclone.

2. Methodology

The experimental apparatus is shown in Fig. 1. The cyclone consists of a cylindrical section with 11.6 cm in height joined to a conical section with 26.1 cm in height. Other dimensions are 5.9 cm in cyclone diameter, 2.7 cm in outlet duct diameter, 1 cm in apex diameter, 3.9 cm of engagement length, 1.4 cm in inlet duct width, 2.9 cm in inlet duct height, and 10 cm in inlet duct length. The liquid is injected by spraying through the nozzle (Full Cone Spray Nozzle, orifice diameter of 1 mm, pressure of 2 kg/m^2, and spray angle of 70^o, Ikeuchi, Co. Japan) into the gas stream in the inlet duct of the cyclone. The outlet concentration of CO_2 was continuously monitored by a CO_2 analyzer (URA-107 Shimadzu, Co. Japan). The experimental conditions are as follows: gas flow rate = 5±0.2 liter/min, liquid rate = 0.35 - 0.8 liter/min; liquid and gas temperatures = 292±1 K; inlet CO_2 concentration = 17±0.1 %; and initial concentration of alkali in solution, C_{Bo}=1×10^{-8} – 0.1 kmol/m^3.

2.1 Mathematical Model

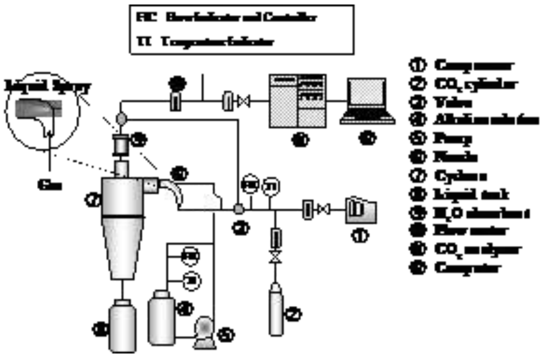

Figure 1. Experimental apparatus.

The absorption in the cyclone occurs in two places, one is in the inlet duct of the cyclone and the other is in the cyclone itself. To simplify the model, several assumptions are made as follows: (a) The liquid droplet to be sprayed is assumed to be spherical shape; (b) The reaction is instantaneous; (c) All the physical properties of gas and liquid are constant throughout; (d) When the absorption occurs at room temperature, the liquid and gas temperatures are constant during the absorption and there is no evaporation of liquid to the gas phase; and (e) The gas velocity in the cyclone was determined by the assumption of Mothes and Loffler (1988) and Paterson and Munz (1996).

Absorption in Inlet Duct

The equation of motion of a liquid droplet derived by Uchida and Wen (1973) in a venturi scrubber is applied to the present case in the inlet duct of the cyclone:

$$\frac{dv_d}{dz} = \frac{3}{4}\frac{C_D}{d_p}\frac{\rho_G}{\rho_L}\frac{(v_G - v_d)|v_G - v_d|}{v_d} \quad (1)$$

The relationships for mass balance between gas and liquid in the inlet duct are used to derive the following set of differential equations:

$$\frac{dC_A}{dz} = \left[\frac{a\rho_m k_L}{L_m / S}\right]\Delta C_A \quad (2)$$

$$\frac{dP_A}{dz} = -\left[\frac{aPk_L}{G_m / S}\right]\Delta C_A \quad (3)$$

$$\frac{dt_i}{dz} = \frac{1}{v_d} \quad (4)$$

This set of differential equations is numerically solved using given initial conditions at the nozzle point.

The liquid-phase mass transfer coefficient with an instantaneous reaction is given as follows if both the diffusivity of the gas and that of the reactant in the liquid are nearly the same (Brunson and Welek, 1970).

$$k_L = [1 + (C_{B0} / C_{Ai})]k_{LP} \quad (5)$$

The mass transfer coefficient for the physical absorption into the droplet and the interfacial concentration of CO_2 can be defined as (Uchida and Wen, 1973).

$$k_{LP} = \frac{2D_A}{r_0}\sum_{m=1}^{\infty} exp\left(-\frac{D_A m^2 \pi^2 t_i}{r_o^2}\right) \quad (6)$$

$$C_{Ai} = (C_A^* - C_{BO}R_{g-L})/(1 + R_{g-L}) \quad (7)$$

$$R_{g-L} = \frac{k_{LP}H}{k_G}, \quad C_A^* = HP_A \quad (8)$$

The solubility, H, and the diffusivity of CO_2 in alkaline solution, D_A, are estimated using the methods presented by Schumpe (1993) and Hikita et al. (1976), respectively. The gas-phase mass transfer coefficient of an individual droplet is calculated by Steinberger and Treybal`s correlation (1960).

$$N_{Sh} = 2 + 0.347(N_{Re}N_{Sc}^{1/2})^{0.62} \quad (9)$$

Where:

$$N_{Sh} = \frac{RT_G k_G}{D_{AG}}, \quad N_{Re} = \frac{d_p v_s \rho_G}{\mu_G}$$

$$N_{Sc} = \frac{\mu_G}{\rho_G D_{AG}}$$

The applicable ranges of this correlation are 1 < N_{Re} < 30,000 and 0.6 < N_{Sc} < 30,000, which are always satisfied in the experimental conditions investigated here.

Mass mean diameter of droplet, d_p, is estimated by Kim and Marshall's correlation (1971) and the slip velocity, v_s, is given by $v_S = v_G - v_d$.

Absorption in Cyclone

The mass transfer in the cyclone scrubber occurs in two places, in the liquid droplets and in the liquid film on the cyclone wall (Johnstone and Silcox, 1947). By assuming that the absorption by the liquid phase is predominant in the cyclone, the mass transfer in the cyclone can be expressed as follows:

$$\int_{P_{A1}}^{P_{A2}} \frac{dP_A}{P^* - P_A} = \frac{PH}{SG_{mf}} \left(k_L A + k_{Lw} A_w \right) \qquad (10)$$

The integral represents the total number of transfer units and the terms on the right represent the number of transfer units resulting from the absorption in the liquid droplets and in the liquid film on the cyclone wall respectively.

The liquid-phase mass transfer coefficient with an instantaneous reaction, k_L, into the droplet is estimated using the same correlations as for the inlet duct (Equation (5)). The effective value of $k_L A$ (cm^3/s) is estimated from the value of k_L into the droplet and the interfacial area of droplets, A. The interfacial area of droplets is the product of the number of droplets moving in the cyclone and the droplet surface area. The number of droplets is determined from the liquid supply, the droplet volume and the flight time. The gas-phase mass transfer coefficient around the droplets, k_G, in the cyclone is estimated from the average value of Sherwood numbers over the velocity calculated at each position in the cyclone which is calculated according to Steinberger and Treybal`s correlation (1960). Analogous with slip velocity in the inlet duct, slip velocity in the cyclone was defined as follows:

$$v_s = v_{G(resultant)} - v_{d(resultant)} \qquad (11)$$

where $v_{G(resultant)} = \sqrt{v_{rG}^2 + v_{\theta G}^2 + v_{zG}^2}$

$v_{d(resultant)} = \sqrt{v_{rd}^2 + v_{\theta d}^2 + v_{zd}^2}$

The gas velocities in the cyclone for the cylindrical section are modeled according to (cylindrical coordinates) (Patterson and Munz, 1996).

$$v_{rG}(r_c) = 0 \,,\; v_{rG}(r_e) = \frac{G}{2\pi r_e (h_t - s)} \qquad (12)$$

$$v_{zG} = \frac{G(h_t - z)}{\pi \left(r_c^{\,2} - r_e^{\,2} \right)(h_t - s)} \qquad (13)$$

$$v_{\theta G} = \frac{v_{\theta w}}{\frac{r}{r_c}\left[1 + D\left(1 - \frac{r}{r_c} \right) \right]} \qquad (14)$$

Equations (12) to (14) can also be used for conical section by changing the cylindrical section radius, r_c, with the conical section radius, r_c^*. The conical section radius is a function of the conical height as follows (Mothes and Loffler, 1988):

$$r_c^{\,*} = \sqrt{\frac{V_{con.}}{\pi z_{con.}}} \qquad (15)$$

The liquid drops trajectories are estimated using differential equations of force balances with cylindrical coordinates (Schrauwen and Thoenes, 1988) as shown in Eqs. (16) to (18).

This set of differential equations is numerically solved using given initial condition at the end of the inlet duct of the cyclone as shown in Figure 2.

The mass transfer coefficient in the liquid film on the cyclone wall, $k_{Lw}A_w$, is predicted by a correlation based on the measurements of Johnstone and Silcox (1947) in a cyclone

$$\rho_L V_d \frac{dv_{rd}}{dt_c} = C_D(v_s) A_d \tfrac{1}{2} \rho_G |v_s|^2 \frac{(v_{rG} - v_{rd})}{|v_s|} + (\rho_L - \rho_G) \frac{v_{\theta d}^{\;2}}{r_d} V_d \qquad (16)$$

$$\rho_L V_d \frac{dv_{\theta d}}{dt_c} = C_D(v_s) A_d \tfrac{1}{2} \rho_G |v_s|^2 \frac{(v_{\theta G} - v_{\theta d})}{|v_s|} - (\rho_L - \rho_G) \frac{v_{rd} v_{\theta d}^{\;2}}{r_d} V_d \qquad (17)$$

$$\rho_L V_d \frac{dv_{zd}}{dt_c} = C_D(v_s) A_d \tfrac{1}{2} \rho_G |v_s|^2 \frac{(v_{zG} - v_{zd})}{|v_s|} + (\rho_L - \rho_G) |g| V_d \qquad (18)$$

spray tower as quoted by Schrauwen (1988) as follows:

$$K_{Lw}A_w=0.0049(v^2_{\theta G}(r_c)+v^2_{zG}(r_c))^{0.37}N_{Sc}^{2/3}2\pi r_c z_w \quad (19)$$

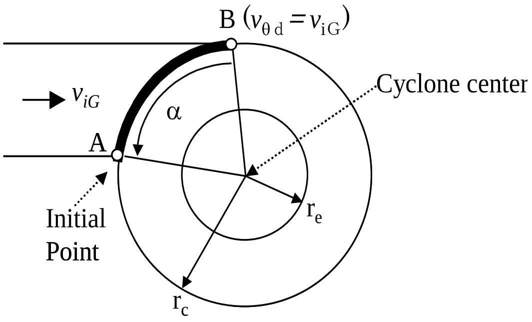

Figure 2. Initial conditions of differential equations inside cyclone.

3. Results and Discussion

Figure 3 shows the effect of the initial concentration of alkali, C_{B0}, on CO_2 absorbed flux for two absorbents at *L/G* of 0.16. The increase in C_{B0} slightly increased the CO_2 absorbed flux. The flux increased significantly from the initial concentration of alkali in solution, C_{B0}=0.001 kmol/m^3.

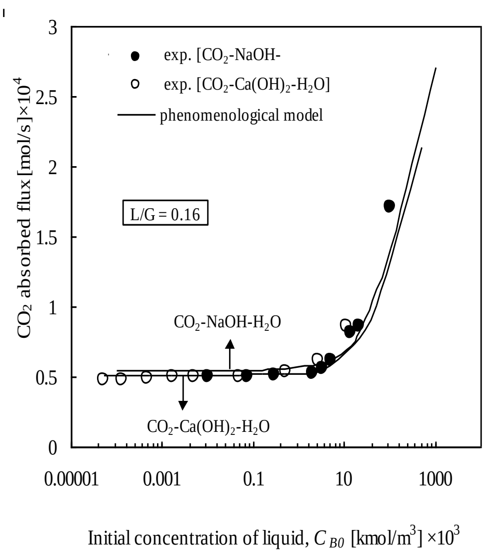

Figure 3. Initial conditions of differential equations inside cyclone.

It indicates that the reaction between CO_2 and the solutions can take place in a basic solution of C_{Bo}=0.001 kmol/m^3 (pH≥11). Although the reaction also occurs at pH lower than 11, it can be considered negligible. In all cases, CO_2 was absorbed significantly when the initial concentration was increased (Camacho et al., 2000). Figure 3 also shows that the calculated values agreed well with the experimental data around C_{B0} ≤ 0.001 kmol/m^3 (pH≤11). The deviation becomes significant with C_{B0}.

The effect of the liquid – gas ratio on absorption is presented in Figure 4 with the constant gas flow rate. The increase in *L/G* obviously increased the CO_2 absorbed flux. The consequence of a higher *L/G* ratio is a higher surface area. According to Jorg and Buttner (1994), the number of droplets increases and thus the mean distance between droplets is reduced and the surface area of droplets significantly increase at a higher *L/G* ratio. Figure 4 also shows that the calculated values also show in good agreement with the experimental data.

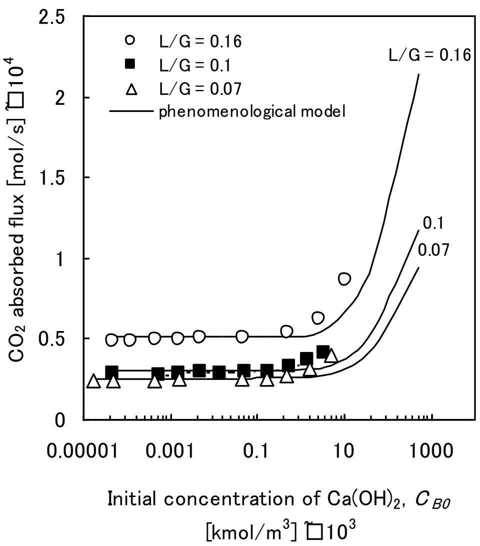

Figure 4. Effect of liquid-gas ratio, *L/G*, on CO_2 absorbed flux.

Figure 5 shows the comparison of the experimental results of CO_2 absorbed flux with the calculated by Eq. (20) using neural network and by the phenomenological model, while the absolute mean relative errors are summarized in Table 1.

$$R.error=\left(\frac{calc.CO_2\ abs.\ flux}{exp.CO_2\ abs.\ flux}-1\right)\times 100\% \quad (20)$$

The largest absolute mean relative error was found to be 8.964% by the calculated values.

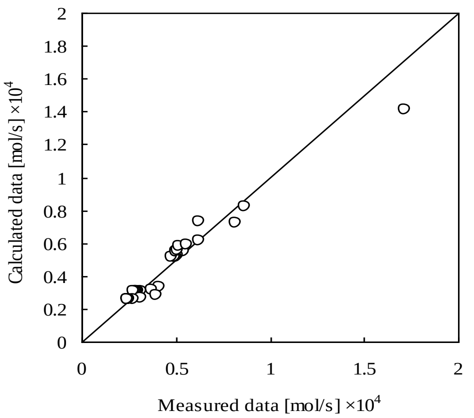

Figure 5. Parity plot of experimental CO_2 absorbed flux *vs* calculated values.

This value is less than 10%, which it is reasonable prediction for a phenomenological model.

Table 1. Mean absolute relative error between experimental and calculated CO_2 absorbed flux.

Gas-liquid system	Mean absolute relative error, %
	Model
CO_2-$Ca(OH)_2$-H_2O:	
L/G = 0.16	4.373
L/G = 0.1	7.944
L/G = 0.07	8.184
CO_2-$NaOH$-H_2O:	
L/G = 0.16	8.964

4. Conclusion

This paper presents modeling strategy by the mathematical model in a cyclone scrubber. The models were built on physical principles.

The comparison of the simulation results with experimental data has been discussed to show the validity of the proposed models. The comparison illustrates that the model is satisfactory with experimental data. In conclusion, the model can be described the performance of gas absorption in the wet cyclone scrubber.

Nomenclature

a = contact area per unit volume, [m^2/m^3]
A = interfacial area of droplet, [m^2]
A_d = cross sectional area of droplet, [m^2]
A_w = interfacial area of wetted wall, [m^2]
C_A = concentration of CO_2 at time, [$kmol/m^3$]
C_A^* = concentration of CO_2 in equilibrium with CO_2 in gas phase, [$kmol/m^3$]
C_{BO} = initial concentration of alkaline solution, [$kmol/m^3$]
C_D = drag coefficient, [-]
d_p = diameter of droplet, [m]
D = momentum exchange parameter, [-]
D_{AG} = diffusivity of CO_2 in gas, [m^2/s]
g = standard acceleration of gravity, [m/s^2]
G = volumetric gas flow rate, [m^3/s]
G_m = molar gas flow rate, [kmol/s]
G_{mf} = molar gas flow through the inlet duct of the cyclone,[$kmol/(s.m^2)$]
H = Henry's constant, [$kmol/(m^3.atm)$]
h_t = total height of the cyclone, [m]
k_G = gas-phase mass transfer coefficient for CO_2, [$kmol/(m^2.s.atm)$]
k_L = mass transfer coefficient for CO_2 with reaction for droplets, [m/s]
k_{Lw} = mass transfer coefficient for CO_2 with reaction for wetted wall, [m/s]
L_m = molar liquid flow rate, [kmol/s]
L = volumetric liquid flow rate, [m^3/s]
P = total pressure of CO_2, [atm]
P_A = partial pressure of CO_2, [atm]
P^* = equilibrium pressure of CO_2, [atm]
P_{A1} = partial pressure of CO_2 in inlet gas, [atm]
P_{A2} = partial pressure of CO_2 in outlet gas, [atm]
r_e = radius of gas outlet duct, [m]
r_o = initial radius of droplet, [□m]
R = gas law constant, [$kmol/(m^3.K)$]
R_{g-L} = ratio of gas-side resistance to liquid-side resistance, [-]
s = engagement length, [m]
S = cross-sectional area of tangential inlet duct, [m^2]
t_i = contact time in tangential inlet duct of the cyclone, [s]
t_c = contact time in cyclone, [s]
v = velocity, [m/s]
T = temperature, [K]
V_{con} = volume of conical section, [m^3]
V_d = volume of droplet, [m^3]
z = distance from nozzle point, [m]
$z_{con.}$ = height position in conical section, [m]
z_w = wetted height of the cyclone, [m]

Greek Letters

ΔC_A = driving force based on liquid concentration, [kg/m^3]
P = density, [kg/m^3]
ρ_m = molar density of liquid, [$kmol/m^3$]
μ = viscosity, [$kg/(m.s)$]

Subscripts

d = droplet

G = gas
L = liquid
r = radial
θ = tangential
w = cyclone wall
z = axial

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