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Kinetic Model for the Reaction of Ca(OH)₂/Fly Ash Sorbents with SO₂ at Low Temperatures

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Sorbents prepared with different Ca(OH)₂/fly ash weight ratios were reacted with SO₂ under conditions similar to those in the bag filters in the spray-drying flue gas desulfurization system. The reaction kinetics was well described by a generalized surface coverage model developed in this study. The model assumes that the sorbent was made up of plate grains and the rate was controlled by the chemical reaction on the grain surface and takes into account the variation in sorbent Ca molar content (M^{-1}) and the surface coverage byproducts. The effect of Ca(OH)₂/fly ash weight ratio on the reaction was represented by the effects of the initial specific surface area (S_{g0}) and M^{-1} of the sorbent on the kinetic parameters. Under the same reaction conditions, the sorbents with weight ratios $\geq 30/70$ had about the same initial reaction rate per unit surface area of the sorbent; their ultimate conversions increased linearly with increasing S_{g0} , being independent of M^{-1} . The effects of relative humidity, SO₂ concentration, and temperature on the reaction were unaffected by the Ca(OH)₂/fly ash ratio. The results of this study are useful to the design and operation of the dry and semidry processes using Ca(OH)₂/fly ash sorbents to remove SO₂ from the flue gas.

Introduction

Abatement of SO₂ emission from power plants is important for environmental protection. Many flue gas desulfurization (FGD) processes are available for the reduction of SO₂ emission. The dry and semidry FGD processes have the advantages of lower capital cost and easier waste treatment in comparison with the wet processes commonly adopted in power plants; however, the conversion of the sorbent, which is mostly hydrated lime [Ca(OH)₂], in the dry and semidry processes is low.

Many researchers have shown that sorbents prepared from hydrated lime and fly ash have higher SO₂ captures and Ca utilizations than hydrated lime alone has.^{1–14} The sorbents were prepared by slurring hydrated lime and fly ash in water for a certain period of time and drying the slurry subsequently. Fly ash is the solid waste generated by coal-fired power plants. Thus, the successful use of this kind of sorbent can reduce not only the cost of sorbent but also the cost of waste treatment for coal-fired power plants. The structural properties and the reactivities toward SO₂ for Ca(OH)₂/fly ash sorbents have been reported to be affected by sorbent preparation conditions, such as the type of fly ash, Ca(OH)₂/fly ash weight ratio, water/solid ratio, the type of additive, hydration temperature, and hydration time.

The literature on the kinetic model for the reaction of Ca(OH)₂/fly ash sorbents with SO₂, however, is scarce. Garea et al.¹¹ studied the sulfation of such sorbents (1/3 weight ratio) and proposed a kinetic model based on the nonideal surface adsorption model.¹⁵ Recently, we reported a surface coverage model for sorbents prepared with a weight ratio of 70/30.¹³

In this work, the effect of Ca(OH)₂/fly ash weight ratio on the kinetics of the reaction of Ca(OH)₂/fly ash sorbents with SO₂ was investigated, with the aim to develop a kinetic model for sorbents prepared with different weight ratios.

Table 1. Ca(OH)₂/Fly Ash Weight Ratios, Sorbent Weights per Mole of Ca, True Densities, BET Specific Surface Areas, and Values of k_1 and k_2^{-1} in eq 1 for Ca(OH)₂/Fly Ash Sorbents^a

Ca(OH) ₂ /fly ash wt ratio	M (g sorbent/ mol Ca)	ρ_g (g/mL)	S_{g0} (m ² /g)	k_1 (min ⁻¹)	k_2^{-1}
raw Ca(OH) ₂	75	2.29	9.6	0.032	0.195
100/0	76	2.31	11.8	0.049	0.241
90/10	86	2.36	19.8	0.115	0.413
70/30	110	2.43	38.0	0.165	0.620
50/50	163	2.41	38.7	0.329	0.752
30/70	252	2.38	27.5	0.354	0.694
10/90	677	2.39	42.3	0.581	1.163

^a Slurrying conditions: 65 °C, L/S = 10/1, and 16 h. Reaction conditions: 60 °C, 70% RH, and 1000 ppm SO₂.

Experimental Section

The Ca(OH)₂ reagent, fly ash, sorbent preparation procedure, and experimental setup and procedure for sulfation experiments used in this work were the same as those described in Liu et al.¹³ and Lin et al.¹⁴ Sorbents with different Ca(OH)₂/fly ash weight ratios, as those listed in Table 1, were prepared at a water/solid weight ratio of 10/1, a slurrying temperature of 65 °C, and a slurrying time of 16 h. The sorbents were reacted with SO₂ mainly under the conditions of 60 °C, 70% relative humidity (RH), and 1000 ppm SO₂.

The conversion, X , of a reacted sample was defined as its SO₃²⁻/Ca²⁺ molar ratio. The SO₃²⁻ content in a sample was determined by iodometric titration, and the Ca²⁺ content by EDTA titration. For each Ca(OH)₂/fly ash weight ratio, the Ca²⁺ molar content in the sorbent was determined by EDTA titration, and its reciprocal, M , the initial sorbent weight per mole of Ca, is listed in Table 1. The M value increases as the Ca(OH)₂/fly ash weight ratio decreases.

The characterization of the Ca(OH)₂/fly ash sorbents has been reported in our recent work.¹⁴ The sorbents contained calcium silicate hydrates, which were formed during the sample preparation period. The amounts of

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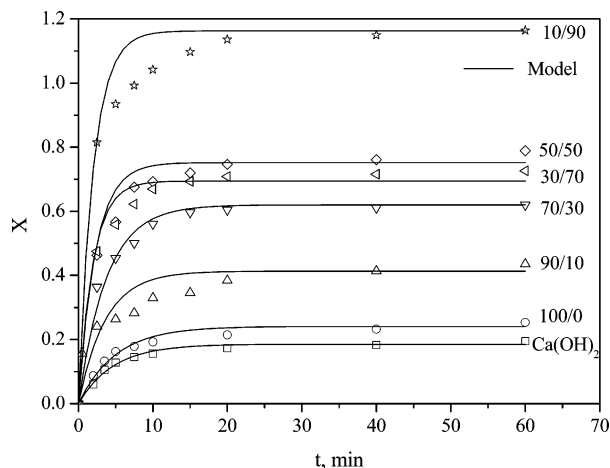


Figure 1. Effect of Ca(OH)_2 /fly ash weight ratio on the reaction of Ca(OH)_2 /fly ash sorbents with SO_2 . Slurrying conditions: 65 °C, $L/S = 10/1$, and 16 h. Reaction conditions: 60 °C, 70% RH, and 1000 ppm SO_2 .

calcium silicate hydrates in sorbents with 70/30 to 30/70 ratios were more than those in sorbents with 90/10 and 10/90 ratios. The mean particle diameters of the sorbents with 70/30 to 10/90 ratios were in the range of 9–35 μm , and those of raw Ca(OH)_2 , slurried Ca(OH)_2 , and the sorbents with a 90/10 ratio were in the range of 4–7 μm . All the Ca(OH)_2 /fly ash sorbents were mesoporous materials; their specific surface areas and pore volumes were larger than those of Ca(OH)_2 or fly ash alone. The BET specific surface area, S_{g0} , of each sorbent is listed in Table 1.

Results and Discussion

Effect of Sorbent Ca(OH)_2 /Fly Ash Ratio on the Reaction. The experimental results for the reaction of the sorbents with SO_2 are shown in Figure 1 in terms of conversion X versus time t . As shown in Figure 1, the sorbent reactivity increases with decreasing Ca(OH)_2 /fly ash ratio except the sorbents with ratios of 50/50 and 30/70; the latter sorbent is slightly less reactive than the former. The reaction of each sorbent is seen to stop at an ultimate conversion after about a 20 min reaction time. The ultimate conversion of the sorbent with a ratio of 10/90 exceeds unity; this is because the contribution of the reactive compounds of Na, K, and Mg other than Ca present in the fly ash particles was also included in the calculation of conversion.

Kinetic Model. The foregoing results show that all the sorbents have similar reaction behavior that the reaction is fast in the initial stage and then levels off abruptly. Among the sorbents, Ca(OH)_2 ^{16,17} and the Ca(OH)_2 /fly ash sorbent with a ratio of 70/30¹³ have been subjected to extensive kinetic studies, and their reaction kinetics have been found to be well described by the surface coverage model proposed by Shih et al.¹⁸

The hypotheses of the surface coverage model are that the sorbent is made up of plate grains and that the reaction rate is controlled by chemical reaction on the surface of a grain and the reacting surface area of the grain decreases with the deposition of solid products. According to this model, the reaction of a sorbent reaches an ultimate conversion when its reacting surface is fully covered by the products.

The surface coverage model proposed in the previous studies^{13,16–18} is for the sorbents which have the same

Ca molar content. The model can be generalized to describe the reaction of the sorbents which have different Ca molar contents.

The reaction rate of a sorbent per unit initial surface area, r_s , can be expressed as

$$r_s = k_s M^{-a} \Phi \quad (1)$$

where k_s is a function of temperature, concentrations of reacting gas species, and relative humidity; M^{-1} is the Ca molar content in the sorbent and the index a represents the effect of Ca content on the sorbent reactivity; and Φ is the fraction of the surface area which is not covered byproducts. The rate of conversion of the sorbent is

$$dX/dt = S_{g0} M r_s = S_{g0} k_s M^{1-a} \Phi \quad (2)$$

where S_{g0} is the initial specific surface area of the sorbent.

The change of Φ with reaction time depends on the reaction rate, the content of Ca, and the way by which the products deposit on the surface. The effect of Ca content on Φ can be seen from Figure 1. Figure 1 shows that the sorbent has a higher initial rate of conversion when its Ca(OH)_2 /fly ash ratio is lower (that is, its M value is larger), but it reaches the ultimate conversion no later. This fact indicates that the rate of change of Φ increased with increasing M . Thus, one may assume that

$$-d\Phi/dt = k_p k_s M^b \Phi \quad (3)$$

where k_p is a proportional constant, which may be also a function of temperature, concentrations of reacting gas species, and relative humidity, and b is an index representing the effect of M . If k_s and k_p do not vary with time, eq 3 can be integrated to get

$$\Phi = \exp(-k_1 k_2 t) \quad (4)$$

where

$$k_1 = k_s S_{g0} M^{1-a} \quad (5)$$

$$k_2 = k_p M^{a+b-1} / S_{g0} \quad (6)$$

By substitution of eq 4 into eq 2, one can integrate eq 2 to obtain the relation between conversion and time

$$X = [1 - \exp(-k_1 k_2 t)] / k_2 \quad (7)$$

From eq 7 one can see that the ultimate conversion is equal to k_2^{-1} . From the differential form of eq 7

$$dX/dt = k_1 (1 - k_2 X) \quad (8)$$

it is obvious that the initial rate of conversion is equal to k_1 .

In the previous studies,^{13,16–18} the same equation as eq 7 was obtained for X as a function of t , but the k_1 and k_2 equations were defined as the case that a and b in eqs 5 and 6 equal zero.

The two parameters, k_1 and k_2 , in eq 7 can be obtained by nonlinear least-squares fitting of the equation to the experimental X versus t data. Table 1 summarizes the

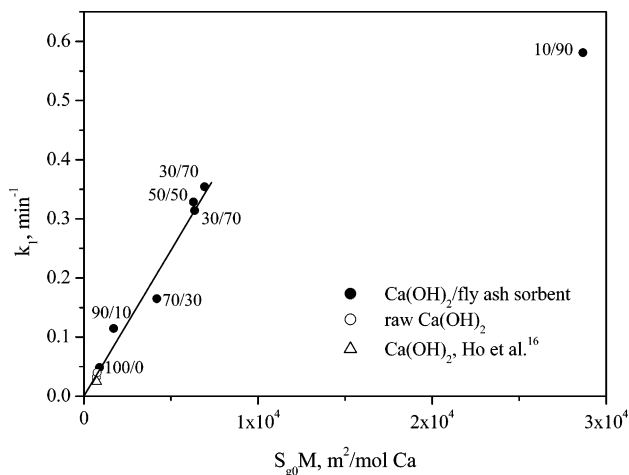


Figure 2. Plot of k_1 versus $S_{g0}M$. Slurring conditions: 65 °C, L/S = 10/1, 16 h. Reaction conditions: 60 °C, 70% RH, and 1000 ppm SO_2 .

Table 2. Values of k_1 and k_2^{-1} for $Ca(OH)_2$ ($M = 74$ g/mol Ca, $S_{g0} = 10.3$ m²/g) and the Sorbent with a $Ca(OH)_2$ /Fly Ash Weight Ratio of 30/70 ($M = 248$ g/mol Ca, $S_{g0} = 25.6$ m²/g) Reacted with SO_2

sorbent	T (K)	RH (%)	y (ppm)	k_1 (min ⁻¹)	k_2^{-1}
$Ca(OH)_2$	333	50	1000	0.033	0.140
	333	70	1000	0.040	0.186
	333	80	1000	0.049	0.255
Ca(OH) ₂ /fly ash	333	30	1000	0.163	0.330
	333	50	1000	0.220	0.527
	333	70	1000	0.314	0.672
	333	80	1000	0.355	0.787
	333	70	5000	0.435	0.694
	353	70	1000	0.466	0.694

values of k_1 and k_2^{-1} thus obtained. The curves plotted in Figure 1 using eq 7 show that the experimental data are well described by eq 7.

Effect of $Ca(OH)_2$ /Fly Ash Ratio on k_1 and k_2 .

From Table 1, one can see that the values of k_1 and k_2^{-1} vary from sorbent to sorbent, indicating that they are affected by the $Ca(OH)_2$ /fly ash weight ratio. However, eqs 5 and 6 predict that the effect of the $Ca(OH)_2$ /fly ash weight ratio on the values of k_1 and k_2^{-1} is entirely represented by the effects of S_{g0} and M . These correlations can be confirmed and the parameters a and b in the equations can be determined using the data of k_1 , k_2 , S_{g0} , and M . In the following analysis, the data listed in Table 1 and those listed in Table 2 for another batch of $Ca(OH)_2$ and another batch of the sorbent with a $Ca(OH)_2$ /fly ash ratio of 30/70 are taken into consideration. The data given by Ho et al.¹⁶ for $Ca(OH)_2$ ($M = 74$ g/mol, $S_{g0} = 10.0$ m²/g) are also included.

The k_1 value for each sorbent is plotted against its $S_{g0}M$ in Figure 2. Except the data for the sorbent with a 10/90 ratio, k_1 and $S_{g0}M$ follow the linear relationship given by eq 5 when $a = 0$. The linear least-squares fitting line in Figure 2 gave

$$k_1 \text{ (min}^{-1}\text{)} = [(5.00 \pm 0.23) \times 10^{-5}]S_{g0}M \quad (9)$$

with a correlation coefficient of 0.992. The standard error of the slope of the line is also indicated in eq 9. This result indicates that under the same reaction conditions all the sorbents except the one with a 10/90 ratio have about the same k_S value or the same initial rate per unit surface area of the sorbent according to eq 1. Moreover, according to eqs 8 and 9, the initial

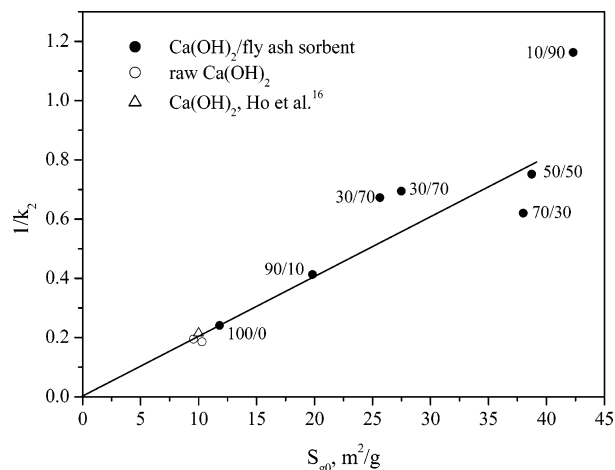


Figure 3. Plot of k_2^{-1} versus S_{g0} . Slurring conditions: 65 °C, L/S = 10/1, 16 h. Reaction conditions: 60 °C, 70% RH, and 1000 ppm SO_2 .

rate of conversion for a sorbent is proportional to its S_{g0} and M .

As shown in Figure 3, there is a linear relationship between k_2^{-1} and S_{g0} , except the data for the sorbent with 10/90 ratio. The linear least-squares fitting line in Figure 3 gave

$$k_2^{-1} = [(2.04 \pm 0.12) \times 10^{-2}]S_{g0} \quad (10)$$

with a correlation coefficient of 0.946. This result indicates that k_2 is independent of M . Thus, b in eq 6 must be unity because a in eq 5 has been found to be zero.

According to eq 7, k_2^{-1} equals the ultimate conversion. Therefore, eq 10 implies that the ultimate conversion of a sorbent is proportional to its S_{g0} and independent of its M .

The reason that the k_1 or k_2^{-1} value for the sorbent with a 10/90 ratio could not be predicted by eq 9 or 10 is thought to be due to the excess of the fly ash content; this sorbent contained much more reactive constituents other than $Ca(OH)_2$ and calcium silicate hydrates than the sorbents with ratios $\geq 30/70$.

Discussion on Ultimate Conversion. For a sorbent made up of plate grains, the conversion of the sorbent can be expressed as¹⁹

$$X = \frac{\Delta r}{r_0} \quad (11)$$

where r_0 is the initial half-thickness of the plate and Δr is the thickness of the outer layer of the original grain that has been reacted. r_0 can be estimated by

$$r_0 = \frac{1}{\rho_g S_{g0}} \quad (12)$$

where ρ_g is the true density of the sorbent. Combining eqs 11 and 12 gives

$$X = \rho_g S_{g0} \Delta r \quad (13)$$

When the reaction stops due to the complete coverage of the reactive surface, X and Δr reach the maximum values, X_m and Δr_m , and

$$X_m = \rho_g S_{g0} \Delta r_m \quad (14)$$

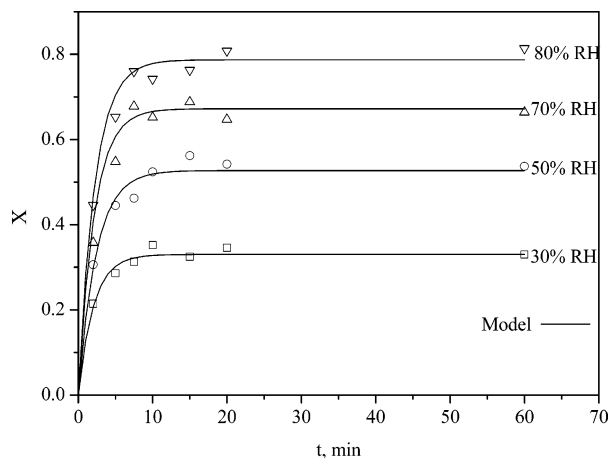


Figure 4. Effect of the RH on the reaction of $\text{Ca}(\text{OH})_2/\text{fly ash}$ (30/70 wt ratio, $M = 248 \text{ g/mol Ca}$) sorbent. Slurrying conditions: 65°C , $L/S = 10/1$, and 16 h. Reaction conditions: 60°C and 1000 ppm SO_2 .

Comparing eqs 6 and 14 gives

$$(k_p M^{a+b-1})^{-1} = \rho_g \Delta r_m \quad (15)$$

Thus, the inverse of $k_p M^{a+b-1}$ can be interpreted as the maximum weight reacted per unit surface area of the sorbent.

According to eq 14, X_m is proportional to S_{g0} alone only when $\rho_g \Delta r_m$ is constant. Thus, the linear relationship between X_m and S_{g0} represented by eq 10 implies that $\rho_g \Delta r_m$ for each sorbent must be about the same. Furthermore, the ρ_g 's of the sorbents, as shown in Table 1, are about the same, being in the range of 2.29 to 2.43 g/cm^3 . Therefore, Δr_m , the maximum thickness of the reacted layer, must be about the same for each sorbent also.

Effects of Reaction Conditions on k_1 and k_2 .

Equations 9 and 10 were obtained under the reactions of 60°C , 70% RH, and 1000 ppm SO_2 . According to Ho et al.¹⁶ and Liu et al.,¹³ k_1 and k_2 are also functions of RH, temperature, and SO_2 concentration, but only RH affects k_1 and k_2 significantly.

To know whether the relationship between k_1 or k_2 and S_{g0} and M is affected by the RH and whether the relationship between k_1 or k_2 and RH is affected by the $\text{Ca}(\text{OH})_2/\text{fly ash}$ weight ratio, samples of $\text{Ca}(\text{OH})_2$ ($M = 74 \text{ g/mol Ca}$, $S_{g0} = 10.3 \text{ m}^2/\text{g}$) and the sorbent with a ratio of 30/70 ($M = 248 \text{ g/mol Ca}$, $S_{g0} = 25.6 \text{ m}^2/\text{g}$) were reacted with 1000 ppm of SO_2 at 60°C and different RHs (30–80% RH). The results for the latter sorbent are shown in Figure 4, indicating that the RH indeed enhances the reaction significantly. The latter sorbent was also reacted at a higher SO_2 concentration (5000 ppm) and a higher temperature (80°C). The X vs t results, not shown here, indicated that the increase in SO_2 concentration or temperature increased only mildly the initial rate of conversion, having a negligible effect on the ultimate conversion.

The k_1 and k_2 values obtained for the foregoing reactions, as shown in Table 2, are compared with those already reported for $\text{Ca}(\text{OH})_2$ ¹⁶ and the $\text{Ca}(\text{OH})_2/\text{fly ash}$ sorbent with a 70/30 ratio¹³ in terms of $\ln[k_1/(S_{g0}M)]$ versus RH in Figure 5 and $\ln[k_2^{-1}/S_{g0}]$ versus \ln RH in Figure 6. According to the correlations given by Liu et al.,¹³ these plots are linear for the sorbent with a 70/30 ratio. As can be seen in Figures 5 and 6, the data for each sorbent seem to exhibit a linear trend in general.

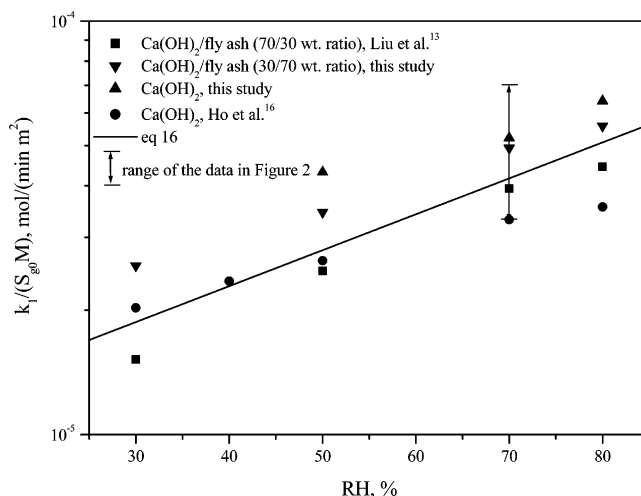


Figure 5. Relationship between k_1 and relative humidity for sorbents. Other reaction conditions: 60°C and 1000 ppm SO_2 .

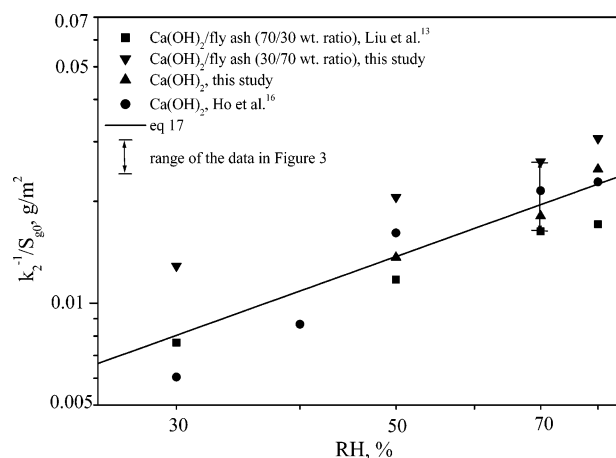


Figure 6. Relationship between k_2 and relative humidity for sorbents. Other reaction conditions: 60°C and 1000 ppm SO_2 .

For $k_1/(S_{g0}M)$ (Figure 5), the range of the data at each RH is smaller than that for the data considered in Figure 2 (70% RH); however, for k_2^{-1}/S_{g0} (Figure 6), the range of the data at 80% RH is greater than that for the data considered in Figure 3 (70% RH). These results indicate that the linear relationship between k_1 and $S_{g0}M$ or between k_2^{-1} and S_{g0} is as good as that at 70% RH for $\text{RH} \leq 70\%$ and that the relationship between k_1 or k_2 and RH is nearly unaffected by the $\text{Ca}(\text{OH})_2/\text{fly ash}$ ratio.

The equations representing the effects of RH (30–70% RH), temperature (T , 333–353 K), and SO_2 concentration (y , 1000–5000 ppm) on k_1 and k_2 for the sorbents with weight ratios $\geq 30/70$ were further derived and the parameters in the equations were determined by multiple regression,¹⁶ using the data shown in Tables 1 and 2, Figures 5 and 6, and those at 70% RH, 70 and 80°C , and 3000 and 5000 ppm SO_2 given in the article by Liu et al.¹³ The resulting k_1 and k_2^{-1} equations are

$$k_1 (\text{min}^{-1}) = (2.15 \times 10^{-4}) S_{g0} M e^{0.022 \text{RH}} y^{0.10} e^{-10000/RT} \quad (16)$$

$$k_2^{-1} = (2.33 \times 10^{-4}) S_{g0} \text{RH}^{1.05} \quad (17)$$

The 95% confidence intervals for the parameters in the above equations are $(2.15 \times 10^{-4}) e^{\pm 5.76} \text{ min}^{-1}$,

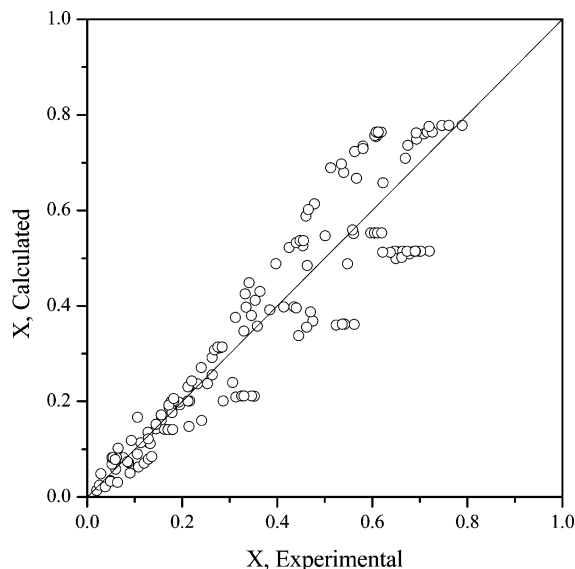


Figure 7. Comparison of the calculated and experimental conversion values.

0.022 ± 0.007 , 0.10 ± 0.20 , and -10000 ± 16000 J/mol, respectively, for eq 16, and $(2.33 \times 10^{-4})e^{\pm 3.19}$ and 1.05 ± 0.78 for eq 17. The standard deviations of k_1 and k_2^{-1} from the values calculated by eqs 16 and 17 are 0.04 min^{-1} and 0.12 , respectively. The lines plotted in Figures 5 and 6 show the agreement of eqs 16 and 17 with the data.

In Figure 7, conversions calculated by eq 7 together with eqs 16 and 17 are compared with the experimental results obtained for the sorbents and reaction conditions mentioned in the above paragraph. The comparison shows that both conversions are in agreement with a standard deviation of 0.09. This agreement is considered to be satisfactory for the $\text{Ca}(\text{OH})_2/\text{fly}$ ash sorbents, which have complex sorbent compositions and reaction behaviors.

The rate-controlling step for the reaction of sorbents is thought to be the dissolution of the Ca-containing solid reactants proceeding through the reaction with the acid formed by the SO_2 and H_2O molecules adsorbed on the sorbent surface. Raising the RH increases the amount of water adsorbed and hence the amount of acid formed and the amount of solid reactants dissolved. A greater amount of adsorbed water also provides a wider range for the product molecules to deposit and thus would result in a lower rate of covering the reaction surface.^{13,16,17} Therefore, the RH showed a significant effect on the reaction rate and the ultimate conversion. The amount of SO_2 molecules dissolved in the water layer may be limited by the amount of the adsorbed water; thus, the reaction would be insensitive to the gas-phase SO_2 concentration. The mild effect of temperature on the reaction rate may be due to the fact that as the temperature increases, the chemical reaction rate constants increase, whereas the amounts of water and SO_2 adsorbed decrease. Although the amount of water adsorbed decreased with increasing temperature, the thickness of the water layer was mainly function of RH and nearly independent of temperature, according to the measurements by Liu et al.¹³ This may be the reason that the ultimate conversion was mainly affected by the RH.

When the reaction conditions vary with time, like the case encountered in industrial FGD processes, the

differential form of the model can be used. Substituting eqs 5 and 6 into eqs 2 and 3 gives

$$dX/dt = k_1\Phi \quad (18)$$

$$d\Phi/dt = -k_1k_2\Phi \quad (19)$$

Substituting eqs 16 and 17 into eqs 18 and 19, the latter two equations can be integrated to obtain X if the variations of reaction conditions with time are known.

Conclusion

From the above analyses, we can conclude that for a $\text{Ca}(\text{OH})_2/\text{fly}$ ash sorbent prepared with a weight ratio $\geq 30/70$, its reaction with SO_2 at low temperatures can well be described by the generalized surface coverage model developed in this study. The model assumes that the sorbent was made up of plate grains and the rate was controlled by the chemical reaction on the grain surface and takes into account the variation in sorbent Ca molar content (M^{-1}) and the surface coverage byproducts. The effect of $\text{Ca}(\text{OH})_2/\text{fly}$ ash weight ratio on the reaction kinetics was represented by the effects of the S_{g0} and M of the sorbent on the kinetic parameters. Under the same reaction conditions, the sorbents with weight ratios $\geq 30/70$, including $\text{Ca}(\text{OH})_2$ alone, had about the same initial rate per unit surface area of the sorbent and their ultimate conversions, being independent of the M value, increased linearly with increasing S_{g0} . The effects of relative humidity, SO_2 concentration, and temperature on the reaction were unaffected by the $\text{Ca}(\text{OH})_2/\text{fly}$ ash ratio. The initial conversion rate and ultimate conversion of a sorbent increased significantly with increasing relative humidity. Temperature and SO_2 concentration had mild effects on the initial conversion rate and negligible effects on the ultimate conversion. The results of this study are useful to the design and operation of the dry and semidry processes using $\text{Ca}(\text{OH})_2/\text{fly}$ ash sorbents to remove SO_2 from the flue gas.

Acknowledgment

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Nomenclature

- a = index of M^{-1} in eq 1, dimensionless
- b = index of M in eq 3, dimensionless
- k_p = constant defined by eq 3, $\text{m}^2\text{mol}^{a+b-1}/\text{g}^{a+b}$
- k_s = constant defined by eq 1, $\text{g}^a\text{mol}^{1-a}/(\text{min m}^2)$
- $k_1 = k_s S_{g0} M^{1-a}$, min^{-1}
- $k_2 = k_p M^{a+b-1}/S_{g0}$, dimensionless
- M = initial weight of solid per mol of Ca, g/mol
- R = gas constant, 8.314 J/mol K
- RH = relative humidity, %
- r_0 = initial half-thickness of a plate grain, m
- r_s = reaction rate of solid, $\text{mol}/(\text{min m}^2)$
- Δr = thickness of reacted layer of a grain, m
- Δr_m = the maximum value of Δr , m
- S_{g0} = initial specific surface area of solid, m^2/g
- T = reaction temperature, K
- t = time, min
- X = conversion, dimensionless
- X_m = the maximum value of X , dimensionless
- y = SO_2 concentration, ppm

Greek Symbols

ρ_g = true density of sorbent, g/mL

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