In-furnace capture of cadmium and other semi-volatile metals by sorbents

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Abstract

An 18 kW, cylindrical (inside diameter = 15-cm), 6-m high, laminar, downflow furnace was used to investigate the mechanisms governing reactive scavenging of cadmium vapors from combustion environments, by hydrated lime and kaolinite powder sorbents. Two major physical mechanisms dominate the reaction rate and sorbent utilization during the capture of semi-volatile metal by kaolinite, temperature-activated eutectic-melting-enhanced capture and excessive-melt deactivation, initiated at a higher temperature than the enhancement. However, cadmium forms higher temperature eutectics than other semi-volatile metals such as lead and sodium, which have a transition to a deactivating melt below 1100 °C. The network modifier responsible for the reaction enhancement is the metal/sorbent reaction product itself, which forms a eutectic with the remaining, unreacted sorbent. Global rate models were developed to describe the reaction of kaolinite with lead, sodium, and cadmium metal vapors. The following reaction scheme was valid for all three metal vapors, Na/Pb/Cd:

\[ \text{Na}_2\text{O} / \text{PbO} / \text{CdO} + \frac{1}{2}(\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2) \rightarrow \text{P}_{\text{Na/Pb/Cd}}. \]

Followed by the substrate (melting) deactivation step for Na and Pb, but not for Cd:

\[ \text{P}_{\text{Na/Pb}} + \frac{1}{2}(\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2) \rightarrow \text{D} + \text{P}_{\text{Na/Pb}}. \]

Eutectic-melting enhancement of cadmium capture by both kaolinite and hydrated lime was initiated between 1160 and 1280 °C. Cadmium is more effectively captured at higher temperatures (i.e., ~1300 °C) than other semi-volatile metals, such as lead and sodium, and requires even higher temperatures to cause sorbent deactivation by excessive melting. Unlike cadmium, lead and sodium were poorly scavenged by hydrated lime.

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1. Introduction

Toxic metals in trace amounts are emitted from power generating boilers and waste incinerators. The accumulation of these toxic metals over
time in localized environments threatens human health. One method of eliminating these toxic metal emissions is to inject a powder sorbent, such as hydrated lime or kaolinite, directly into the combustion zone of boilers and incinerators. In a combustion environment, these powder sorbents can reactively capture toxic metals, are collectable in conventional particulate collection devices, and can be disposed of in a safe manner.

The capture of cadmium by kaolinite, bauxite, and hydrated lime has been reported from low temperature benchscale experiments [1–3] and larger laboratory scale experiments [4–7], with temperatures, residence times, and gas atmospheres indicative of industrial boilers and incinerators (such as the experiments performed in this work). One of the most important of these was work done by Linak et al. [4], which showed that cadmium could be effectively captured either by kaolinite or hydrated lime injection into 1300°C post-flame gases. Both the kaolinite and hydrated lime product particles exhibited evidence of melting from SEM morphological observations [4]. However, in the absence of cadmium, the fired hydrated lime particles remained crystalline, angular, and appeared not to have melted. In the case of hydrated lime, acidic cadmium oxide was credited with forming a eutectic with basic calcium oxide [4], thus causing the melt to occur. Lower temperature bench-top work [3] failed to effectively capture cadmium with either kaolinite or hydrated lime at temperatures insufficient to cause melting. Calcium sorbents have also been found to be effective at reactively scavenging arsenic from flue gas [8].

The work of Linak and coworkers [4] was qualitative. Since then, techniques have improved for the quantification of metal capture by sorbents from high-temperature gas environments [7,9–11]. This work endeavors to quantify and to obtain global rates of capture for cadmium across the temperature regime of low to high reactivity with both hydrated lime and kaolinite. In addition, the mechanisms and rates of cadmium capture will be compared with those of lead and sodium.

Previous utilization of the quantitative metal capture methods mentioned [5,7,9–11] for the capture of lead, sodium, and cadmium by kaolinite powder has produced an understanding of the mechanisms governing single-metal capture of semi-volatile metals by kaolinite and the independence of each metal in multi-metal systems. Among other things, the important role of eutectic melting, both in inhibition and enhancement of metal capture, has been elucidated.

The fundamental semi-volatile metal reaction processes with kaolinite in high-temperature entrained-flow environments are summarized [5,7,11] as follows: Soon after injection, kaolinite flash-calcines to form layers of single meta-kaolinite (aluminosilicate) crystal platelets separated by open meso-pore gaps. Hence, transport limitations are minimal, and most of the active sites are on available surface. At low temperatures, the reaction rate is slow, limited by the closely packed crystal structure and aluminosilicate reaction rate. At higher temperatures, the initial products are aluminosilicates, but these initial products induce a eutectic-melt that breaks down the closely packed crystal structure, thus allowing more degrees of freedom and greater capture [11]. As the reaction continues, the aluminosilicate structure completely breaks down, allowing the formation of silicates and aluminates. In the case of sodium, silicates and aluminates allow for at least twice the sorbent utilization available from sodium aluminosilicate reaction products alone [7,11]. At still higher temperatures, the eutectic-melt becomes excessive, thus filling in the meso-pore gaps lying between the platelets, and the sorbent is deactivated before complete sorbent utilization can be achieved [11].

Multi-metal mechanisms governing capture by dispersed kaolinite powder were found to be complex [5,7]. It was found that cadmium capture by kaolinite, at temperatures between 1000 and 1300°C, is enhanced by the melting and restructuring of the meta-kaolinite crystal caused by the presence of another metal, such as lead or sodium. Cadmium, in turn, enhances the capture of lead and sodium at these same temperatures by inhibiting (postponing) sorbent deactivation [5,7] through meso-pore closure. On the other hand, for the same temperature range, competition between sodium and lead capture on kaolinite strongly favored sodium capture. A higher reaction rate allows sodium to dominate through direct competition and also by reacting with the sorbent before the deactivating melt, initiated either by the sodium or lead products, significantly deactivates the sorbent [5,7]. It was also previously found that sodium dominates over lead by effectively displacing lead already captured, possibly by causing lead aluminosilicate products to break down into lower order sodium and lead silicates, and aluminates [5,7].

2. Experimental

The downflow furnace, a 6 m tall, 0.15 m ID, vertical combustor, was operated at 18 kW load [5,7,10], and possessed a temperature profile shown in Fig. 1, which was unchanged between test conditions. The quarl and upper wall of the furnace was constructed with SiC-lined refractory, to prevent metal uptake by the furnace wall. The lower wall was constructed of vacuum-formed Yttria-stabilized zirconia (ZrO2·Y2O3) cylinders [7], specifically because cadmium was less reactive with the zirconia than with alumina. In addition to the furnace wall inertness with respect to cad-
mium, tests proved that loss of sorbent (by settling) to the furnace wall was less than 10% of the total furnace sorbent concentration.

Aqueous metal acetates were introduced with a plain jet-air blast atomizer through the center of a natural gas flame, fired by a premixed burner. An air/fuel ratio of 1.2 was maintained for all experiments in this work. Dewpoints were calculated using a multi-component chemical equilibrium analysis program (CEA) [12].

Sorbent powders, either hydrated lime or Burgess-40 kaolinite, were injected at constant rates between 0.05 and 2.0 g/min axially into the combustion gas stream, along the centerline of the furnace [7]. Sorbent was injected either one or two meters below the burner, while sampling took place at ~1000 °C for all conditions. Thus, as shown in Fig. 1, all experiments were conducted at either a 1280 or 1160 °C sorbent-injection condition, with associated residence times of 1.15 and 0.86 s, respectively.

The contribution of micro- and macro-pores was insignificant for both sorbents investigated. The structure of the sorbents and the nature of the calcination process (dehydration through rapid heating) are such that the flash-calcined products, either meta-kaolinite or quicklime, also contain insignificant porosity [11], other than meso-porosity. Table 1 contains the average pore diameter and meso-pore surface area of each sorbent. Flash calcination, which occurs upon sorbent injection into the furnace, may increase the meso-porosity and internal surface area of each sorbent by an order of magnitude.

Extent of metal capture and the sorbent/metal equivalence ratio were determined by the aerosol size fractionation method (ASFM) [7,9–11]. This method uses a rapid dilution aerosol sampling probe followed by a Berner low-pressure impactor (BLPI) [13,7], to create a bimodal metal distribution, with a distinct separation between the unreacted and captured metal, as illustrated in Fig. 2. Samples were withdrawn below the sorbent injection point but above the calculated dewpoints, before any physical condensation in the furnace was possible. Thus, metal vapor at the sampling point was manifested as an ultrafine mode in the particle size distribution (PSD) obtained in the BLPI. This ultrafine mode yields the fraction of metal that was still vapor before sampling, together with the fraction of metal scavenged by dispersed sorbent, which is contained in the super-micron mode of the sampled PSD, found in the BLPI. The use of the ASFM as established [7,9–11] guaranteed that metals collected on the sorbent plates were indeed 'reactively' captured by sorbent material, and were not condensed equilibrium products.

### Table 1: Sorbent characteristics

<table>
<thead>
<tr>
<th>Sorbent composition</th>
<th>Average pore diameter (nm)</th>
<th>Mass mean size (μm)</th>
<th>N$_2$ BET SA (m$^2$/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite Al$_2$O$_3$ · 2SiO$_2$ · 2H$_2$O</td>
<td>24.0</td>
<td>2–6</td>
<td>21.0</td>
</tr>
<tr>
<td>Hydrated lime Ca(OH)$_2$</td>
<td>14.5</td>
<td>5–8</td>
<td>19.5</td>
</tr>
</tbody>
</table>

*a* As measured from furnace.

### 3. Results and discussion

#### 3.1. Cadmium capture data

Figure 3 illustrates the capture of cadmium as a function of sorbent/metal equivalence ratio at the low and high temperature sorbent injection conditions. The top graph shows that cadmium is captured much more effectively by kaolinite at the high temperature condition than at the low-temperature condition. It appears that sorbent...
utilization may exceed that based on single-oxide aluminosilicates at lower equivalence ratios, especially at the high temperature condition. Indeed, for single-metal and bimetal systems of lead, sodium, and cadmium, a sorbent utilization limit based on twice that predicted by the formation of single-oxide aluminosilicates (i.e., CdO $\cdot$ Al$_2$O$_3$ $\cdot$ 2SiO$_2$) was observed (see Fig. 4A and B) [7,11]. Hence, the reactions described below and capture-rate equations described later are based on this observed kaolinite utilization limit. For reactants PbO, CdO, and 2NaOH (forming products associated with Na$_2$O [11]), the reactions may be described thus:

$$\text{react.} + \frac{1}{2}(\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2) \xrightarrow{k_{\text{react}}} \text{P}_i,$$

followed for Pb and Na (but not Cd) by the deactivation step:

$$\text{P}_i + \frac{1}{2}(\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2) \xrightarrow{k_{\text{deact}}} \text{D} + \text{P}_i,$$

where $\text{P}_i$ are the reaction products of metal $i$ (Pb, Cd, or Na), and D is deactivated sorbent, caused by a catastrophic melt initiated by P$_{\text{Pb}}$ and/or P$_{\text{Na}}$, but not induced by P$_{\text{Cd}}$ for the temperature range described. Eq. (2) describes the deactivation of sorbent as a self-induced catalytic-like process, because the deactivation is not actually due to the formation of a product, but rather to the mere presence of the product, which induces melting.

The hydrated lime utilization limit has been less extensively investigated, although the stoichiometry presented below for the cadmium/hydrated lime system is consistent with the sorbent utilization data obtained in this work.

$$\text{Cd} + \text{CaO} \xrightarrow{k_{\text{HL}}} \text{P}_{\text{Cd.HL}}.$$

The product species formed from the reaction of cadmium with hydrated lime are unknown. However, the size fractionation method used [7,9–11], including a rapid nitrogen quench and sampling above the dewpoint, has assured that the capture products were indeed formed by reaction. Any sampled cadmium vapor homogeneously nucleated and coagulated to form a submicron aerosol separate and distinct from the supermicron-size sorbent upon which cadmium was reactively captured in the furnace.

The capture of cadmium by hydrated lime at the high-temperature condition was extremely
fast, and the sorbent utilization was high. Very low sorbent-feed rates were necessary to obtain data for less than 100% capture. Consequently, the lowest high-temperature cadmium-capture data point in the lower graph of Fig. 3 may have suffered from sorbent-feed errors (associated with an extremely low sorbent feed rate), such that the measured equivalence ratio may be higher than the actual equivalence ratio [7].

As shown in Fig. 3, cadmium is effectively captured by both kaolinite and hydrated lime. However, at temperatures causing a eutectic melt to occur (1280 °C condition), the capture rate is greatly enhanced.

Figures 5A and B shows FE SEM micrographs of cadmium/kaolinite product particles from the low- and high-temperature conditions, respectively. Clearly, the cadmium/kaolinite particles, formed at the high-temperature condition, experienced more of a melt than particles formed at the low-temperature condition. Similar morphologies were observed for hydrated lime. Sorbent particles, exposed to either temperature of injection, remained crystalline in the absence of captured metal (see Fig. 5C). Hence, the eutectic (or near eutectic) melting was induced by captured metal acting as a network modifier.

The cadmium reactions, in the particular temperature region investigated (1000–1300 °C), can be reasonably described by a continually increasing rate (as opposed to lead and sodium capture by kaolinite, which rates decrease with increasing temperature in this temperature region), with respect to increasing temperature [7,14], as explained below. Morphological (see Figs. 5A and B) and rate (see Fig. 3) investigations of the cadmium/kaolinite system indicate that for the low-temperature sorbent-injection condition of this work, cadmium capture does not benefit from eutectic-melt enhancement. However, melting and an increased capture rate were observed for the high-temperature condition. In addition, multi-metal investigations have shown that cadmium capture is greatly enhanced by melting induced by other semi-volatile metals that form eutectics with kaolinite at lower temperatures than does cadmium [5,7].

Cadmium capture was enhanced by the presence of other semi-volatile metals, even at the high-temperature injection condition of this work [5,7], where cadmium itself initiates extensive melting and capture enhancement (see Figs. 5B and 3). This indicates that the self-initiated eutectic melt associated with cadmium capture was still on the increase, even for the highest temperature here investigated. Hence, the major effect being investigated in this work for the cadmium/kaolinite system was the increase in rate with temperature, entirely due to an increase in the reaction-product-initiated eutectic melt, which increased the capture rate orders of magnitude above that of the pre-melt intrinsic rate.

3.2. Lead/kaolinite and sodium/kaolinite systems

The lead/kaolinite and sodium/kaolinite systems have been investigated extensively, and models have been developed describing the rates of metal capture, including reaction-induced eutectic melting and subsequent sorbent deactivation [5,7,11,14,15]. In addition to the melting enhancement and deactivation mechanisms, the eutectic temperature of the metal/kaolinite reaction product is approximately the same for each metal [11]. In other words, the initiation of eutectic melt-
ing begins to occur for the sodium/kaolinite system at approximately the same temperature and concentration of metal as is the case for the lead/kaolinite system. In addition, the extent of excessive (deactivating) melt is approximately the same for both systems. Hence, the same model was used to describe both systems, with a slight change in the magnitude of the constants to account for the faster reaction of the sodium/kaolinite system [11].

### 3.3. Metal-scavenging rate models

It is postulated here that the cadmium/kaolinite and cadmium/hydrated lime systems behave similar to that of the lead/kaolinite and sodium/kaolinite systems, with the exception that cadmium forms a much higher temperature eutectic with both kaolinite and hydrated lime. As discussed above, the temperature region across which sorbent deactivation reduces sodium and lead capture with increasing temperature is the same region (1160–1280 °C) across which an enhancing eutectic melt significantly increases cadmium capture.

Based on the similarity of reaction for all three metals compared in this work, the same set of equations used to describe lead and sodium capture by kaolinite may be used to describe the capture of cadmium either by kaolinite or hydrated lime. The following rate equations describe the time resolved concentration profiles of metal, sorbent, products, and sorbent deactivation, due to the reactions described in Eq. (1)–(3).

\[
\frac{dC_i}{dt} = -k_iC_iC_S,
\]

\[
\frac{dC_D}{dt} = k_DC_PIC_S,
\]

where \(C_i\) (mol/cc) is the in-furnace concentration of the metal, \(k_i\) is the rate constant for metal capture, \(C_P\) is the concentration of products (metals/kaolinite reaction products, \(P_i\)), \(C_D\) is the concentration of deactivated sorbent, and \(C_S\) is the concentration of sorbent.

By rearranging the equation for lead and sodium capture, the reaction stoichiometry of Eqs. (1)–(3)), and metal/kaolinite reaction products, \(P_i\). The quantity \(\alpha\) was introduced into Eq. (6) in previous work to account for the fact that NaOH, the reactive sodium species, has a higher diffusivity and is a smaller molecule than lead oxide, the reactive lead species [7,11]. Therefore, the deactivating melt will be somewhat less deactivating for sodium than for lead, since it will experience less resistance to diffusion. Accordingly, the concentration of deactivated sorbent was reduced by a factor of \(\alpha\), which is 1 (complete barrier) for lead, 0.9 (partial barrier) for sodium (which was determined by non-linear regression to fit the data [11]), and does not apply for cadmium in this temperature region. The concentration of deactivated sorbent, \(C_D\) for lead or \(\alpha C_D\) for sodium, is relative, differing by the factor \(\alpha\) between the lead and sodium models. As discussed in the previous work [11], it is only necessary for \(C_D\) or \(\alpha C_D\) to be greater than or equal to zero for mass to be conserved. Agreement between the models and experimental data is shown elsewhere [5,7,11,14].

### 3.4. Rate comparisons of metal scavenging

Sorbent-melting enhancement of metal capture as well as excessive-melt sorbent deactivation was observed both by kinetic measurements and by SEM analysis of sorbent/metal product particles. The global model presented above describes both of these observed sorbent melting effects on metal capture. The Arrhenius form was used to describe the temperature dependence of the rate constants for both Eqs. (4) and (5). Kinetic parameters that fit the data are shown in Table 2 [7,11,14]. Eqs. (4)–(6) along with the constants in Table 2 were used to create the rate comparisons in Fig. 6 for the reaction of Pb, Na, and Cd with kaolinite at 25%, 50%, and 75% sorbent utilization. Each point along each curve represents the rate of metal capture on kaolinite at a constant temperature, with 50 ppmv of metal (based on PbO, CdO, or Na_2O) in the furnace, \(\phi = 1\), and at the sorbent utilization of the given curve. The 50% and 75% sorbent-utilization curves for lead and sodium in Fig. 6 end abruptly, because the sorbent utilizations of the respective curves were not achievable at higher temperatures due to sorbent deactivation.

### Table 2

Kinetic parameters for reaction of metals with kaolinite and hydrated lime – \(k_i = A_i \exp\left(-E_i/RT\right)\)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Sorbent</th>
<th>(A_i) (cc/mol s)</th>
<th>(E_i) (J/mol)</th>
<th>(A_D) (cc/mol s)</th>
<th>(E_D) (J/mol)</th>
<th>(\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>Kaolinite</td>
<td>3.720e9</td>
<td>0.0</td>
<td>7.930e13</td>
<td>1.1e5</td>
<td>0.9</td>
</tr>
<tr>
<td>Lead</td>
<td>Kaolinite</td>
<td>2.949e9</td>
<td>0.0</td>
<td>7.930e13</td>
<td>1.1e5</td>
<td>1.0</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Kaolinite</td>
<td>3.114e26</td>
<td>4.8e5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Hydrated lime</td>
<td>1.360e31</td>
<td>6.0e5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
As shown (see Fig. 6), the reaction rate of lead with kaolinite is similar to that of sodium with kaolinite, especially at lower sorbent utilization, before significant sorbent deactivation potential has been generated. Sodium does have a slightly higher reaction rate with kaolinite than does lead, even before sorbent deactivation is significant. It is this slightly higher reaction rate, along with a smaller and more diffusive reactant molecule, NaOH ($\alpha_{Na} = 0.9$), that creates the larger gap in the global reaction rate between sodium and lead, for the higher sorbent utilization curves.

The slightly higher intrinsic rate of sodium reaction with kaolinite allows the sodium capture to stay just ahead of sorbent deactivation, resulting in significantly more capture of Na than Pb, at temperatures where sorbent deactivation is significant. The melting and deactivation rates of the meta-kaolinite particles in the furnace are essentially the same for the Pb/kaolinite and Na/kaolinite systems [11]. However, more sodium than lead is captured by the time the deactivation occurs. This advantage for sodium is quite dramatic for bimetal systems reacting with kaolinite [5], where the presence of sodium has been shown to dramatically inhibit the capture of lead by kaolinite, through enhancing the rate of sorbent deactivation, while the presence of lead had little effect on the capture of sodium [5].

As shown in Fig. 6, the rate of cadmium capture by kaolinite increases dramatically through the temperature range investigated. At temperatures from 1000 to 1100 °C, the reaction rate of cadmium with kaolinite is much less than that of sodium or lead with kaolinite. Eutectic temperatures for the Pb/kaolinite and Na/kaolinite systems are such that significant sorbent-particle melting occurs at very low sorbent utilization, even for the lowest temperatures investigated in this work [11]. Hence, the reaction rates for lead and sodium are high at the low-temperature condition, because of eutectic-melt enhancement, and the melt-induced enhancement has passed its maximum with respect to temperature, even for the low temperature condition.

As illustrated in Fig. 7, Na and Pb were much less effectively captured by hydrated lime than was cadmium at the same 1160 °C sorbent injection condition. Cadmium forms a much higher temperature eutectic than does lead or sodium. In fact at 1160 °C, the eutectics formed by lead and sodium with kaolinite initiated excessive partially deactivating melts [11], while cadmium did not even initiate a melt sufficient to induce enhancement (see Fig. 5). However, cadmium did initiate melting and very significant capture-enhancement at 1280 °C (see Fig. 6). Cadmium eutectics may initiate excessive-melt sorbent deactivation at still higher temperatures than examined in this work (i.e., >1300 °C).

4. Conclusions

Cadmium was found to be effectively captured by both kaolinite and hydrated lime. However, for both sorbents, the high temperature condition (1280 °C) produced a much greater capture, due to a eutectic melt initiated by the cadmium/sorbent products, than the low-temperature condition (1160 °C), where no melting was observed. At the high-temperature condition, significant sorbent utilization was obtained, for both sorbents. The capture of cadmium both by hydrated lime and by kaolinite was shown to be through chemical reaction.

A global rate model was developed to describe the increase in cadmium capture rate across the temperature range of self-enhancing eutectic melting. It was shown that cadmium forms higher-temperature eutectics with kaolinite and hydrated lime than other semi-volatile metals, such as Na and Pb, thus avoiding the excessive-melt rate
capture was not limited by intra-particle diffusion un-

in referenced work [5,7,11,15 in paper] that the metal

scribe metal capture under conditions relevant to full-

mass transfer limitation?

Centre, Finland.

Does the C-capture model consider

data interpretation and model development.

measurements, by laser, or otherwise, would greatly aid in
ture by high-temperature sorbents. Clearly, precise in situ
tiques. Rather, it was about the mechanisms of metal cap-
paper and presentation were not about measurement tech-

be expanded to other (semi) volatile metals.

While we truly appreciate this suggestion, the
paper and presentation were not about measurement tech-
iques. Rather, it was about the mechanisms of metal cap-
ture by high-temperature sorbents. Kaolinite for example, upon injection into
the furnace flash calcines to form metakaolinite, which
is composed of mono-crystal layer thin platelets sepa-
rated by very accessible meso-pore gaps, through which
metals can pass and react with the sorbent without
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is composed of mono-crystal layer thin platelets sepa-
rated by very accessible meso-pore gaps, through which
metals can pass and react with the sorbent without

metals.

der these conditions, prior to sorbent-melt deactivation.
This is consistent with the nature of these powdered sorbents. Kaolinite for example, upon injection into the furnace flash calcines to form metakaolinite, which is composed of mono-crystal layer thin platelets separated by very accessible meso-pore gaps, through which metals can pass and react with the sorbent without mass transfer limitations. There may be mass transfer issues related to diffusion of the metal through molten layers on surfaces, but these have been lumped into the global kinetic model presented.

Christian Mueller, Åbo Akademi Process Chemistry Centre, Finland. Does the C-capture model consider mass transfer limitation?

Reply. The global rate model developed for cadmium capture by powder sorbents was derived to de-
scribe metal capture under conditions relevant to full-
scale industrial boilers and incinerators. It was shown in referenced work [5,7,11,15 in paper] that the metal capture was not limited by intra-particle diffusion un-

der these conditions, prior to sorbent-melt deactivation.

Keith Schofield, University of California, Santa Bar-
bara, USA. What is your opinion of the sorbent mecha-
nisms? For cadmium and lime one has to surmise that it
must be a mutual solution rather than a chemical inter-
action and so will need temperatures such that molten
states exist.

Reply. As discussed in the paper and presentation, the cadmium capture rate was greatly increased at temperatures (i.e., ~1300°C) where the cadmium/lime prod-

Christian Mueller, Åbo Akademi Process Chemistry Centre, Finland. Does the C-capture model consider mass transfer limitation?

Reply. The global rate model developed for cadmium capture by powder sorbents was derived to de-
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scale industrial boilers and incinerators. It was shown in referenced work [5,7,11,15 in paper] that the metal capture was not limited by intra-particle diffusion un-
some initial amount of reactive CdO capture by the injected hydrated lime particles. A mutual solution of cadmium and lime is a plausible suggestion for the reacted products. However, this does not explain the initial steps in the capture process, which was not that of simple condensation.