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Estimation of Collection Efficiency Change of Moving Granular Bed Filter by Dust Load

Keywords: Moving Granular Bed, Hot Gas Cleaning, Dust Load, Single Body Collection Efficiency

Introduction

Dust in exhaust gas from an electric arc furnace (EAF) for the steel production, which is generated ca. 0.5 million ton/year in Japan (1999), contains a large amount of metallic components such as Fe, FeO and ZnO[1,2]. The EAF dust, therefore, can be regarded as a metallic resource so that it has been collected and re-heated to separate Zn[2]. About 60% of dust has been re-melted under the deduction atmosphere for Zn recovery while remaining 30% was landfilled[2]. Problems with conventional EAF dust treatments are 1) high cost and energy consumption, 2) heavy environmental loads, e.g., leaching of heavy metal, emission of dioxins and depletion of disposal site[1]. In order to solve such problems, the process has to be simplified by directly recovering Zn from the high temperature EAF exhaust gas.

A new process for the material recovery from EAF dust and energy saving has been developed by the Japan Research and Development Center for Metals (JRCM) group and the performance of this process has been so far tested on a pilot scale plant [2-5]. As a metal classifier in this process, a coke bed filter has been developed. **Figure 1** depicts the concept of a coke bed filter: it consists of a bed of coke granules flowing opposite to the gas flow through a cylindrical tubular chamber[2]. While

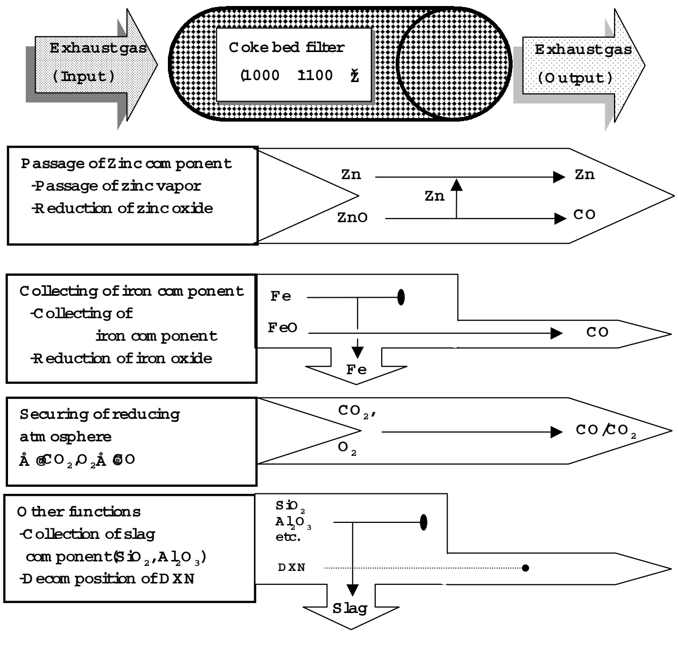

Fig.1 Concept of a coke bed filter

the exhaust gas from EAF passes through the coke bed filter operated around 1000°C, dust and fumes are collected on coke granules. **Figure 2** shows a equilibrium phase diagram of Zn-Fe-C-O components, which exist in the coke bed, in relation to temperature and pressure ratio of CO_2 and CO[5)]. When the exhaust gas passing through the coke bed under the condition of 1100 °C and P_{CO_2}/P_{CO} = 20/80, a typical operating condition of the filter, solid FeO dusts and condensed Fe vapor are collected on coke particles while ZnO is reduced to Zn vapor, which passes through the coke bed then collected in a metal condenser. Slug fragments such as SiO_2 and Al_2O_3 are also colleted on coke granules. Some amount of dioxins may be decomposed. Reduced atmosphere in the coke bed filter is kept by CO in the exhaust gas and the oxidation of coke granules. JRCM calls this filtration process as "direct recovery process of valuable metals from EAF dust." The coke bed filter can be called as a material classifier. Similar ideas have been proposed but no practical process has not been established[6)].

Since the dust concentration of EAF exhaust gas is extremely high (60-100g/Nm^3) at the filter inlet, void spaces in coke bed are filled with dust so that the cake filtration may dominate the filtration mechanism in this region. A large portion of incoming dust is collected by the cake filtration while remaining dust penetrates downstream the bed by EAF gas flow to the filter outlet. Concentration of the penetrating dust, mostly from collapsed cake, may be low enough to be collected by the depth filtration, i.e., dust is collected on coke surface but there still exists a large portion of dust free voids. The filtration of penetrating dust is essentially important to increase the purity of recovered Zn at the vapor condenser and also to remove trace elements and hazardous components such as dioxin. It is probably reasonable to regard so that the coke bed consists of three different zones: 1) cake filtration zone near the filter inlet, 2) depth filtration zone downstream the filter, and 3) intermediate zone between cake and depth filtration zones where dust cake collapse due to bed motion. It is important to understand such characteristics of the coke bed filter to discuss the filtration performance, chemical reactions such as reduction of ZnO as well.

There have been some investigations on the theoretical description of the collection performance of a fixed granular bed filter but most of discussion has been focused on the initial period of filtration or on low dust concentration conditions[7,8)]. For higher dust loading conditions, some theoretical descriptions on the dust collection mechanism have been proposed[9-12)]. As to the depth filtration by a fibrous air filter, there have been some models

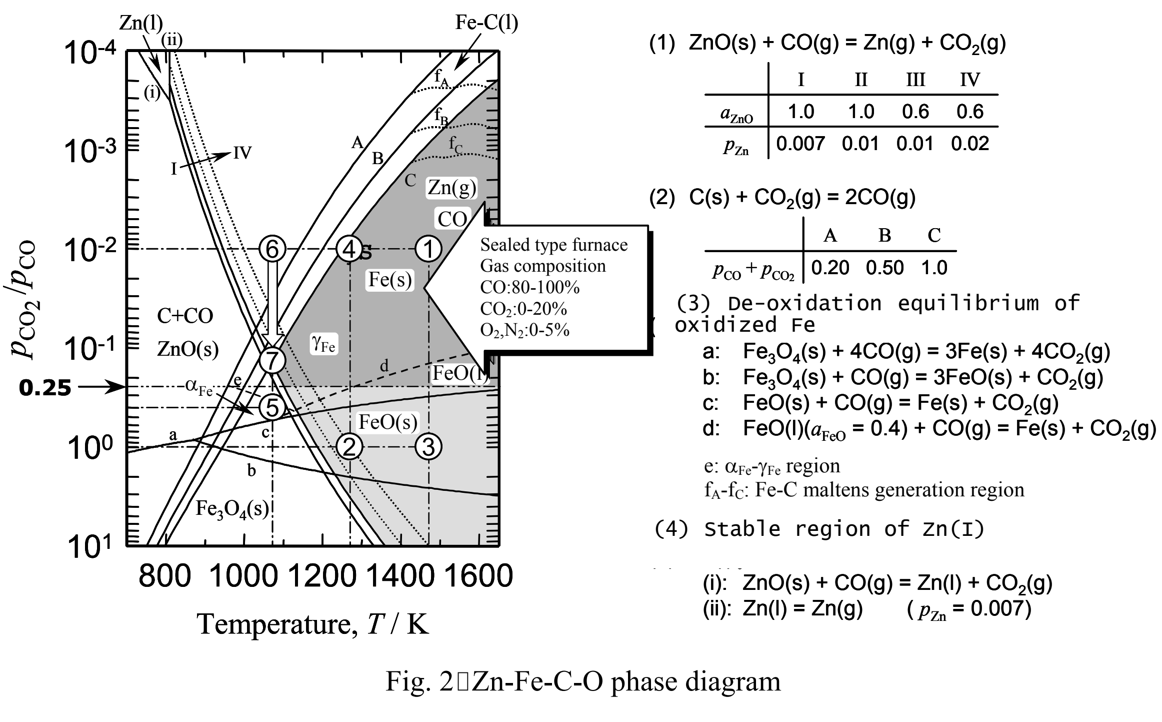

Fig. 2 Zn-Fe-C-O phase diagram

and results from numerical simulations on an influnce of dust load on the collection performance[13]. When applying the equations for the fibrous filter to a granular bed, followings should be taken into account: 1) geometry difference in a collecting body, 2) higher volume fraction of collecting medium, which leads to a significant influence of interaction between dust loaded coke granules, 3) re-suspension due to moving bed. It may be, therefore, hard to directly apply equations for fibrous air filter to the coke bed filtration.

Objective

Final goal of this study is to theoretically describe effects of influencing factors on the performance of the coke bed filter as a material classifier and to predict its optimal operating condition. In this paper, the author focuses on the basic investigation on collection mechanism of a fixed coke bed filter on the basis of the depth filtration theory, in which an influence of dust load on the dust collection efficiency.

Approach

The coke bed filter was modeled to discuss influences of filtration condition such as granular size, volume fraction of coke granules and dust load on the dust collection efficiency, limiting the discussion on the dust collection mechanism in an area where the mechanism can be described by the depth filtration. An increase in the collection efficiency due to the dust load was assumed to be proportional to dust load per unit filter volume. Results were compared with those from cold tests conducted independently by a research group in JRCM project in order to discuss the adoptability of the present model.

Project Description

1. Equations describing dust load distribution inside the coke bed filter

1.1 Assumptions

In order to theoretically discuss the collection mechanism of the coke bed filter, followings were assumed: 1) the coke bed is fixed, 2) the coke bed consists of uniform and smooth spherical coke granules, 3) an uniform packing structure, 4) dust are collected inside the coke bed, i.e., the depth filtration, 4) no change in the geometry of granule due to chemical reactions or abrasion, 5) no bouncing and re-entrainment of collected dust and 6) no dust collection into micro pores in granule.

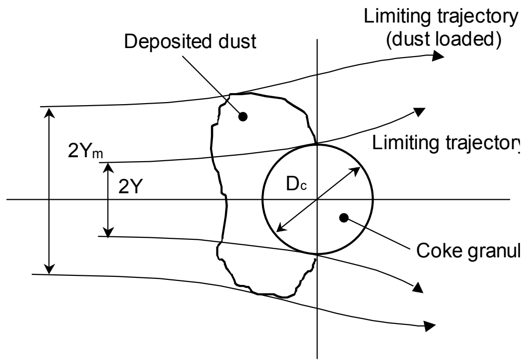

Fig.3 Limiting trajectory of particle

1.2 Mass balance of dust inside the coke bed

According to the above assumptions and following the same manner with the depth filtration theory for fibrous filter[14], the dust concentration distribution inside the coke bed can be expressed as follows:

$$\frac{\partial C}{\partial x} = -\frac{\alpha_0}{1-\alpha_0}\cdot\frac{3}{2}\cdot\frac{1}{D_c}\cdot\eta_0\cdot C \qquad (1)$$

where C is the dust concentration, D_c the coke granule diameter, α_0 the volume fraction of coke granules and η_0 the single coke granule collection efficiency. Using a radius Y of the limiting trajectory of particle moving toward a single coke granule, η_0 is defined as eq.(2)(See **Fig.3**):

$$\frac{\pi Y^2}{\pi \left(\frac{D_c}{2} \right)^2} = \frac{4Y^2}{D_c^{\ 2}} = \eta_0 \qquad (2)$$

From the mass balance through the bed, one obtains a following equation:

$$\frac{\partial C}{\partial x} = -\frac{1}{v}\frac{\partial m}{\partial t} \qquad (3)$$

where v is the superficial velocity, m the mass of dust load per unit filter volume.

1.3 Single granule collection efficiency as a function of dust load and dust load distribution

The collection efficiency of a coke granule may increase with dust load because of an increase in apparent cross section for particle collection, that is, an increase in radius of limiting trajectory from Y to Y_m (See Fig.3). As the first approximation, the collection efficiency η_m of a single coke granule with dust load is here assumed as following equation:

$$\eta_m = (1 + \lambda m)\eta_0 \qquad (4)$$

where m is the mass of dust load per unit filter volume and λ the collection efficiency increasing factor, which is a function of filtration conditions such as filtration velocity, particle size, that is, Peclet number, Stokes number and interception parameter[13].

Taking into account an increase in interstitial velocity due to the dust load, one obtains

$$\frac{\partial C}{\partial x} = -\frac{\alpha_0}{1-\alpha_m}\cdot\frac{3}{2}\cdot\frac{1}{D_c}\cdot\eta_m\cdot C \qquad (6)$$

When $\alpha_0 = \alpha_m$, eqs.(3), (4) and (6) can be analytically solved and m is obtained as a function of elapsed time t from the initiation of filtration and depth from bed inlet x:

$$m = -\frac{1}{\lambda}\frac{\exp(-\lambda A C_i v t) - 1}{\exp(-\lambda A C_i v t) + \exp(Ax) - 1} \qquad (7)$$

where $$A = \frac{3\alpha_0 \eta_0}{2D_c(1-\alpha_0)} \qquad (8)$$

and C_i denotes the inlet dust concentration. An overall collection efficiency E for the filter of depth L can be, therefore, written as a function of elapsed time t:

$$E = 1 - \frac{\exp(-\lambda A C_i u t)}{\exp(-\lambda A C_i u t) + \exp(-AL)} \qquad (9)$$

Since generally $\alpha_0 \neq \alpha_m$, eq.(6) has to be solved numerically.

1.4 Pressure drop through dust loaded filter

Pressure drop may be evaluated from the dust load distribution described by eq.(7) as being similar to fibrous filters. By assuming the dust cake of particle volume fraction α_{cm} is uniformly formed on a coke granule, the pressure drop through the coke bed filter with filter depth L can be described by the Ergun's equation[12], that is,

$$\Delta P = \int_0^L \left[150\frac{\alpha_0^{\ 2}}{(1-\alpha_m)^3}\frac{\mu}{D_p^{\ 2}}u + 1.75\frac{\alpha_0}{(1-\alpha_m)^3}\frac{\rho}{D_p}u^2 \right] dL \qquad (10)$$

where

$$\alpha_m = \alpha_0 + \frac{m}{\alpha_{cm}\rho_p} \qquad (11)$$

$\alpha_{cm}\rho_p$ denotes the apparent density of deposited dust and μ the air viscosity. If α_{cm} is known, the dust load distribution can be calculated from eqs.(7),(10) and (11) as described later.

2. Experiments

Figure 4 shows an experimental setup for the cold test[5] using a model filter. The test rig consists of a stuck of annular elements filled with coke granules, which can be disassembled into each element. The dust load distributions can be measured by weighing amounts of dust in each element after a test run. At each element, the static pressure was measured using a pressure transducer to monitor an increase in dust load during filtration. Properties of coke granules are listed in **Table 1**. As test dusts, glass beads and Aerosil particles were used to discuss the influence of particle size. Since the size of typical EAF dust ranged from 0.1 to 10 μm and had mean value about 2.7 μm[2,5], the test particles could cover this range. Dust-laden air for test run was supplied from the bottom of the coke bed filter. Experimental conditions and properties of test particles are also listed in Table 1. See detail in the JRCM report[5].

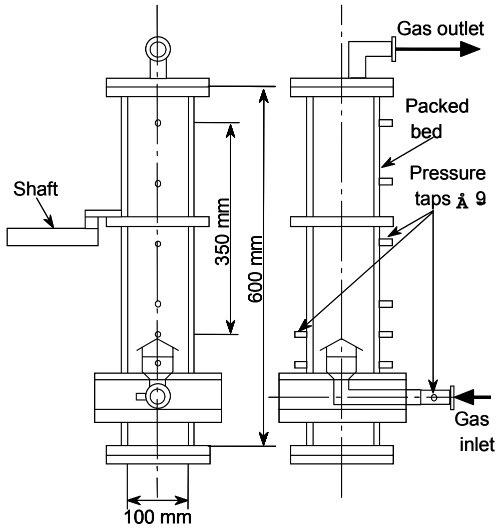

Fig.4 Test rig for the cold test

Table 1 Experimental conditions and properties of test particles

	Experiment 1	Experiment 2
Test dust	Glass beads	Aerosil particles
50 % mean diameter of test dust (μm)	44.0	0.03
dust concentration (g/m^3)	280.0	0.733
50% mean diameter of coke granules (mm)	2.9	9.1
mean coke granule volume fraction (-)	0.56	0.49
filtration velocity (m/s)	0.65	

3. Results and Discussion

Figure 5 shows the time change of pressure drop measured at four different heights after starting the test run. The pressure drop rapidly increased at the earlier period while it becomes constant after some period of filtration at every position. Pressure drop increased almost linearly with the distance from the bed inlet. Glass beads may be large enough to bounce when they collide the coke granules. Hence, the bouncing effect may significantly influence the dust load distribution. The time change of pressure drop when the Aerosil particles were dispersed is depicted in **Fig.6**. Since the Aerosil particles are agglomerates of primary particles with size ca. 30nm, the bouncing may be not likely to take place. This results in a continuous increase in the pressure drop with the filtration period though the pressure increment seems to gradually decrease.

As previously described, the pressure distribution can be transformed into the dust load distribution using eqs.(10) and (11). The particle volume fraction of dust cake α_{cm} was experimentally determined so as to describe experimental hold-ups measured after the test run. Since the present model does not take into account the bouncing or re-entrainment effect leading to an uniform dust load distribution at the final period of test run, in the following, the discussion on the dust load distribution is limited for the earlier period of filtration, during which the pressure drop increases with time and there still exists a pressure distribution inside the coke bed.

For the case when the glass beads dispersed air was supplied, dust load distributions inside the coke bed filter, which are evaluated from the pressure distribution, are plotted in **Fig.7** with the elapsed time as a parameter. The initial single coke granule collection efficiency η_0 was determined from a change in pressure drop at the initial period of filtration. Experimental η_0 is much lower than that from a theoretical prediction (almost unity) by Otani et al.[7] This may be an evidence of bouncing. As the distance from the filter inlet increases, the dust load mass m per unit filter volume exponentially decreases except the data at the final stage of coke bed. Curves in Fig.7 denotes results calculated from eqs.(7), (10) and (11) using experimental η_0, where the collection efficiency increasing factor λ was determined so

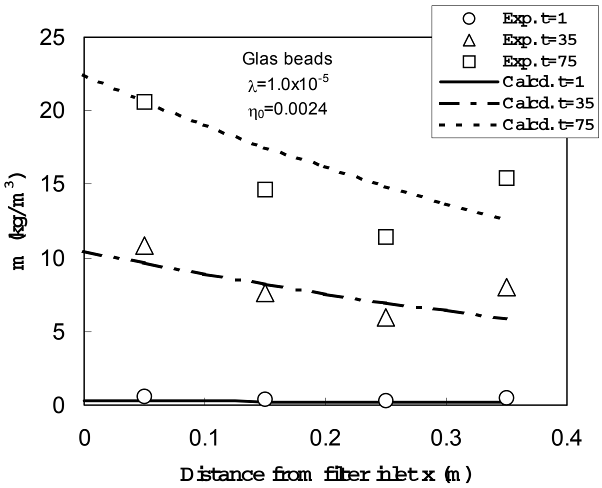

Fig.7 Dust load distribution evaluated from experimental pressure drop for glass beads compared with calculated results

...d that the earlier period of filtration process of ...ed by the depth filtration model with a fitted ...ge seems to deviate. At the final stage of coke ...e accumulated. The fact the fitted value of λ is ...articles was negligible because of the particle

...istributions for the Aerosil particles. The value ...o that captured particles may growth on coke ...fficiency. However, further filtration made dust ...annot be explained by the calculation with a ...he bouncing of Aerosil agglomerates may not ...m grown structures of captured agglomerates ...n order to confirm this, an in-situ measurement of dust concentration is needed. And the present model should take into account the influence of re-suspension, which may be important in the actual coke bed filter in the depth filtration region.

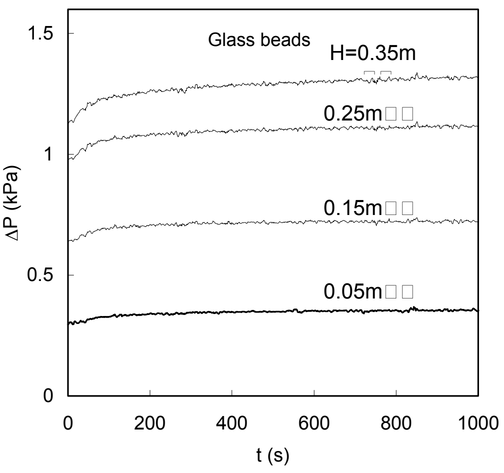

Fig.5 Time change of pressure drops measured in four different positions in the coke bed (glass beads)

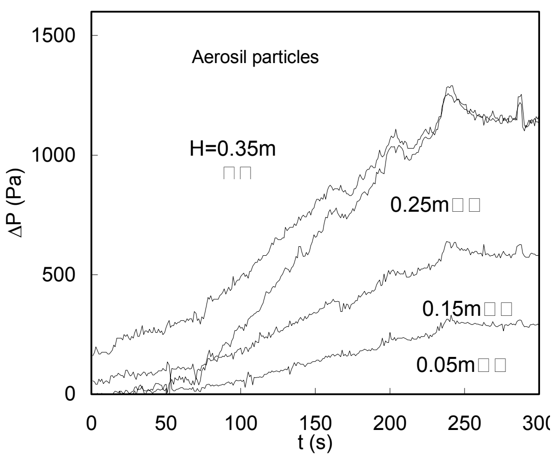

Fig.6 Time change of pressure drops measured in four different positions in the coke bed (Aerosil particles)

4. Conclusions

1) It is reasonable to adopt the depth filtration model to the coke bed filtration under when the conditions under which influencing factors such as the collection efficiency increasing factor can be regarded as constant.
2) Dust load distribution in side the coke bed can be evaluated from the pressure distribution by using the present model and Ergun's equation.
3) Bouncing and re-suspension effects should be taken into account to describe the collection mechanism in the depth filtration region.

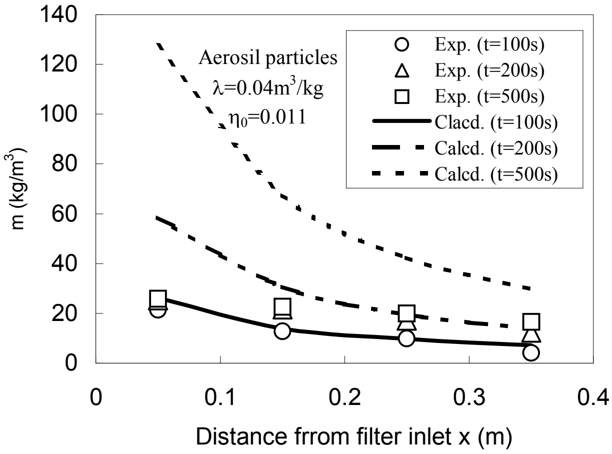

Fig.8 Dust load distribution evaluated from pressure drop for Aerosil particles compared with calculated results

Application

The coke bed filter itself can be used as a material classifier as well as the separator of Zn vapor in the JRCM process. Although the present model is just the first step to describe the filtration mechanism and performance of such material classifier, it can be used to predict the filtration performance of a granular bed filter under the conditions of increase in the collection efficiency caused by dust load.

Future Activities

In order to describe the filtration mechanism and chemical reactions in the actual coke bed filer, followings will be investigated:

1) Account for predominant filtration mechanisms for each part of the coke bed filter

At the filter inlet, because of the dust high concentration (~100 g/m^3), dust removed by a cake on the bed surface while in the downstream, the depth filtration is the predominant mechanism for dust collection. For the moving bed filtration, a dust re-entrainment due to dust cake corruption may be an important mechanism, which has to be considered in order to evaluate an amount of "dust feed" to the depth filtration region. Difference in mechanism will be taken into account in a future modeling.

2) Dust collecting mechanism for dust loaded coke granules in the depth filtration region

Following factors will be taken into account in the model: a) bouncing and re-entrainment of particles at coke granule surface, b) interaction between dust deposition on granules, c) size and shape distributions of coke granules

3) Chemical reactions

Chemical reactions such as CO or CO_2 generation from coke granules by de-oxidation of FeO and ZnO may lead to a size reduction of granules and a change in CO and CO_2 distributions inside the coke bed filter. An amount and geometry of dust deposition may also affect the reaction rate because dust deposition covers the reactive coke surface. Interaction between the dust collection and chemical reaction will be investigated.

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