Research Article

Material Cost and Benefit Analysis for Dust Injection Technology in EAF Steelmaking Process and EAF Dust Treatment with CaO Addition

Shunsuke Koide,1,2 Akira Tsubone,3 Shusei Kubota,2 Kazuyoshi Yamaguchi,2 and Tetsuya Nagasaka4

1Hoei Metal Co., Ltd., Toyota 4730932, Japan
2Department of Metallurgy, Graduate School of Engineering, Tohoku University, Sendai 9808579, Japan
3Aichi Steel Corporation, Tokai 4768666, Japan
4Department of Metallurgy, Graduate School of Engineering, New Industry Creation Hatchery Center, Tohoku University, Sendai 9808579, Japan

Correspondence should be addressed to Shunsuke Koide; s.koide@hoei-shokai.co.jp

Received 29 September 2022; Revised 19 July 2023; Accepted 9 August 2023; Published 22 August 2023

Academic Editor: Antonio Riveiro

Copyright © 2023 Shunsuke Koide et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In the electric arc furnace (EAF) steelmaking process, electric arc furnace dust (EAFD) is inevitably generated. The dust injection method is known as one of the effective technologies to reduce the total amount of EAFD generation. In this technology, Zn in the injected dust is enriched in the secondary dust, and Fe is transferred to the slag. In this work, the effect of dust injection technology on the recovered/lost amounts of Zn and Fe is quantitatively evaluated based on the mass balance calculation. Furthermore, in terms of dust and slag treatment costs, the potential of new EAFD treatment technology (the lime addition method) which enables simultaneous Zn and Fe recovery is discussed. By introducing the lime addition method, Zn and Fe can be recovered as resources, and the total income from these sales outweighs the cost of the chemicals used for recovery. This indicates that the treatment costs paid by EAF companies can be significantly low. The dust injection technology reduces the total quantity of dust shipped, but increases the total amount of slag and Fe loss. Therefore, it is necessary to determine the appropriate value of the amount of dust injection by balancing the waste treatment cost and the amount of metal resource recovery.

1. Introduction

The electric arc furnace (EAF) is widely used in steelmaking all over the world as a conventional technology for the melting of iron/steel scrap. In 2019, the EAF produced 64.93 million tons of the 157.08 million tons of crude steel produced in the EU (41.3%), 61.17 million tons of the 87.76 million tons produced in the United States (69.7%), 24.30 million tons of the 99.28 million tons produced in Japan (24.5%), and 22.7 million tons of the 71.41 million tons produced in South Korea (31.8%) [1]. Globally, EAF steel accounts for 523.14 million tons of the 1,875.16 million tons of crude steel produced (27.9%). Even in China, where steel is being accumulated in society, the share of EAF steel is estimated to be 103.2 million tons (10.4%) of the total crude steel production, at 996.34 million tons. Due to the recent trend toward carbon neutrality, crude steel production is expected to shift from blast furnaces to electric arc furnaces with lower CO₂ emissions, and the amount of production by electric arc furnaces is expected to increase.

In the steelmaking process using EAF, fine particle substances called electric arc furnace dust (EAFD) are inevitably generated. The amount of EAFD generated per ton of crude steel production varies widely from 5 to 25 kg dust/ton-steel depending on the scrap grade and the operation techniques of EAF. According to Liebman’s reports [2, 3],
the average dust generation rate in the US is estimated to be about 17 kg dust/ton-steel. In Japan, the average dust generation rate has been reported to be in the range of 15 to 17 kg dust/ton-steel [4, 5]. While there are no accurate statistics on total EAFD generation in the world, by multiplying the above-mentioned total EAF steel production figures for 2019 with an approximated average dust generation rate of 17 kg dust/ton-steel, it would be 8.89 million tons for that year. The generation of EAFD is increasing, especially in developed countries. Therefore, EAF steelmakers are facing the challenge of treating this large amount of dust. It is necessary to take the cost, the environment, and resource conservation into consideration.

EAFD is generated in the arc melting process of iron/steel scrap. The generated EAFD always contains Fe from iron/steel sources charged in EAF and Zn from the surface coated layer of galvanized steel scrap together with other volatile components such as Pb, Cd, Mn, Cl, F, and Cr. The amount and chemical composition of EAFD vary depending on the scrap properties charged into the EAF. Since scrap is a kind of waste product, it is no exaggeration to say that dust contains all kinds of elements, even in trace amounts. Some of these elements include toxic heavy metals such as Pb, Cd, and Cr. Therefore, the US Environmental Protection Agency (EPA) [6] and the Landfill Directive of the EU [7] classify electric furnace dust as hazardous waste. This situation is no exception in Japan [8], where EAFD is designated as a specially controlled industrial waste.

On the other hand, EAFD also acts as the sole carrier of the recycling route for Zn from used products [9, 10]. That is, the EAF plays a decisive role not only in steel but also in Zn circulation. Despite this, EAF steelmakers are often forced to outsource dust treatment, which is troublesome. The dust treatment residue (clinker) after a pyrometallurgical zinc recovery by the Waelder process, etc., contains a large amount of Fe, and assuming that the average Fe concentration in the dust is 30 mass%, the total amount is expected to be 2.67 million tons worldwide. However, no cases have been reported in which clinker has been reused as an iron resource.

As a measure against these dust problems, some EAF companies have adopted the ECOARC and Consteel processes [11–15], where the scrap packed bed is equipped with the EAF and charged scrap is preheated by the exhaust gas from the EAF. By applying these processes, it is possible to reduce the amount of dust generated, increase the Zn concentration, and decrease the Fe concentration in the dust. In both processes, dust generated in the EAF adheres to the scrap as it passes through the scrap-packed bed and returns to the inside of the EAF again. That is, since the scrap-packed bed acts as a kind of filter, the amount of dust generated is reduced. However, due to their high volatilities, Zn, Pb, Cd, and halogens are eventually discharged outside of the furnace, resulting in an increase in their concentration in the dust. On the other hand, since most of the Fe adhering to the scrap transfers to the slag phase, the Fe concentration in the dust decreases while the Fe loss to the slag increases. By passing high-temperature off-gas from EAF through the scrap-packed bed when preheating scrap, the ECOARC and Consteel processes contribute to the energy savings of the EAF operation.

Another measure to control the amount of dust generated is the dust injection technology for EAF reported by Drissen et al. [16, 17] and Tsubone et al. [18]. As described later, when dust is injected into a high-temperature EAF, the Zn in the injected dust revolatilizes and the Zn concentration of the generated dust increases. However, since halogens also volatilize again, their concentrations also increase, which makes dust treatment more difficult. Since Fe and other minerals in the injected dust transfer to the slag phase, the slag volume increases, but the total amount of dust shipped decreases. If the cost of slag treatment is lower than the cost of dust treatment, the cost of total waste treatment can be reduced.

Because dust injection technology can be basically applied to existing EAF facilities without major equipment modification, it is widely used to control the amount of dust shipped and to enrich Zn. However, since this technology also results in Fe loss and enriches the halogens and Pb in the dust, its use should be considered from the perspective of resource recovery and processing costs. In particular, since the Fe in dust cannot be recovered at present, the understanding of the cost benefit would likely change if new dust treatment technology to recover Fe was available.

Most of the previous investigations on scrap preheating technology discuss the reduction of EAF operating energy, and there is no research on energy analysis in EAFD treatment. In the dust injection technology, no research has been carried out on the treatment of the shipped dust and slag. Some research has been done aiming to reduce the amount of EAFD shipped, while few discussions have been made on the treatment of dust and slag shipped by these operations and its treatment costs and benefits. In fact, no information is available on the advantages or disadvantages of these operations when considering the treatment of by-products.

In this paper, we first analyze the general characteristics of dust composition reported in previous studies on EAFD. Then, the EAFD, slag generation rate, and Zn and Fe losses are quantitatively determined by analysis of EAF operation data and the simple mass balance calculation. Furthermore, the effect of the dust injection technology on the rate of dust and slag shipment and the loss/recovery amount of Zn and Fe is also quantitatively determined. Finally, the potential of new dust treatment technology developed by the authors [19–21] is discussed in terms of the cost of dust and slag treatment by accounting for the outgoing/incoming costs of each process.

### 2. Overview of General Feature of EAFD Generation

Each composition of EAFD and its concentration vary widely depending on the operating characteristics of the EAF and the properties of the charged scrap. In order to ensure the versatility of the results in this paper, we first examined the general tendency of the component concentration of EAFD. In particular, when trying to quantitatively...
examine the potential for metal resource recovery and the cost of waste treatment in EAF operations, reliable data on the quantity and composition of slag as well as those of dust are indispensable. Since the technology for treating EAFD is such an important challenge in the steel industry, the previous research works on EAFD treatment have been extensively reviewed by Nyirenda [22], Matsubae and Nagasaka [5], Jha et al. [23], Lin et al. [24], and Kaya et al. [25]. However, while the dust composition is shown, it is rare that the amounts of dust and slag generated together with their compositions are all clarified. However, in the study of Sasamoto et al. [4, 26, 27] and Tsubone et al. [18], the chemical nature of charged scrap as well as the amount and composition of dust and slag were systematically investigated and reported in detail, including the experiments in the 10-ton test EAF. Their results can be used to estimate important EAF operation parameters such as dust and slag generation rates and their composition. That is, this technique can be used to determine these data for dust and slag which are not reported in the literature.

In this study, we first analyzed the general trend of dust composition reported in previous works on EAFD. Figure 1 shows the relationship among the Fe, Pb, Cl, and F concentrations and the Zn concentration in EAFD reported in previous works [4, 18, 22–63], including the results of our own field work. According to Figure 1, the concentrations of F, Cl, and Pb tend to be proportional to that of Zn in EAFD, and it is considered that almost all of them transfer from the scrap to the dust during melting due to volatilization. The proportional relationship between Zn and F is not as clear as in the case of Cl and Pb, indicating that the decision to add or not to add fluorite, etc., to the EAF slag for dephosphorization or desulfurization may affect the results. However, Zn and Fe contents in EAFD have a clear negative correlation, even though the properties and quantities of the charged scrap in EAF are likely to vary significantly. It is well known that Zn in EAFD exists as zinc ferrite (ZnO–Fe2O3) and ZnO, while their share in EAFD varies depending on EAF operating conditions and the properties of charged scrap [5, 22–25]. In spite of the total amount of generated EAFD, when the amount of Zn transferred into the dust is higher, the relative amount of Fe will be lower and vice versa, according to Figure 1(a).

The dust generation rate \( D^0 \) is plotted against the sum of the quantities of Zn and Fe in EAFD \( (D^0_{Zn+Fe}) \) in Figure 2. The data are from the practical 150 t EAF operation and the experimental results with 10 t test EAF reported by Sasamoto et al. [4, 26, 27] and Tsubone et al. [18]. In their campaign, the quality of charged scrap in EAF was approximately constant. As shown by the good linearity in Figure 2, Zn and Fe comprise approximately half of the dust. This is consistent with the many dust compositions found, which are indicated on the dotted line drawn as (mass%Zn) + (mass%Fe) = 50% in Figure 1(a).

The ratio of the generation of dust and slag generation in EAF is represented in Figures 3 and 4. The dust generation rate \( D^0 \) is plotted against the Fe distribution ratio between slag and dust. Although the data scatter is rather large, the
The relationship between the two can be approximated as a linear function. Though the precise physicochemical implication of this trend is unknown, this figure suggests that the dust generation rate can be estimated when the Fe distribution ratio (mass%Fe)_{slag}/(mass%Fe)_{dust} is known.

\[
D^0 = 27.5 \times \frac{(\text{mass}\% \text{Fe})_{\text{slag}}}{(\text{mass}\% \text{Fe})_{\text{dust}}}
\]  

(1)

Figure 2: Relationship between dust generation rate \( D^0 \) and the sum of the quantities of Zn and Fe in EAFD \( D^0_{\text{Zn+Fe}} \). Red keys correspond to the compositions of d1 to d5 listed in Table 1.

Figure 3: Variation of the dust generation rate \( D^0 \) with the Fe distribution ratio between slag and dust. Red keys correspond to the compositions of d1 to d5 listed in Table 1.

Figure 4 shows the variations of the slag generation rate \( S^0 \) with Fe concentration in slag. An inverse proportional relationship is observed between the two as approximated by the dotted line in the figure, and equation (2) for 10 t and 150 t EAF operations is given as follows:

\[
S^0 \times (\text{mass}\% \text{Fe})_{\text{slag}} = 2400.
\]  

(2)

In Figure 4, it is indicated that the amount of Fe in the slag per ton of steel, that is, the amount of Fe loss into the slag, may not depend on the capacity of the EAF and may be regarded as almost constant (24 kg-Fe/t-steel). However, when the dust injection technology is applied to conventional EAF operations, most of the Fe in the injected dust transfers to the slag phase. This explains the increase in the amount of Fe loss (the number 2400 in equation (2) becomes larger).

3. Materials and Methods

3.1. Dataset. Based on the trend of EAFD compositions shown in Figure 1, six compositions were selected as the analysis targets in this study by considering their Zn concentrations. The compositions of selected EAFDs are listed in Table 1. The dust shown in Table 1 was collected through a series of experiments in which the following parameters were measured: the amounts of dust and slag, the major chemical composition in the dust, and the Fe concentration in the slag. Among the EAFDs listed in Table 1, d1 to d5 were collected from the conventional EAF operation without dust injection, and d6 was obtained from ECOARC.
Table 1: Composition and dust generation rate \( D^0 \) of selected EAFD and corresponding Fe content and generation rate \( S^0 \) of slag [4, 18, 26, 27].

<table>
<thead>
<tr>
<th>No.</th>
<th>Fe (mass%)</th>
<th>Zn (mass%)</th>
<th>Cl (mass%)</th>
<th>Pb (mass%)</th>
<th>F (mass%)</th>
<th>Na (mass%)</th>
<th>K (mass%)</th>
<th>Rate (kg/t-steel)</th>
<th>( D^0 )</th>
<th>( D^0_{Zn+Fe} )</th>
<th>Composition</th>
<th>Rate ( S^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>d1</td>
<td>38.6</td>
<td>13.5</td>
<td>1.33</td>
<td>1.89</td>
<td>0.24</td>
<td>2.18</td>
<td>1.59</td>
<td>16.6</td>
<td>8.65</td>
<td></td>
<td></td>
<td>22.9</td>
</tr>
<tr>
<td>d2</td>
<td>29.7</td>
<td>19.8</td>
<td>3.01</td>
<td>0.95</td>
<td>0.59</td>
<td>3.12</td>
<td>1.64</td>
<td>15.4</td>
<td>7.62</td>
<td></td>
<td></td>
<td>19.0</td>
</tr>
<tr>
<td>d3</td>
<td>28.2</td>
<td>20.2</td>
<td>5.31</td>
<td>0.92</td>
<td>0.60</td>
<td>3.30</td>
<td>0.85</td>
<td>18.3</td>
<td>8.86</td>
<td></td>
<td></td>
<td>22.5</td>
</tr>
<tr>
<td>d4</td>
<td>29.5</td>
<td>20.3</td>
<td>4.20</td>
<td>1.13</td>
<td>0.46</td>
<td>3.00</td>
<td>1.99</td>
<td>20.0</td>
<td>9.96</td>
<td></td>
<td></td>
<td>21.8</td>
</tr>
<tr>
<td>d5</td>
<td>23.8</td>
<td>28.4</td>
<td>4.12</td>
<td>1.00</td>
<td>0.53</td>
<td>2.97</td>
<td>0.65</td>
<td>19.2</td>
<td>10.02</td>
<td></td>
<td></td>
<td>16.7</td>
</tr>
<tr>
<td>d6</td>
<td>16.0</td>
<td>41.0</td>
<td>3.76</td>
<td>0.61</td>
<td>0.41</td>
<td>2.28</td>
<td>1.39</td>
<td>10.8</td>
<td>6.16</td>
<td></td>
<td></td>
<td>31.7</td>
</tr>
</tbody>
</table>

The EAFD and slag by-products discharged from EAF are transferred to a waste treatment company for a fee in many cases. Their treatment costs were calculated by multiplying each generation rate \( (D^0 \) and \( S^0 \)) by each of the treatment costs listed in Table 2. Each material cost was evaluated as an average value of the reported market price in Japan, and other process costs were obtained by our own field work. On the other hand, the disposal of slag as a road construction material, for instance, results in Fe loss. In addition, 99.76% of the Zn in scrap charged into EAF transfers to dust, while the others transfer to the molten steel and slag phases [18], resulting in resource loss as Zn, although their amounts are small. To convert these resource losses into costs, the estimated quantities of Zn and Fe transferred in slag were multiplied by the unit costs of ZnO and calcium ferrite listed in Table 2.

The Materials and Methods section should contain sufficient detail so that all procedures can be repeated. It may be divided into headed subsections if several methods are described.

3.2. Materials Flow through Dust Injection Technology. A major issue for EAF manufacturers is the reduction of energy intensity by improving productivity and steel output yield. At the same time, efforts are being made by EAF steelmaking companies to reduce the waste processing costs. Recently, new technologies have been implemented in an effort to reduce the quantity of EAFD, including injecting dust directly into an EAF through a lance or an oxygen burner [16–18]. While these methods effectively enrich the Zn in the dust, the other volatile components are also concentrated in the regenerated dust.

Tsubone et al. [18] quantitatively investigated changes in the amount and the composition of EAFD generated through dust injection technology (see Figure 5). The results of their mass balance analysis before and after dust injection for 5.5 kg/t-steel revealed that 31.2% of the injected dust transferred to secondary dust and 64.2% transferred to slag. The following empirical equations were proposed based on these results:

\[
D^0 = D^0 + \beta \cdot D^{\text{ini}}, \quad (3) \\
S^0 = S^0 + \gamma \cdot D^{\text{ini}}, \quad (4)
\]

Table 2: Cost of materials as recovered and used for treatment and treatment cost for EAFD and slag.

<table>
<thead>
<tr>
<th>Material or process</th>
<th>JPY (¥)/kg</th>
<th>EUR (€)/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic Zn</td>
<td>360</td>
<td>2.541</td>
</tr>
<tr>
<td>ZnO</td>
<td>63</td>
<td>0.445</td>
</tr>
<tr>
<td>Crude calcium ferrite</td>
<td>12.75</td>
<td>0.090</td>
</tr>
<tr>
<td>Ca(OH)₂</td>
<td>18.5</td>
<td>0.131</td>
</tr>
<tr>
<td>Coke</td>
<td>26</td>
<td>0.183</td>
</tr>
<tr>
<td>Metallic Fe</td>
<td>35</td>
<td>0.247</td>
</tr>
<tr>
<td>NaCO₃</td>
<td>24</td>
<td>0.169</td>
</tr>
<tr>
<td>H₂SO₄</td>
<td>40</td>
<td>0.282</td>
</tr>
<tr>
<td>Dust treatment</td>
<td>20</td>
<td>0.141</td>
</tr>
<tr>
<td>Slug treatment</td>
<td>7</td>
<td>0.049</td>
</tr>
</tbody>
</table>

1 € = 141.7 ¥ at 18 June, 2022. *2CaO–Fe₂O₃ containing Al₂O₃, MgO, SiO₂, etc., of approximately 30% in total.

where \( D^0 \) and \( D^{\text{ini}} \) denote dust generation rate in EAF operation with and without dust injection, and \( D^{\text{ini}} \) is dust injection rate in (kg/t-steel), respectively. \( D^0 \) was 16.3 kg/t-steel on average at their campaign. \( S^0 \) and \( S^{\text{ini}} \) are the slag yields with and without dust injection. \( \beta \) and \( \gamma \) are the recollected ratios into the secondary dust of injected dust (\( \beta = 0.312 \)) and recollected ratio into the slag of injected dust (\( \gamma = 0.642 \)), respectively. The net dust shipment rate \( D \) and the net slag shipment rate \( S \) are expressed as follows:

\[
D = \frac{D^0 - D^{\text{ini}} + D^0}{2} = \frac{D^0 - (1 - \beta \cdot D^{\text{ini}})}{2},
\]

\[
S = \frac{S^0 + S^{\text{ini}}}{2} = \frac{S^0 + \gamma \cdot D^{\text{ini}}}{2}.
\]

According to the mass balance, the concentrations of Zn, Fe, Cl, and F in secondary dust are given by the following equation:

\[
\%M^0 = \frac{\%M^0 \cdot D^0 + \alpha_M \cdot \%M^{\text{ini}} \cdot D^{\text{ini}}}{D^0 \cdot \beta \cdot D^{\text{ini}}}.
\]
Based on the results reported by Tsubone et al., the effects of dust injection rate on the materials and cost balances in EAF operation including dust treatment process are evaluated in this study. The set of two EAF operations schematically shown in Figure 5 was taken into consideration. EAF-1 is a conventional process without dust injection, and EAF-2 is a process with dust injection. A part of the exhausted dust from EAF-1 is injected into EAF-2 during its operation. Based on this hypothetical case, average values of the generation and composition of slag and dust were calculated. The effect of dust injection technology on the materials and the cost balance were extensively evaluated.

By applying equations (3), (4), and (6), variations of the secondary dust generation rate ($D_{n}$), the quantity of slag generated with dust injection ($S_n$), and the composition of secondary dust (Zn, Fe, Cl, and F concentrations) can be quantitatively discussed as a function of the dust injection rate ($D_{inj}$) into EAF-2. $D_{n}$ was varied up to 16 kg/t-steel, which is equivalent to the average amount of primary dust generation ($D_0$ = 16.3 kg/t-steel). Since d3 in Table 1 is selected as the primary dust from EAF-1 and the injected dust into EAF-2, the standard states of $D_0$ and $S_0$ correspond to that of d3 ($D_0$ = 16.3 kg/t-steel and $S_0$ = 114 kg/t-steel).

### 3.3. Dust Treatment Process

Together with EAF operation with and without dust injection, the authors have developed an EAFD treatment process by the lime addition method and have succeeded in recovering Zn in the dust as metallic Zn or ZnO and converting Fe in the dust into calcium ferrite (2CaO–Fe₂O₃) as a raw material for blast furnace ironmaking [19–21]. The process flow is schematically exhibited in Figure 6. The basic reactions involved in this process are as follows:

![Figure 6: Outline of the EAF dust treatment process proposed by Koide et al. [21].](image)

\[
\text{ZnO–Fe}_2\text{O}_3 + 2\text{CaO} = \text{ZnO} + 2\text{CaO–Fe}_2\text{O}_3, \tag{7}
\]

\[
\text{ZnO} + \text{C} = \text{Zn(g)} + \text{CO}, \tag{8}
\]

\[
\text{ZnO} + \text{CO} = \text{Zn(g)} + \text{CO}_2. \tag{9}
\]

In addition to being able to recover Zn as a metal or oxide, this is the first process which makes it possible to recycle Fe, potentially resulting in the recovery of more than 2 million tons of Fe annually in the EAF industry around the world.
This process enables the recovery of not only Zn but also Fe in EAFD, and cost and material balances for manufacturing EAFD and selling zinc oxide (ZnO) and crude calcium ferrite (2CaO–Fe₂O₃ containing Al₂O₃, MgO, SiO₂, etc., of approximately 30% in total) are considered. As shown in Figure 6, the outline of the process is as follows:

1. Lime is added (slaked lime, Ca(OH)₂) for the conversion of zinc ferrite (ZnO–Fe₂O₃) to ZnO and calcium ferrite together with carbon source (coke) for the reduction to EAFD, and its mixture is heated. As a result, ZnO is reduced and evaporated together with the volatile impurity elements, such as Pb and Cl.

2. The evaporated matter is deposited in the low-temperature zone of the reactor and collected in a bag filter.

3. Impurities such as Pb and Cl are removed from the recovered solid materials by a hydrometallurgical treatment (halogen removal process), and thus high-purity ZnO is obtained. This is sold to a Zn producer.

4. Solid residue (clinker), mainly consisting of calcium ferrite, is coproduced as a raw material of the blast furnace ironmaking process.

According to this process, the cost and material balances are quantitatively evaluated for the EAFD listed in Table 1 based on the following conditions:

(i) Slaked lime for equation (7) is added to EAFD at Ca/Fe = 1.4 in molar ratio. Excess calcium is needed at 0.4 because of the consumption of CaO by other minerals such as SiO₂, Al₂O₃, etc., in EAFD [19, 20].

(ii) Coke as a reducing agent is added to EAFD at C/Zn = 1.0 in molar ratio.

(iii) The mixture is heated and reacts in a rotary kiln. During the heating, most of Zn and all of Pb, Cl, and F evaporate as Zn vapor, PbCl₂, NaCl + KCl, and HF. Some of Zn remains in the kiln residues.

(iv) Recovered crude ZnO is supplied to a hydrometallurgical washing process to remove the halogens and heavy metals deposited on the surface [64]. In this process, Ca(OH)₂ and an equimolar mixture of Na₂CO₃ and NaOH are used. Their amounts are adjusted to the Cl, F, and Pb contents in the clinker. After treatment, H₂SO₄ is added for neutralization.

(v) The recovery ratios of Zn and Fe against the original EAFD are approximately 90% and 95%, respectively [21].

The cost of each material in JPY/kg (EUR/kg) is assumed and is listed in Table 2. These values are used to calculate the cost balance. It should be noted that, in this calculation, costs related to infrastructure and energy input are not taken into account.

4. Results and Discussion

4.1. Materials and Cost Balances in Conventional EAF Operation. Figure 7 shows the quantities of dust and slag generation and those of Fe and Zn lost into slag for d₁ to d₆. Outcoming or loss (EUR/t-steel) for d₁ to d₆ is shown in Figure 8. These costs are used to calculate the cost balance. It should be noted that, in this calculation, costs related to infrastructure and energy input are not taken into account.
the Fe adhering to the scrap transfers to the slag, the concentration of Fe in the slag is higher.

Figure 8 shows the converted quantities presented in Figure 7 into costs. The dust and slag treatment costs tend to be higher with higher Zn concentrations in the dust (d1 to d5), and the total treatment cost including (treatment cost + value loss of resource) increases. From these results, it can be concluded that when the chemical composition of the EAFD changes, the quantity of Fe in the slag is almost constant and the total processing cost is essentially determined by the quantity of dust and slag generated. That is, controlling the amount of dust and slag generated when the Zn concentration in the dust changes is crucial from the viewpoint of cost management of the EAF operation.

4.2. Materials and Cost Balances by considering the Dust Treatment Process. The impact of introducing the new dust treatment process shown in Figure 6 on the materials and cost balances was determined. Figure 9 exhibits the quantities of slaked lime, coke, and chemicals for halogen treatment (total), which are necessary for the treatment of the six kinds of EAFD listed in Table 1, and ZnO and crude calcium ferrite, which are products of the treatment process. This crude calcium ferrite can be supplied to the steel industry as a raw material for blast furnace ironmaking. The quantity of coke for dust reduction and that of chemicals used for halogen treatment are relatively small compared to the amount of Zn and Fe recovered and lime added in the six cases. The results show that the Zn concentration in EAFD increases in order from d1 to d6, whereas the Fe concentration is the opposite. However, the quantity of auxiliary materials required for treatment did not change accordingly. This suggests that the concentration of EAFD components is important in dust treatment, while the quantity of components is more important for the quantity of auxiliary raw materials input and resource recovery.

Figure 10 shows the result of converting the quantity in Figure 9 into cost and calculating the balance between incomings and outgoings. In each of the six cases, the total income from the sale of steel raw materials and ZnO exceeds the total costs incurred from the purchase of coke and additives for halogen treatment and the loss of Fe and Zn in slag. This indicates that, without considering the capital costs, the dust treatment industry is potentially profitable, and the processing costs paid by EAF companies can also be reduced if the costs of operation energy and transportation required for processing can be minimized.

4.3. Materials and Cost Balances by considering Dust Injection Technology. Figure 11 shows the variations in the calculated net dust shipment and the element concentration in the dust with the dust injection rate. As the dust injection rate increases, the quantity of dust generated from EAF-2 is greater than the primary dust generation rate $D^0$, which is the net amount of dust shipped $(D = (D^0 - D^{00} + D^0)/2)$ is smaller than $D^0$. While the concentrations of Zn, Pb, Cl, and F in the secondary dust become higher, the Fe concentration is lower than that in the primary dust, as represented in Figure 11.

The total amount of slag shipped was calculated in the same manner as in the case of dust. Furthermore, the amounts of Zn and Fe transferred to the slag due to dust injection were calculated as Zn and Fe losses. Figure 12 represents the total quantity of slag shipped. As the dust injection rate increases, the total amount of slag shipped becomes greater than that of primary slag $S^0$, and the Fe loss also increases. However, since only an extremely small amount of Zn occurs, the total recoverable quantity of Zn in EAFD does not change regardless of the dust injection operation.
In order to convert these mass quantities into costs, the processing costs and recoverable resource values were calculated by multiplying the total amounts of dust and slag by the processing costs represented in Table 2. The results of these calculations are shown in Figure 13. According to this figure, the slag treatment cost is the largest, and this increases with a higher dust injection rate. Large reductions in dust treatment costs can be made by implementing the dust injection technology. When Fe and Zn are regarded as resources, the amount transferred to dust by injecting dust is effectively recovered as a valuable resource in the subsequent dust treatment process. However, the amount transferred to slag in EAF-2 is considered as a loss. The losses of Zn and Fe resource values increase with higher dust injection rates, while the loss of Zn is rather small. The transfer of Fe in EAFD to slag, resulting in Fe loss as a resource. Fe loss increases unilaterally with higher dust injection rates. It can therefore be concluded that dust injection effectively suppresses the amount of dust shipment but also results in Fe loss.

5. Conclusions

The effects of the new dust treatment process (the CaO addition process) and dust injection technology on the materials and cost balance in the operation of the electric arc furnace (EAF) for steelmaking were evaluated by considering Zn and Fe recovery from the electric arc furnace dust (EAFD). The Zn and Fe recovery efficiencies and their losses with and without the new dust treatment process (CaO addition process) and dust injection technology are taken into account. The following findings were obtained from the results:

(1) The Zn and Fe concentrations in the dust are in an inversely proportional relationship, and the sum of the two is approximately 50 mass%. When the Zn concentration in the dust is higher, the concentrations of Pb and halogens, which are volatile elements, tend to be higher.

(2) The amount of dust generated from EAF tends to increase as the distribution ratio of Fe between slag and dust \((\text{mass}\%\text{Fe}_{\text{slag}}/\text{mass}\%\text{Fe}_{\text{dust}})\) is higher.

(3) The benefit of recovering both Zn and Fe in EAFD outweighs the cost of the chemicals used for recovery. Therefore, dust treatment is potentially profitable, and the treatment costs paid by EAF companies can be reduced by introducing the CaO addition process for EAFD treatment if the costs of operation energy and transportation required for processing can be minimized.
Since the dust injection technology can reduce the gross quantity of dust shipment, on the condition that the treatment cost is much lower for slag than for EAFD, the use of dust injection can reduce the total waste treatment cost. However, dust injection also results in an increased quantity of Fe lost to slag, which equates to the loss of the resource value of Fe. Therefore, it is necessary to determine the appropriate value of the amount of dust injection by the balance between the waste treatment cost and the amount of metal resources which can be recovered.

These results may help EAF steelmakers and dust and slag treatment companies to establish an optimal total steelmaking process, from steelmaking to treatment of by-products, by considering steelmaking and dust treatment methods and evaluating the cost of details.

**Notations**

- $D^0$: Dust generation rate in EAF operation without dust injection
- $S^0$: Slag generation rate in EAF operation without dust injection
- $D^\alpha$: Dust generation rate in EAF operation with dust injection
- $S^\alpha$: Slag generation rate in EAF operation with dust injection
- $D^{inj}$: Dust injection rate in EAF operation
- $\beta$: Recollected ratio into the secondary dust of injected dust ($\beta = 0.312$)
- $\gamma$: Recollected ratio into the slag of injected dust ($\gamma = 0.642$)
- $[\%M]^0$: Concentration of component $M$ in the original dust
- $\alpha_M$: Recollected ratio into the secondary dust of given component $M$
- $D$ : Net dust shipment rate
- $S$ : Net slag shipment rate

**Data Availability**

The data used to support the findings of this study are included within the article and are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest.

**Acknowledgments**

Helpful comments, discussions, encouragements, and support given by EAF Division of ISIJ, Dr. E. Webeck (TEQED), and Hoei Metal Co., Ltd, are gratefully acknowledged. This work was supported by the Japan Science and Technology Agency (JST) by NexTEP Project in 2014 to 2019, ISIJ Innovative Program for Advanced Technology, and ISIJ Research Promotion Grant, the Iron and Steel Institute of Japan.

**References**


