Off-Gas Waste Heat Recovery for Electric Arc Furnace Steelmaking Using Calcium Hydroxide (Ca(OH)$_2$) Dehydration

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Off-gas waste heat recovery for electric arc furnace (EAF) steelmaking is challenging because high off-gas velocity, fluctuating temperature, and high dust contents must be considered. In addition to the harsh off-gas conditions, a heat storage system must be included to balance power-off times of the EAF during tapping or charging. However, waste heat recovery offers a significant potential for further efficiency improvements in EAF steelmaking. Herein, a novel process concept for extraction, storage, and utilization of off-gas waste heat via entrained flow dehydration of calcium hydroxide (Ca(OH)$_2$) for efficient power generation is described. The use of waste heat exchangers is avoided, and small heat storage units are achieved. The process concept, Ca(OH)$_2$ dehydrolysis and heat storage mechanism as well as important process parameters are discussed. Finally, the energy balance of the waste heat recovery process and further process improvements are presented.

1. Introduction

Currently off-gas waste heat recovery for electric arc furnace (EAF) steelmaking is not a wide spread technology and so up to one-third of the energy input is lost via off-gas waste heat in most EAFs.$^{[1,2]}$ Obstacles for the implementation of waste heat recovery processes are the fluctuating temperature, changing mass flow, and high dust content (up to 25 g m$^{-3}$ (STP)) of the EAF off-gas and high payback times of the investment.$^{[3,4]}$ Process-related a heat storage device is necessary to balance power-off times during tapping and charging.

In existing facilities, waste heat boilers and steam accumulators for waste heat extraction and storage are utilized.$^{[5,6]}$ Critical about this approach is corrosion and erosion of the waste heat exchanger, low temperature level of heat extraction and storage density. Therefore single power generation is not efficient enough to be economical feasible and combined heat and power generation or direct use of steam must be realized.$^{[4]}$ Consequently steel plants require today an internal or external heat consumer for a profitable implementation of a waste heat recovery system.

To solve this problem, novel waste heat recovery concepts for the EAF steelmaking process must be developed, which focus on efficient power generation for internal use by the mini mill. Such a concept would overcome the dependency and allow a wide spread utilization of off-gas waste heat recovery in EAF steelmaking.

Based on this findings, a novel waste heat recovery concept as retrofit option for existing steel plants is currently developed at the Institute of Combustion and Power Plant Technology (IFK). The aims of the process development are avoidance of an off-gas waste heat exchanger, higher heat storage density and increase in heat extraction temperature for efficient power generation. A process with less operational problems caused by corrosion and erosion, small heat storage units and reduced investment costs should be achieved.

2. Reference Plant

As reference for the process development a carbon steel-producing EAF was selected. The off-gas systems of the applied EAF consists of a postcombustion chamber, settling chamber, water quench and bag filter (Figure 1). During the scrap melting, off-gas is sucked into the postcombustion chamber and mixed with ambient air, which enters the postcombustion chamber via the gap between EAF elbow and postcombustion chamber. The high off-gas temperature causes the complete combustion of partly oxidized off-gas components like H$_2$ and CO. Temperatures of up to 1400 °C are reached inside the postcombustion chamber (Figure 2). After the post combustion, the settling chamber follows for the separation of coarse dust particles. The following water quench mitigates the formation of polychlorinated dibenzodioxins (PCDDs), or simply dioxins, via de novo synthesis. The de novo synthesis requires long residence times at a temperature range between 250 and 450 °C (in some sources 600 °C).$^{[8]}$ The rapid off-gas cooling via quenching is minimizing the time within this temperature range and oppresses dioxin formation.

After quenching the EAF off-gas is mixed with air from the suction hood and lead to the bag filter house. The air mass flow is roughly four times higher than the EAF off-gas mass flow.
3. Off-Gas Waste Heat Potential

The applied off-gas data for the process design (mass flow and temperature) are shown in Figure 2. The fluctuation in mass flow and temperature of the off-gas between melting and charging (0:18–0:22/Figure 2) are obvious. During melting temperature, peaks of 1400°C are reached. During charging the off-gas temperature decreases rapidly to 250°C before the melting of the second scrap bucket starts (0:18–0:22/Figure 2). When the EAF lid is closed and the electric arc ignites the off-gas temperature increases dramatically again to 800°C. As off-gas quenching is required in the reference plant off-gas waste heat will be just extracted at temperatures above 600°C (Equation (1)). About 600°C is chosen to definitely ensure the mitigation of dioxin formation via de novo synthesis. Consequently, a waste heat extraction is only possible during scrap melting with this limitation (Figure 2).

\[
\dot{Q}_{\text{OG}} = \begin{cases} 
\dot{m}_{\text{OG}} \cdot c_{p,\text{OG}} (\theta_{\text{OG}} - 600^\circ\text{C}) & \theta_{\text{OG}} > 600^\circ\text{C} \\
0 & \theta_{\text{OG}} < 600^\circ\text{C} 
\end{cases}
\]  

(Equation (1))

Similar to the off-gas temperature, the usable waste heat flow indicates a harsh fluctuation with peaks up to 26.6 MWth (Figure 2). The average waste heat potential for a waste heat recovery above temperatures of 600°C is 14.7 MWth. If a different method for the reduction of dioxin emissions like application
of absorbers would be used a lower temperature could be utilized and the off-gas waste heat potential would increase. In addition to the off-gas waste heat flow, the amount of electric arc furnace dust (EAFD) must be considered for the process design. The reference steel plant has a dust load of 20 g m⁻³ (STP) after off-gas quenching, which results in an average mass flow of 580 gₑAFD·s⁻¹.

4. Process Concept

As a higher heat storage density compared with steam (latent heat storage) is requested, the application of thermochemical heat storage materials becomes necessary. Calcium hydroxide (Ca(OH)₂) is an interesting heat storage material for the reference case. For a detailed explanation of the heat storage material selection and characteristics of Ca(OH)₂, see Hartfuß et al.⁹

Using Ca(OH)₂, off-gas waste heat could be stored by dehydrating Ca(OH)₂ to calcium oxide or lime (CaO) and steam (H₂O) at higher temperatures (Equation (2)). At lower temperatures, the dehydration reaction can be reversed (hydration) and the thermochemical stored heat is released.

\[
\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O} \quad \Delta H_R = 104 \text{kJ mol}^{-1} \quad (2)
\]

Important for the heat storage process is the chemical equilibrium of dehydration and hydration, which depends on the steam partial pressure (Figure 3).

At off-gas compositions for EAF steelmaking with 5%vol steam, dehydration is possible above temperatures of 384 °C (Figure 3). More important is that even in pure steam just a temperature above 519 °C is necessary to dehydrate Ca(OH)₂. As off-gas waste heat should be recovered just to a temperature of 600 °C dehydration is always possible and Ca(OH)₂ is a good suited heat storage material.

To solve the challenge of waste heat exchanger avoidance calcium hydroxide (Ca(OH)₂) particles will be used in an entrained flow to extract and store the off-gas waste heat. The idea is to use the existing off-gas system (postcombustion chamber to quenching chamber exit) as entrained flow reactor and inject 200 °C hot Ca(OH)₂ particles into the postcombustion chamber, if a temperature above 600 °C is detected (Figure 4). While the Ca(OH)₂ particles pass through the off-gas system, heating and thermochemical decomposition occur. At the exit of the quenching chamber 600 °C hot lime particles are formed and separated by a cyclone separator.

The particles must be small enough to pass the settling chamber and dehydrate completely. For the reference plant, a maximal particle size of ≈500 μm was determined. The water quench is switched off during particle injection, but the quenching chamber is kept to increase the residence time of the particles within the off-gas flow and as backup system. The water quench becomes needless since the off-gas is cooled by the dehydration of Ca(OH)₂ particles to 600 °C, which is enough to quench the off-gas with air from the suction hood (Figure 1). A change of the quenching concept from water to air rather than a shutdown of the quench is proposed.

These measurements allow the residence times of minimal 2.5 s and average 4.0 s. The outlet of the shutoff quenching chamber follows a cyclone separator. The hot lime particles are separated while the off-gas flows on to the bag filter house.

The separated hot lime particles are lead to a storage tank. This storage tank has the task to balance EAF idle times. A continuously operating conveyer feeds a fluidized bed reactor with hot lime particles. Inside the fluidized bed reactor, hydration and steam generation are performed. The reactor is therefore equipped with heat exchanger internals and steam is partly used for fluidization. Steam for the lime hydration is extracted from an extraction condensing steam turbine. The produced high pressure superheated steam (450 °C/70 bar) is used to run an extraction condensing turbine to generate electric power.

At the outlet of the fluidized bed reactor a second storage tank is applied to store the reformed Ca(OH)₂ particles before their reuse for another cycle.

5. Dehydration Rate of Ca(OH)₂ Particles

Important for the required Ca(OH)₂ particle mass flow, respectively, achievable heat storage density and size of the heat storage tank is the dehydration rate of Ca(OH)₂ particles. Unfortunately, literature data for dehydration rates focus on fixed and fluidized bed reactors, as the Ca(OH)₂/CaO reactions system is mostly analyzed for heat storage applications in solar or conventional power plants, were these reactor types would be applied. One model to describe Ca(OH)₂ dehydration is based on thermogravimetric analysis (TGA) and formulated by Criado et al.¹¹ The model indicates, that 500 μm-sized Ca(OH)₂ particles will be completely dehydrated within 4 s at a temperature of 625 °C and 5%vol steam atmosphere. As the particles are injected inside the postcombustion chamber at mostly higher temperatures (Figure 2), a complete dehydration could be expected within this concept. Furthermore, the maximum diameter for usable Ca(OH)₂ particles in the reference off-gas system is 500 μm.

To check if this model and assumption are appropriate for the determination of entrained flow dehydration experiments were performed at the IFK. The experiments were conducted with the entrained flow reactor DIVA. DIVA is an electrical heated semitechnical reactor with a length of 12.4 m and diameter of ≈70 mm.¹² The reaction temperature is controlled during the experiments by the electrical heating. Residence time and steam atmosphere are varied by compositions and volume flow of the fluidization agent. Ca(OH)₂ particles are injected at the bottom of

![Figure 3. Chemical equilibrium of dehydration and hydration.¹⁰](image-url)
the DIVA reactor with a mass flow of 1.5 kg Ca(OH)\textsubscript{2} \cdot h\textsuperscript{-1}. As in the process concept, the particles pass through the reactor and dehydrate. At the top of the DIVA reactor, the particles are separated by a cyclone and fall into a sample glass. To stop the reaction, an air quench is installed and the sample glass purged with nitrogen. During the experiments, the steam amount is measured with a Fourier-transform infrared spectrometer Gasmet dx4000. The particle size distribution of the applied Ca(OH)\textsubscript{2} is shown in Table 1. After the experiments, the remaining amount of Ca(OH)\textsubscript{2} was determined using a Leco TGA 701 analyzer. The remaining Ca(OH)\textsubscript{2} amount was specified by the mass change during sample heating to 600 °C (complete dehydration).

Using this procedure, several experiments with the variations of residence time, temperature and steam amount are conducted. The variation range for all parameters is shown in Table 2.

### Table 1. Particle-size distribution of the applied Ca(OH)\textsubscript{2} for the entrained flow experiments.

| Particle fraction | \(d_{p,10}\) | \(d_{p,50}\) | \(d_{p,90}\) |
|------------------|-------------|-------------|-------------|
| Particle size [μm] | 127.5 | 235.7 | 406.1 |

### Table 2. Variation range of the experiment parameters.

| Parameter         | Temperature in °C | Residence time in s | Steam content in %vol |
|-------------------|-------------------|---------------------|-----------------------|
| Variation range   | 450–600           | 3–6                 | 0–30                  |

The results of the entrained flow experiments show a much faster reaction compared with the model of Criado et al.\textsuperscript{[11]} As an example, the results of the tests at a temperature of 500 °C are shown in Figure 5. According to Criado et al., a dehydration of around 10% was expected for Ca(OH)\textsubscript{2} particles with an average diameter of 235 μm, at dry atmosphere within 3 s, but the entrained flow experiments resulted in 73% dehydration for the same conditions. All entrained flow experiments indicate a much faster dehydration compared with the findings of Criado et al.\textsuperscript{[11]} It has to be concluded that the higher turbulence and better heat transfer of an entrained flow system enhance the dehydration rate dramatically.

As the model already predicted a complete conversion of the Ca(OH)\textsubscript{2} particles in the reference plant, the DIVA experiments confirmed that a full dehydration of the Ca(OH)\textsubscript{2} particles can be expected.
6. Heat Storage Density and Required Mass Flow of Ca(OH)$_2$

After determination of the expected dehydration rate of the applied Ca(OH)$_2$ particles, the heat storage density can be calculated. The heat storage takes place in three steps. First, Ca(OH)$_2$ is heat up from 200 °C to equilibrium temperature, then nearly isothermal dehydration occurs, before the formed lime is overheated to 600 °C. In total, sensible and thermochemical heat storage must be considered (Equation (3)).

\[ q_{\text{Ca(OH)}_2} = c_p,\text{Ca(OH)}_2 \cdot (184 \, \text{K}) + X_{\text{Ca(OH)}_2} \cdot \Delta H_{R,\text{Ca(OH)}_2} + c_p,\text{CaO} \cdot (216 \, \text{K}) \cdot \frac{M_{\text{CaO}}}{M_{\text{Ca(OH)}_2}} + c_p,\text{H}_2\text{O} \cdot (216 \, \text{K}) \cdot \frac{M_{\text{H}_2\text{O}}}{M_{\text{Ca(OH)}_2}} + \frac{M_{\text{CaO}}}{M_{\text{Ca(OH)}_2}} \cdot \Delta H_{R,\text{Ca(OH)}_2} \]

\[ q_{\text{Ca(OH)}_2} = 1.43 \, \text{kJ} \cdot \text{K}^{-1} \cdot \text{kg}_{\text{Ca(OH)}_2}^{-1} \cdot 184 \, \text{K} + 1.0 \cdot 1403 \, \text{kJ} \cdot \text{kg}_{\text{Ca(OH)}_2}^{-1} + 1.02 \, \text{kJ} \cdot \text{K}^{-1} \cdot \text{kg}_{\text{CaO}}^{-1} \cdot 216 \, \text{K} + 2.12 \, \text{kJ} \cdot \text{K}^{-1} \cdot \text{kg}_{\text{H}_2\text{O}}^{-1} \cdot 216 \, \text{K} \]

\[ q_{\text{Ca(OH)}_2} = 1833 \, \text{kJ} \cdot \text{kg}_{\text{Ca(OH)}_2}^{-1} + 111 \, \text{kJ} \cdot \text{kg}_{\text{Ca(OH)}_2}^{-1} = 1944 \, \text{kJ} \cdot \text{kg}_{\text{Ca(OH)}_2}^{-1} \]

Overall, a heat storage density of 1833 kJ · kg$_{\text{Ca(OH)}_2}^{-1}$, of which 23% are related to sensible and 77% to thermochemical heat storage. An additional heat loss of 111 kJ · kg$_{\text{Ca(OH)}_2}^{-1}$ due to the superheating of released steam occurs. As the superheated steam passes through the cyclone, its energy cannot be used for the further waste heat recovery process. On a volumetric base, a heat storage density of 2025 MJ · m$^{-3}$ is achieved (bulk density of Ca(OH)$_2$ equals 1105 kgCa(OH)$_2$ · m$^{-3}$).

Using the required heat amount for Ca(OH)$_2$ dehydrating and heating of lime and steam to 600 °C, the necessary mass flow of Ca(OH)$_2$ particles for the off-gas waste heat extraction follows. The extraction of the off-gas waste heat peaks of 26.6 MW$_{th}$ requires the injection rate of 13.7 kg$_{\text{Ca(OH)}_2}$ · s$^{-1}$, whereas on average, a mass flow of 7.54 kg$_{\text{Ca(OH)}_2}$ · s$^{-1}$ must be injected to extract the average off-gas waste heat potential of 14.7 MW$_{th}$, where by 0.83 MW$_{th}$ are lost via superheated steam.

7. Mixing of EAFD and Heat Storage Material

The application of the entrained flow concept avoids the use of a waste heat boiler, but in contrast, it has one huge disadvantage. The formed lime particles are mixed with EAFD. The EAFD particles could replace Ca(OH)$_2$/CaO and reduce the heat storage density. The whole concept would collapse, if no sink for the EAFD contamination is integrated to the process. Two effects are used to stop the EAFD enrichment. First, most of the EAFD will pass the cyclone, and second, contaminated lime can be reused as slag former and exchanged with fresh lime.

7.1. Cyclone Separation

The proposed cyclone is designed to separate 98.5% of the lime particles at average volume flow (Table 3). A separation efficiency of 98.5% was considered as good compromise between separation efficiency and pressure drop.

To achieve the required separation efficiency for lime particles a cut size ($d_{x,50}$) of 38.8 μm is necessary. The total separation efficiency for different particle sizes is determined according to Hoffmann et al. with a medium selectivity (selectivity factor $k$ equals 3) (Equation (4)).

\[ \eta = \frac{1}{1 + \left(\frac{d_{x,50}}{d_{x,50}}\right)^k} \quad \text{with} \quad k = 3 \]  

In comparison with lime particles, EAFD particles are much smaller but have a four times higher particle density (Table 3). Consequently, the cut size for EAFD is just 20.5 μm using the same cyclone due to the higher particle density. Nevertheless, just 14.8% of the EAFD particles are separated, because 90% of them are smaller than 25.2 μm (Table 3). Accordingly, a separated EAFD mass flow of 86 g$_{\text{EAFD}}$ · s$^{-1}$ has to be expected. In summary, 5.62 kg$_{\text{CaO}}$ · s$^{-1}$ and 86 g$_{\text{EAFD}}$ · s$^{-1}$ are separated on average and lead to the heat storage tank (Figure 4). The heat storage material will be contaminated with 1.5% EAFD after each cycle. However, the cyclone helps as first step to reduce the amount of EAFD contamination of the heat storage material, but more important is the second measurement of reusing contaminated lime and replacing it with fresh lime.

Note that, the average mass flow of 7.54 kg$_{\text{Ca(OH)}_2}$ · s$^{-1}$ is reduced about 1.83 kg$_{\text{H}_2\text{O}}$ · s$^{-1}$, which refer to the released steam mass flow during dehydration, an incomplete particle separation.
of the cyclone (86 g CaO \cdot s^{-1}). The cyclone losses of lime must be replaced by fresh lime.

7.2. Reuse of Contaminated Lime as Slag Former

The cyclone selectivity may reduce the separated EAFD mass flow, but nevertheless EAFD would enrich inside the heat storage material until the process collapses. A sink for the EAFD contamination must be found. An option to stop EAFD enrichment is to reuse contaminated lime as slag former and replace the withdrawn material by fresh pure lime. Using this method, the level of contamination will stabilize at a certain level. The level of EAFD contamination depends on cyclone selectivity and mass flow of exchanged lime (Equation (5)). Where in the process, the lime exchange that takes place will be discussed in the following sections, when the fluidized bed

\[
\frac{m_{\text{EAFD}}}{m_{\text{fresh CaO}}} = \frac{m_{\text{EAFD}}}{m_{\text{cyclone loss}} + m_{\text{slag former}}} = \frac{0.086 \frac{kg_{\text{CaO}}}{s}}{0.086 \frac{kg_{\text{CaO}}}{s} + 0.28 \frac{kg_{\text{CaO}}}{s}} = 0.235 \frac{kg_{\text{EAFD}}}{kg_{\text{CaO}}}
\]

reactor is described.

As an example, it is assumed that the reference steel plant will utilize 0.28 kg CaO \cdot s^{-1} or 1 kg CaO \cdot h^{-1} of lime from the waste heat process as slag former. With this use of lime, the contamination is stopped at a level of 23.5% EAFD within the heat storage material (Equation (5)). Before contaminated lime is reused in the EAF, a reduction of the EAFD amount by sieving is possible. In lab scale test, a reduction of EAFD contamination of about 60% to a level of 14% was achieved.

Note that, in the further process discussion, the heat storage density of the 23.5% EAFD will not be considered, but the EAFD mass is added to the necessary mass of Ca(OH)₂ or lime.

8. Size of the Heat Storage Tank

After the calculation of separated mass flow and remaining EAFD contamination, the size of the heat storage tank can be determined (Figure 4). According to the usable waste heat flow (Figure 2), the injected, respectively, separated mass flow is the input to the storage tank, whereas simultaneously, the average mass flow of 5.62 kg CaO \cdot s^{-1} and 1.32 kg EAFD \cdot s^{-1} is extracted from the storage tank. The hot material is fed into the fluidized bed reactor (continuous operation). Consequently, the storage tank will be filled during melting and emptied during the charging of the EAF (Figure 6). In addition, a backup mass equal to 15 min of operation is stored inside the tank in case of operation problems at the EAF. This backup mass is in total 6.25 tons, 5.06 and 1.19 tons of lime and EAFD, respectively.

At the end of the melting period at 0:15, the heat storage tank is filled with a total mass of 8.92 tons and is than emptied until at 0:29 only the backup mass remains inside the tank (Figure 6). For the storage task, a tank with a volume of just 6.5 m³ is required. This small storage tank size is possible due to the high heat storage density of the Ca(OH)₂.

9. Fluidized Bed Reactor

The continuously operating fluidized bed reactor has the task of lime particle hydration and steam generation to run the extraction condensing steam turbine. The reactor is divided in three compartments, which are equipped with bundle heat exchangers inside the bed and connected by bed overflows. Inside, the first compartment particles are cooled down from 600 to 400 °C (hydration side of the chemical equilibrium). As no hydration occurs, an air fluidization is sufficient. The lime exchange is placed at the outlet of this compartment. At this point, the sensible heat of the lime cooling could be used and no hydration has occurred. This is important, because the use of Ca(OH)₂ instead of lime as slag former would cause a higher energy consumption of the EAF.

The hydration and release of the thermochemical stored heat takes place in the second compartment at a temperature of 400 °C. The steam must be used as a fluidization agent. The required steam flow originates from the extraction condensing steam turbine (Figure 4). In the last compartment, the reformed Ca(OH)₂ particles are further cooled to 200 °C and again air is used to fluidize the bed. The heat flow of all three compartments is used to produce a high pressure steam mass flow of 4.3 kg H₂O \cdot s^{-1} (450 °C, 70 bar).

Also, the heat loss in the heating of air and steam to the particular bed temperatures must be considered. To minimize the heat loss, a mild fluidization velocity in the range of 0.25 m \cdot s^{-1} (bubbling bed) is applied. For the second compartment, the loss of steam has a huge impact on the overall heat loss of the reactor. Most of the steam is incorporated by lime during particle hydration, but as just a limited residence time for the steam inside the fluidized bed could be realized, some steam will leave the reactor.

In general, the reactor height should be as high as possible with low fluidization velocity to increase the residence time and amount of incorporated steam. In the further process discussion, an unreacted steam amount of 20% in relation to the required steam mass flow (1.83 kg H₂O \cdot s^{-1}) is assumed. Using this assumption, a steam mass flow of 2.2 kg H₂O \cdot s^{-1} must be provided for complete particle hydration.

Overall the reactor has a heat loss of 1.6 MW, which are caused by the exiting air and steam flow.
10. Energy Balance

To summarize the waste heat recovery processes, the energy balance of the process will be presented (Figure 7). At the beginning, the usable off-gas waste heat potential of 14.7 MW\textsubscript{th} is applied for Ca(OH)\textsubscript{2} particle dehydration and steam superheating. The superheating of steam causes an energy loss of 0.83 MW\textsubscript{th}. At the cyclone, 1.5\% or 0.2 MW\textsubscript{th} of the extracted waste heat are lost due to incomplete cyclone separation. Another minor heat loss with 0.15 MW\textsubscript{th} is caused by the exchange of contaminated with fresh lime particles. The heat loss, which relates to the heating of fluidization agents, is by far the greatest with 1.6 MW\textsubscript{th}. At the end, the available heat flow for the steam generation is reduced by \(\approx 3\) to 11.8 MW\textsubscript{th}. An extraction condensing turbine is applied to generate electric power, because a steam extraction for feed water degassing and lime hydration is necessary. Especially, the extraction of steam after the high pressures turbine causes an efficiency drop. Nevertheless, a gross power output of 2.95 MW\textsubscript{el} could be realized. To compensate the pressure drop of cyclone and fluidized bed reactor, additional power for fan and air blower of 0.15 MW\textsubscript{el} are necessary. Finally, a net power output of 2.8 MW\textsubscript{el} is generated, that relates to an annual power production of 21.0 GWh\textsubscript{el} (annual operation of 7500 h).

11. Possible Process Improvements and Future Research

Some process improvements are possible, that are not discussed so far. First, it is possible to decrease the temperature of the heat extraction. The applied 600 °C is used to ensure the avoidance of dioxin formation. This limitation would be obsolete in steel plants with absorber injection as method to minimize dioxin emissions. Another reason why a low temperature could possibly be applied is caused by the entrained flow concept itself. The direct contact of chlorine and lime, for example, will form calcium chloride (CaCl\textsubscript{2}). The incorporated chlorine is no longer present for the de novo synthesis, and a quench becomes unnecessary at all. The formation of CaCl\textsubscript{2} was analyzed in lab scale test and simulations show a chlorine incorporation of up to 97\%, but this must be further investigated in a larger scale. In addition, the heat loss for steam superheating would decrease and usable waste heat recovery potential improved.

The second important improvement is the use of lime particles with a larger diameter of the fine particle fraction. This would require a purchase of lime with a narrow particle size distribution or sieving on-site. The cyclone loss would be reduced, which is less important to minimize the heat loss but to reduce the operational costs of the waste heat recovery process.

The third significant process improvement is the utilization of additional waste heat sources inside the steel plant to generate steam as fluidization agent. In addition to the increase in total recovered waste heat, the extraction steam mass flow of the turbine could be reduced or ideally avoided. The efficiency of the power generation would improve since more steam is lead through the low pressure turbine. Steam for fluidization just needs a pressure in the range of 1.5 bar (depending on bed height). So every waste heat source with a temperature above 120 °C like off-gas of the reheat furnace can be used.

The next step of the process development will be the building of a pilot plant for experimental analysis of the presented waste heat recovery concept. Especially, the interaction of lime particles and EAF off-gas, reuse of contaminated lime as slag former and long-term Ca(OH)\textsubscript{2}/CaO particle behavior must be investigated.

12. Conclusions

A novel waste heat recovery process concept for EAF steelmaking based on entrained flow dehydration of Ca(OH)\textsubscript{2} particles was presented. Main process aspects are discussed using off-gas data of a reference steel plant with a usable waste heat potential of 14.7 MW\textsubscript{th}. Advantages of the entrained flow concept are avoidance of waste heat boilers and high heat storage density as
well as temperature. As complete dehydration of the Ca(OH)$_2$ particles is crucial for minimal particle mass flow and heat storage tank size, experiments in a semi-technical entrained flow reactor were performed. Expectable dehydrations rates of the Ca(OH)$_2$ particles were determined and compared with existing literature findings. It was found that for the reference plant, a complete dehydration of the Ca(OH)$_2$ particles can be expected. Consequently, a maximal particle mass flow of only 13.7 kg Ca(OH)$_2$·s$^{-1}$ and stored mass of 8.92 tons are necessary. Overall, a net power generation of 2.8 MW$_{el}$ can be achieved.

The major disadvantage is the mixing of EAFD and heat storage material, which must be limited by reusing contaminated lime as slag former. An outlook on possible further process improvements and future research tasks is given.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

electric arc furnace steelmaking, off-gas waste heat recovery, thermochemical energy storages

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