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(54) **METHOD AND SYSTEM FOR MONITORING THE CONTENT OF IRON CONTAINING MATERIALS IN A PARTICULATE ASH STREAM OF A FLUIDIZED BED BOILER**

(57) Disclosed is a method for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler, characterized by the steps of:
a. measuring magnetic susceptibility of a particulate ash stream from an ash outlet of the boiler;
b. magnetic separation of this ash stream into a magnetizable and non-magnetizable fraction;
c. measuring magnetic susceptibility of the magnetizable fraction;
d. calculating the weight specific magnetic susceptibility of the particulate ash stream and the magnetizable fraction;
e. calculating the normalized magnetic susceptibility by dividing the weight specific magnetic susceptibility of the particulate ash stream through the weight specific magnetic susceptibility of the magnetizable fraction;
f. using this normalized magnetic susceptibility as an indicator of the content of iron containing materials in the ash stream.

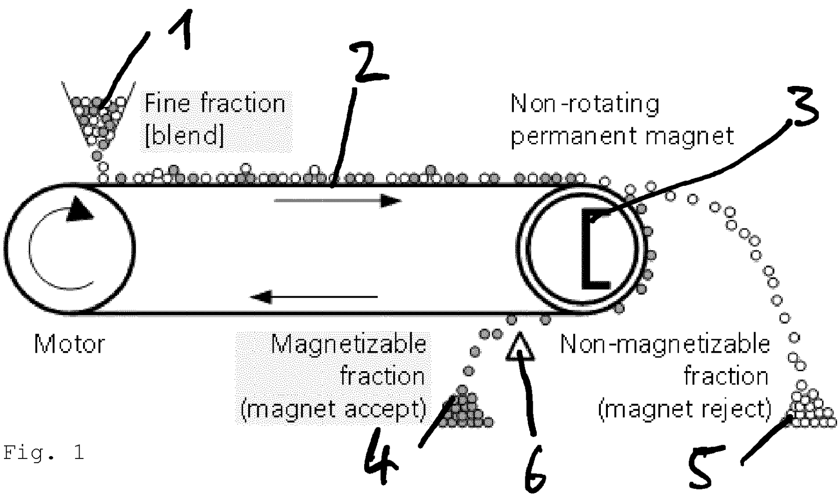

Fig. 1

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Description

[0001] The invention is directed to a method for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler; a system for monitoring the content of such iron containing materials; and a fluidized bed boiler comprising such a system.

[0002] Fluidized bed combustion is a well-known technique, wherein the fuel is suspended in a hot fluidized bed of solid particulate material, typically silica sand and/or fuel ash. Other bed materials are also possible. In this technique, a fluidizing gas is passed with a specific fluidization velocity through a solid particulate bed material. The bed material serves as a heat carrier and promotes rapid mass and heat transfer. At gas velocities below the minimum fluidization velocity, the bed remains static. Once the velocity of the fluidization gas rises above the minimum fluidization velocity, at which the forces of the fluidization gas balance the gravity force acting on the particles, the solid bed material behaves in many ways similarly to a fluid and the bed is said to be fluidized. In bubbling fluidized bed (BFB) boilers, the fluidization gas is passed through the bed material to form bubbles in the bed, facilitating the transport of the gas through the bed material and allowing for a better control of the combustion conditions (better temperature and mixing control) when compared with grate combustion. In circulating fluidized bed (CFB) boilers the fluidization gas is passed through the bed material at a fluidization velocity where the majority of the particles are carried away by the fluidization gas stream. The particles are then separated from the gas stream, e.g., by means of a cyclone, and recirculated back into the furnace, usually via a loop seal. Usually oxygen containing gas, typically air or a mixture of air and recirculated flue gas, is used as the fluidizing gas (so called primary oxygen containing gas or primary air) and passed from below the bed, or from a lower part of the bed, through the bed material, thereby acting as a source of oxygen required for combustion. A fraction of the bed material fed to the combustor escapes from the boiler with the various ash streams leaving the boiler, in particular with the bottom ash. Removal of bottom ash, i.e. ash in the bed bottom, is generally a continuous process, which is carried out to remove alkali metals (Na, K) and coarse inorganic particles/lumps from the bed and any agglomerates formed during boiler operation, and to keep the differential pressure over the bed within a desired interval. In a typical bed management cycle, bed material lost with the various ash streams is replenished with fresh bed material.

[0003] From the prior art it is known to replace a fraction or all of the silica sand bed material with ilmenite particles in the CFB process (H. Thunman et al., Fuel 113 (2013) 300-309). Ilmenite is a mineral which consists mainly of iron titanium oxide ($FeTiO_3$) and can be repeatedly oxidized and reduced. Due to the reducing/oxidizing feature of ilmenite, the material can be used as oxygen carrier in fluidized bed combustion. A bed material that can be repeatedly oxidized and reduced is referred to as active bed material in the context of the present invention. The combustion process can be carried out at lower air-to-fuel ratios with the bed comprising ilmenite particles as compared with non-active bed materials, e.g., 100 wt.-% of silica sand or fuel ash particles.

[0004] It is an object of the invention to provide a method and system allowing to monitor the content of ilmenite or another iron containing material in the bed of a fluidized bed boiler.

[0005] The object is solved by a method for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler, comprising the steps of:

a. measuring magnetic susceptibility of a particulate ash stream from an ash outlet of the boiler;
b. magnetic separation of this ash stream into a magnetizable and non-magnetizable fraction;
c. measuring magnetic susceptibility of the magnetizable fraction;
d. calculating the weight-specific magnetic susceptibility of the particulate ash stream and the magnetizable fraction;
e. calculating the normalized magnetic susceptibility by dividing the weight-specific magnetic susceptibility of the particulate ash stream through the weight-specific magnetic susceptibility of the magnetizable fraction;
f. using this normalized magnetic susceptibility as an indicator of the fraction by weight of iron containing materials in the ash stream.

[0006] In an alternative embodiment, the object is solved by a method for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler, comprising the steps of:

a. measuring magnetic susceptibility χ_{blend} and density ρ_{blend} of a particulate ash stream from an ash outlet of the boiler;
b. magnetic separation of this ash stream into a magnetizable and non-magnetizable fraction
c. measuring magnetic susceptibility χ_{magnet} and density ρ_{magnet} of the magnetizable fraction;
d. calculating the content f_{active} of iron containing materials in the particulate ash stream using the formula

$$f_{\text{active}} = k \cdot \frac{\chi_{\text{blend}}}{\chi_{\text{magnet}}} \cdot \frac{\rho_{\text{magnet}}}{\rho_{\text{blend}}}$$

with k being a proportionality constant.

[0007] First, several terms are explained in the context of the invention.

[0008] Fluidized bed boiler is a term well known in the art. The invention can be used for bubbling fluidized bed (BFB) boilers and circulating fluidized bed (CFB) boilers, in which CFB boilers are preferred. A fluidized bed boiler used in the context of the present invention is a device having the purpose of continuously producing heat through the combustion of solid fuel. Continuously means that the process of combustion and producing heat is carried out continuously for hours, days, weeks or longer. It further means that there is no operation in batches and no separate designated reaction zones e.g. for oxidation and reduction as in chemical looping combustion (CLC) known from the prior art. Preferably, the combustion process is carried out with air as fluidizing gas for fluidizing the bed material.

[0009] Solid fuel is any solid combustible material, e.g. coal, wood, other solid biomaterial, or waste.

[0010] A fluidized bed boiler using an oxygen carrying bed material described below can be operated at an excess air ratio (λ) below 1.3. The excess air ratio λ is a common parameter in the operation of fluidized bed boilers and is defined as the mass ratio of air to fuel ($MR_{air/fuel} = m_{air}/m_{fuel}$) actually present in the combustion process divided by the stoichiometric mass ratio of air to fuel. That is, $\lambda = (MR_{air/fuel})_{ac\text{-}tual}/(MR_{air/fuel})_{stoichiometric}$. The mass ratio of air to fuel actually present in the boiler is determined by the amount of fuel and air supplied to the boiler. The stoichiometric mass ratio of air to fuel is the mass ratio required by stoichiometry for complete combustion of the provided fuel and can be calculated for any given fuel composition.

[0011] In preferred embodiments, λ is 1.25 or less, more preferably 1.2 or less, more preferably 1.1 or less, most preferably between 1.05 and 1.1. Preferably, for the combustion of waste-based fuel, λ is 1.23 or less, more preferably 1.1 or less, more preferably between 1.05 and 1.23, most preferably between 1.05 and 1.1. For the combustion of biomass fuel, λ preferably is 1.19 or less, more preferably 1.1 or less, more preferably between 1.05 and 1.19, most preferably between 1.05 and 1.1.

[0012] The fluidizing bed comprising an oxygen carrying bed material described below, preferably ilmenite, is a means for aiding the combustion of the solid fuel. This is in contrast to fluidized bed reactors wherein the bed material is treated or otherwise manipulated to modify this bed material and produce a desired modified material.

[0013] Fluidized bed boilers in the context of the invention are to be distinguished from laboratory-scale reactors. Laboratory-scale reactors have the main purpose of research, they do not have the main purpose of producing heat on a commercial scale. Typically, laboratory-scale reactors have a thermal output of less than 1 MW, if any. Such laboratory-scale reactors are not to be understood as fluidized bed boilers in the sense of the present invention.

[0014] The fluidized bed comprises oxygen carrying materials containing iron and are designated as iron containing materials in the context of the present invention. Preferred iron containing materials are ilmenite, LD slag and Sibelco Calcine. Definitions of the material designations are given below.

[0015] Ilmenite is a mineral which consists mainly of different iron-titanium-, iron- and titanium oxides. In the context of this document, the term ilmenite refers to the bulk bed material, as opposed to the mineral phase FeTiO3, which is expected to change during operation.

[0016] Ilmenite can be repeatedly oxidized and reduced and has been used as a redox material in chemical looping combustion (CLC). From the prior art it is known to replace a fraction of the silica sand bed material with ilmenite particles in the CFB process (H. Thunman et al., Fuel 113 (2013) 300-309). Due to the reducing/oxidizing feature of ilmenite, the material can be used as oxygen carrier in fluidized bed combustion. With ilmenite as bed material, the combustion process can be carried out at lower air-to-fuel ratios with the bed comprising ilmenite particles as compared with non-active bed materials, e.g., 100 wt.-% of silica sand or fuel ash particles. The ilmenite particles used in the invention can for example be ilmenite sand or crushed rock ilmenite. Sand ilmenite is mined in a sand-like form, and it is found relatively close to the surface. In contrary, rock ilmenite is mined from deeper rock formations.

[0017] After having experienced an initial activation phase, ilmenite particles undergo chemical aging as they are subjected to repeated redox-conditions during combustion in fluidized bed boilers. Additionally, the physical interactions with the boiler structures and other fluidized particles induce mechanical wear on the ilmenite particles.

[0018] LD slag is an industrial by-product from steel production: During the basic oxygen-blown converter process (aka Linz-Donawitz process), carbon-rich, molten pig iron is converted into steel, and a slag is formed. This slag is referred to as LD slag.

[0019] Sibelco Calcine is an enriched, heat treated manganese ore that is traded by SCR-Sibelco N.V. of Belgium. To be used in a fluidized-bed process, the material is crushed and sieved.

[0020] In the claimed method, the first step is measuring the magnetic susceptibility of a particulate ash stream from an ash outlet, preferably a bottom ash outlet, of the boiler. Measuring magnetic susceptibility is a well-known method and described further in the examples section below.

[0021] The next step is magnetic separation of this ash stream into a fraction that contains mostly material that is attracted by a magnet, i.e. magnetizable, and one that contains particles that are mostly not attracted by a magnet, i.e. non-magnetizable.

[0022] Preferably the magnetic separator comprises a rare earth roll (RER) or rare earth drum (RED) magnet. Corresponding magnetic separators are known in the art per se and are e.g. available from Eriez Manufacturing Co. (www.eriez.com). Rare earth roll magnetic separators are high intensity, high gradient, permanent magnetic separators for the separation of magnetizable and weakly-magnetizable iron particles from dry products. The bottom ash stream is transported on a belt which runs around a roll or drum comprising rare earth permanent magnets. While being transported around the roll ilmenite remains attracted to the belt whereas the non-magnetizable particle fraction remains unaffected. A mechanical, spatial separator separates these two particle fractions.

[0023] Subsequently, the magnetic susceptibility of the magnetizable fraction obtained after magnetic separation is measured.

[0024] Using the measured weight of the samples used for measuring magnetic susceptibility, the weight specific magnetic susceptibility of both the particulate ash stream and the magnetizable fraction are calculated.

[0025] Next, the normalized magnetic susceptibility is calculated by dividing the weight specific magnetic susceptibility of the particulate ash stream through the weight specific magnetic susceptibility of the magnetizable fraction.

[0026] This normalized magnetic susceptibility could be shown to correlate well with the fraction by weight of iron containing materials in the ash stream (see examples below).

[0027] In an alternative embodiment of the invention (claim 2) both the magnetic susceptibility and density of

- a particulate ash stream from an ash outlet of the boiler, and
- the magnetic fraction obtained after magnetic separation

are measured and the content f_{active} of iron containing materials in the particulate ash stream is calculated using the formula

$$f_{\text{active}} = k \cdot \frac{\chi_{\text{blend}}}{\chi_{\text{magnet}}} \cdot \frac{\rho_{\text{magnet}}}{\rho_{\text{blend}}}$$

with k being a proportionality constant.

[0028] The measurement of density is well known to the skilled person and sensors for inline and at-line measurements of density are e.g. available from TEWS Elektronik GmbH & Co. KG, Hamburg.

[0029] Both magnetic susceptibility and density of the ash stream can be measured inline and continuously so that a continuous monitoring of the iron material content in the ash stream is possible.

[0030] Preferably, the method further comprises a pre-classification step, in which the particles in the ash stream are pre-classified before step a.; wherein preferably the pre-classification comprises mechanical particle classification and/or fluid driven particle classification, more preferably sieving and/or gas driven particle classification. In fluid driven particle separation, the particles are separated based on their fluid-dynamic behavior. A particularly preferred variant for fluid driven separation comprises gas driven particle separation.

[0031] Preferably, the mechanical particle classification comprises sieving with a mesh size from 500 to 1,000 μm, preferably 500 to 800 μm, further preferred 650 to 750 μm.

[0032] The invention has found out that the majority of ilmenite (or other iron containing materials) in the bottom ash comprises a particle size of 700 μm or lower so that the mechanical classifier provides a fine particle size fraction having a more homogenous size distribution while still comprising the majority of the ilmenite particles. The magnetic separation in the subsequent step can be carried out more efficiently.

[0033] The initial mechanical classification in particular serves three purposes. First, it contributes to protect the magnetic separator from large magnetizable objects such as nails which could otherwise damage the magnetic separator or its parts. Second, it reduces the load on the magnetic separator by reducing the mass flow. Third, itsorts out larger particles which are less likely to be fluidized and circulated and, therefore, are less likely to contribute to the combustion above the bottom bed in the boiler..

[0034] In a particularly preferred embodiment, the mechanical classifier comprises a rotary sieve which has been found effective to pre-classify the bottom ash to remove coarse particles.

[0035] In one embodiment of the invention the mechanical classifier further comprises a primary sieve prior to the mechanical classifier having the mesh size as defined above (e.g. the rotary sieve) to separate coarse particles having a particle size of 2 cm or greater, e.g. coarse particle agglomerates of golf ball size.

[0036] The method may comprise a step for separating elongate ferromagnetic objects from the ash stream prior to the magnetic separator. The mechanical classifier can comprise a slot mesh to remove pieces of metal wire or nails that tend to plug mesh holes and also affect the magnetic separation in the subsequent step.

[0037] Preferably the magnetic separator comprises a field intensity of 2,000 Gauss or more, preferably 4,500 Gauss or more on the surface of the transport means of the bed material. This has been found effective to separate ilmenite from ash and other non-magnetizable particles in the particle stream.

[0038] It is also possible to utilize the magnetic separator having the field intensity or field strength as indicated above without prior mechanical classification or mechanical sieving. This may be beneficial for fluidized bed boilers, where fuels with a low ash content are used, i.e., wood chips or low-ash forest residues as fuels as opposed to fuel mixes that contain industrial waste or waste wood.

[0039] In one embodiment the magnetic field is axial, i.e. parallel to the rotational axis of the drum or roll. An axial magnetic field with the magnets having a fixed direction causes strongly magnetizable material to tumble as it passes from north to south poles, releasing any entrapped non-magnetizable materials.

[0040] In another embodiment, the magnetic field is radial, i.e. comprising radial orientation relative to the rotational axis. Generally, a radial orientation has the advantage of providing a higher recovery rate of all weakly magnetizable material which can come at the cost of less purity due to entrapped non-magnetizable material.

[0041] It is also possible to use a two-stage magnetic separation with a first step using axial orientation thereby helping to release entrapped non-magnetizable material and the second step using radial orientation to increase the recovery rate.

[0042] Preferably the measurement of magnetic susceptibility is carried out at a defined temperature, preferably a defined temperature between 20 and 40°C or 20 and 30°C. The dependence of magnetic susceptibility on temperature differs for different iron oxides, titanium oxides and iron-titanium oxides, e.g. Fe_2O_3, Fe_3O_4, TiO_2, $FeTiO_3$ or Fe_2TiO_5. Further, the different oxides may occur in different crystal structures, e.g. α-Fe_2O_3 or γ-Fe_2O_3, which also has an impact on magnetic properties and their temperature dependency.

[0043] Another aspect of the invention is a system for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler, characterized in that it comprises:

a. means for measuring magnetic susceptibility of a particulate ash stream from an ash outlet of the boiler;
b. means for magnetic separation of this ash stream into a magnetizable and non-magnetizable fraction;
c. means for measuring magnetic susceptibility of the magnetizable fraction.

[0044] This system can be utilized in a method as previously described.

[0045] For practicing the method according to claim 2, the system preferably further comprises means for measuring the density of the particulate ash stream from an ash outlet of the boiler; and means for measuring the density of the magnetizable fraction.

[0046] Another aspect of the invention is a fluidized bed boiler, characterized that it comprises a system as previously described.

[0047] The boiler preferably is a circulating fluidized bed boiler (CFB) or a bubbling fluidized bed boiler (BFB).

[0048] Further preferred, it comprises a nominal thermal power of 1 MW or more.

[0049] The following examples illustrate the invention. The attached drawings show:

Fig.1: Schematically the principle of magnetic separation with the rare earth roll (RER) belt magnet;

Fig. 2: The schematic setup of an online monitoring system for a fluidized bed boiler;

Fig. 3: Measured magnetizable fraction in sieved bottom ash samples as well as consumption of fresh bed material (Improbed™ 0-15.9 d, silica sand 15.9-29 d) during Improbed™ test campaign at Örtoftaverket. Bed material consumption is shown as metric tons per day.

Fig. 4: Measured magnetizable fraction in sieved bottom ash samples as well as consumption of fresh bed material (only consumption of Improbed™ shown) during Improbed™ test campaign at Vattumannen CFB. Bed material consumption is shown as percentage points of silo level per day. A boiler trip occurred between days 1.9 and 3.4.

Fig. 5: Measured magnetizable fraction in sieved bottom ash samples as well as consumption of fresh bed material (only consumption of Improbed™ shown) during Improbed™ test campaign at Åbyverket P5. Bed material consumption is shown as cubic meters per day.

Fig.6: Measured magnetizable fraction in sieved bottom ash during three separate Improbed™ test campaigns at Handeloverket P14.

Fig. 7: Measured magnetizable fraction in sieved bed ash samples during different test campaigns at Chalmers boiler. Note the different ranges on x- and y-axes. With sand ilmenite as bed material, two separate campaigns were carried out at the Chalmers boiler, whereas only one campaign was carried out with each of the other materials.

Fig. 8: Normalized magnetic susceptibility, $\bar{\chi}$, of bottom ash samples at different fluidized-bed combustors and different active bed materials as a function of measured magnetizable fraction. A simple linear regression (SLR) model (R^2=0.931) through the origin is shown with 90 % prediction bounds.

Methods section

[0050] This describes the methods used in the subsequent examples.

Measurement of magnetic susceptibility

[0051] The equipment used to determine magnetic susceptibility was from Bartington Instruments Ltd and consisted of an MS3 Magnetic Susceptibility Meter and an MS2B Dual Frequency Sensor, which were operated via the software Bartsoft. The magnetic susceptibility of an ash sample was determined for a fixed sample volume for each test series, 10-12 ml, by means of a low-frequency field measurement, 465 Hz. To improve reproducibility of the measurements, a powder sample is poured into a sample container until the powder overflows, whereupon excess material is scraped off with a spatula so that a flat surface is created on top of the container. In that way, differences in packing between the different samples are reduced. The sample containers used consisted of polypropylene, PP, or polystyrene, PS, and the magnetic susceptibility of an empty container was usually two to four orders of magnitude lower than that of the ash sample. Hence, the resulting error of the measurement of magnetic susceptibility is 1 % or less.

Weight specific magnetic susceptibility

[0052] In addition to magnetic susceptibility, χ, the net weight of the sample (i.e., not including the weight of the container), m, was determined, and a weight-specific magnetic susceptibility, χ_w, was calculated according to Equation (1), which is also referred to as "measured magnetic susceptibility".

$$\chi_w = \frac{\chi}{m} \qquad (1)$$

[0053] To be able to compare measurements at different boilers and different iron-containing materials, the magnetic susceptibility was normalized, $\bar{\chi}$, by dividing the blend samples weight-specific magnetic susceptibility, $\chi_{w,\mathrm{blend}}$, with the weight-specific magnetic susceptibility of the magnetizable fraction of the sample, $\chi_{w,\mathrm{magnet}}$, see Equation (2), which is also referred to as "normalized magnetic susceptibility".

$$\bar{\chi} = \frac{\chi_{w,\mathrm{blend}}}{\chi_{w,\mathrm{magnet}}} = \frac{\chi_{\mathrm{blend}}}{\chi_{\mathrm{magnet}}} \cdot \frac{m_{\mathrm{magnet}}}{m_{\mathrm{blend}}} \qquad (2)$$

Density measurement

[0054] Sensors for inline and at-line measurements of density are e.g. available from TEWS Elektronik GmbH & Co. KG, Hamburg.

Correlation of magnetic susceptibility and density

[0055] Equation (3) shows the correlation, where the weight fraction of active material in the ash stream is proportional to the product of the ratios for magnetic susceptibility, χ, and bulk density, ρ, for the blend sample and the magnetizable fraction. The corresponding equation that can be used in an online measurement system is presented in Equation (4), where a proportionality constant k is used.

$$f_{\mathrm{active}}\ [\mathrm{wt\%}] \propto \frac{\chi_{\mathrm{blend}}}{\chi_{\mathrm{magnet}}} \cdot \frac{\rho_{\mathrm{magnet}}}{\rho_{\mathrm{blend}}} \qquad (3)$$

$$f_{\text{active}} = k \cdot \frac{\chi_{\text{blend}}}{\chi_{\text{magnet}}} \cdot \frac{\rho_{\text{magnet}}}{\rho_{\text{blend}}} \quad (4)$$

Magnetic separation

[0056] Fig. 1 illustrates the working principle of a rare earth roll belt magnet.

[0057] The fine fraction 1 of the ash, i.e. blend fraction, is fed and distributed onto the belt 2 of a rare earth roll belt magnet 3 and separated into magnetizable and non-magnetizable fractions 4, 5, i.e., magnet-accept and magnet-reject fractions. Here, the magnetizable content is defined as the magnetizable fine fraction 5 of the blend fine fraction 1 by weight. The triangle 6 below the permanent magnet 3 indicates the position of the separation line between accept- and reject fractions, which is offset by about one roller radius from the roller axle.

Examples

Example 1: Online monitoring of a fluidized bed boiler

[0058] Fig. 2 shows the schematic setup of an online monitoring system for a fluidized bed boiler.

[0059] The layout of the online measurement system consists of different measurements that are performed at two sampling points, see Fig. 2. Sieving of the bottom ash (mesh size 710 μm) is carried out as handling of more homogeneous ash becomes easier, and, additionally, coarse objects, like stones, agglomerates or scrap metal (depending on the type of fuel used) might skew the result.

[0060] At each sampling point, three types of measurements are made: magnetic susceptibility, temperature, and bulk density. The temperature at which magnetic susceptibility is determined should be constant for both samples at the two measuring points and samples over time.

[0061] At sampling point 1, a sieved ash fraction that contains a blend of magnetizable and non-magnetizable material, i.e., iron-containing and non-iron-containing bed material, or active and non-active bed material is measured. The ratio of magnetizable and non-magnetizable bed material at this sampling point is representative for the ratio that is fluidized in the furnace.

[0062] At sampling point 2, the magnetizable fraction of the ash stream that passed the magnetic separation is measured.

[0063] This online monitoring allows to achieve a desired concentration of active bed material in the furnace, while keeping the make-up feed of fresh, active bed material as low as possible. The active fraction is separated from the non-active fraction and the active fraction is returned to the combustion process while the non-active fraction is removed.

Test runs in commercial fluidized bed boilers

[0064] The inventive method was tested in a number of commercial fluidized bed boilers. All test runs were carried out according to the method disclosed in claim 1 and the corresponding description.

[0065] In all test runs, bottom ash samples were taken out and sieved using a mesh size of 710 μm. The fine fraction (sieve accept fraction) was used to determine magnetic susceptibility and weight specific magnetic susceptibility as described above in the method's section.

[0066] Magnetic separation was carried out as described in the method's section. The magnetizable fraction (magnet accept fraction) was used to determine magnetic susceptibility and weight specific magnetic susceptibility as described above in the method's section.

[0067] The percentage of the magnetizable fraction in the fine fraction (sieve accept fraction) was also determined in a separate weighting step.

[0068] The percentage (weight percent) of the magnetizable fraction to that of the fine fraction was correlated with the determined normalized magnetic susceptibility as explained below.

[0069] The company Improbed AB, trades a bed material with the same name, Improbed™. The material is derived from mineral ilmenite and consists of an iron-titanium oxide. This material was used in the test runs.

Example 2: Ortoftaverket, Ortofta

[0070] The circulating fluidized-bed boiler Örtoftaverket is located in Skane county, and it is operated by Kraftringen Energi, a municipally-owned utility company. The boiler was designed and constructed by Amec Foster Wheeler (now: SHI Foster Wheeler) and has been in operation since 2014. The boiler was designed for 110 MW steam power but has been upgraded to 115 MW by Kraftringen Energi. It is operated as a combined heat and power baseload plant, usually between October and April. At the time of the test campaign, the fuel mix consisted mainly of waste wood but also contained bark, forest residues and stem wood. There are about 60 t of bed material in the boiler. The cross section of the furnace is 2.2 m x 8.8 m at the level of the fluidizations nozzles and expands to 5.5 m x 8.8 m higher up. The height of the furnace from fluidization grid to roof is 28.4 m. The boiler has two cyclones and two loop seals, with submerged steam super-heaters. A flue gas condenser is used to recover additional heat from the flue gases after the convection heat exchangers, i.e., super heaters, economizers and air preheaters.

[0071] The transition from silica sand to Improbed™ operation was done without stopping the boiler. Prior to Improbed™ operation, the bed pressure drop was reduced, and the sand silo was emptied. The silo was then filled with Improbed™ bed material, which was fed to the boiler; firstly, to bring the bed pressure drop back to normal levels and secondly, as continuous make-up feed. This resulted in initial fast increase in Improbed™ content in the bed material. Figure 3 shows the development of the content of active bed material, measured as magnetizable fraction, as well as the bed-material consumption, i.e., make-up feed, over the course of the test campaign.

Example 3: Vattumannen CFB, Eskilstuna

[0072] The circulating fluidized-bed boiler at the Vattumannen plant is located in Sodermanland County, and it is operated by ESEM, a municipally-owned utility company. The boiler was designed and constructed by Götaverken and has been in operation since 1986. The boiler has been converted from coal with co-fired biomass to 100 % biomass and its power output has been increased. By the time of the test campaign the boiler had a nominal steam power of about 66 MW. It is operated after heat demand, usually between September and Mars. At the time of the test campaign, the fuel mix consisted mainly of forest residues but also contained bark and stemwood. There are about 25 t of bed material in the boiler. The cross section of the furnace is 3.5 m x 5.75 m, and the height of the furnace from fluidization grid to roof is about 20 m. The boiler has two cyclones and two loop seals, and a flue gas condenser is used to recover additional heat from the flue gases after the convection heat exchangers, i.e., economizers.

[0073] The transition from silica sand to Improbed™ operation was done without stopping the boiler, similar to the procedure described for the test campaign at Örtoftaverket above. Figure 4 shows the development of the content of active bed material, measured as magnetizable fraction, as well as the bed-material consumption, i.e., make-up feed, over the course of the test campaign.

Example 4: Åbyverket P5, Orebro

[0074] The circulating fluidized-bed boiler P5 at the Åbyverket plant is located in Örebro County, and it is operated by E.ON, an international utility company. The boiler was designed and constructed by Götaverken and has been in operation since 1989. The boiler has been converted from coal to biomass, and by the time of the test campaign it had a nominal steam power of about 170 MW. It is operated after heat demand, usually between November and April, but also produces electricity. At the time of the test campaign, the fuel mix consisted of forest residues, peat, creosote, stemwood and bark. There are about 30-40 t of bed material in the boiler. The cross section of the furnace is 4.65 m x 12.0 m, and the height of the furnace from fluidization grid to roof is about 40 m. The boiler has four cyclones and four loop seals, and a flue gas condenser is used to recover additional heat from the flue gases after the convection heat exchangers, i.e., superheaters, economizers and air preheaters.

[0075] The transition from silica sand to Improbed™ operation was done without stopping the boiler, similar to the procedure described for the test campaign at Örtoftaverket above. Figure 5 shows the development of the content of active bed material, measured as magnetizable fraction, as well as the bed-material consumption, i.e., make-up feed, over the course of the test campaign.

Example 5: Händelöverket P14, Norrkoping

[0076] The boiler P14 at the plant Handeloverket is located in Ostergotland County. It is operated by E.ON, an international utility company. Boiler P14 was constructed in 2002 by Kvaerner. It is a circulating fluidized-bed boiler with a nominal thermal power of 75 MW, usually fired with a mix of household waste and light industrial waste. It is operated all year around, and part of the produced steam is usually used to produce electricity. The cross section of the furnace is 2.5 m x 8.4 m at the level of the fluidizations nozzles and expands to 3.9 m x 8.4 m higher up. The height of the furnace from fluidization grid to roof is about 23 m. The boiler has two cyclones and two loop seals with in-bed superheaters. After the cyclones, the flue gases pass an empty pass, convective heat exchangers and several flue gas cleaning units before they are released to the atmosphere through the stack.

[0077] The transition from operation with silica sand to Improbed™ operation was done without stopping the boiler. At boiler P14, there is a dedicated silo and feeding system for fresh Improbed™-material. During an Improbed™ test campaign, Improbed™-material was fed instead of silica sand. Several test campaigns have been carried out since 2014, and Fig. 6 shows for the three most recent ones the development of the content of active bed material, measured as magnetizable fraction over the course of each campaign.

Example 6: Chalmers CFB (CB), Gothenburg

[0078] The CFB boiler at Chalmers University of Technology has a maximum thermal power of 12 MW. It is usually fired with wood chips, which is a rather clean fuel with a low ash content. The major part of the fuel ash leaves the boiler as fly ash, and only small amounts of the fuel ash are retained in the bed.

[0079] The tests carried out at the research boiler at Chalmers University of Technology differ somewhat from the tests described above. The Chalmers boiler is smaller, and it contains significantly less bed material. This allows for more flexibility during operation with respect to bed material changes. Prior to a test, the boiler was stopped, emptied and filled with a certain fraction of active bed material. In this way, test operation was started with a bed that already contained a certain fraction of the active bed material. During test operation more of the active bed material or alternatively inert silica sand was added to regulate the active content in the bed. Fig. 7 shows progresses of magnetic content over the course of the different test campaigns with different active bed materials, i.e., rock ilmenite, sand ilmenite, LD slag and Sibelco Calcine. Only with the sand ilmenite there were two test campaigns conducted, otherwise one.

Results of the test runs

[0080] Fig. 8 shows normalized magnetic susceptibility, $\overline{\chi}$ (see equation (2) above), of different bottom ash samples at different fluidized-bed combustors and different active bed materials against the magnetizable fraction determined by magnetic separation. Also displayed in the figure is a simple linear regression model that was fitted to the data points and that was forced through the origin. Further displayed are 90 % prediction bounds. The coefficient of determination for the model is high and 0.931, which means that 93 % of the variation in the data can be explained by the regression model.

[0081] The model based on existing data can be used to predict the magnetizable fraction of a new sample if the normalized magnetic susceptibility is known, as would be the case in an online monitoring system. For the chosen confidence interval for predictions of 90 %, this means in practice that the uncertainty of predictions is ±10.8 wt%. The boundaries of the prediction interval are not linear, and hence there is a variation of the uncertainty along the interval of 0 wt% to 100 wt% of magnetizable fraction. Due to the relatively even distribution of data points along the interval, the variation of the uncertainty is very small, i.e., ≤0.07 wt%, and it bears no relevance in practice. Predictions of magnetizable fractions based on normalized magnetic susceptibility can be done according to Equation (5).

$$f_{\text{magnet}}\,[\text{wt\%}]\,\left(90\ \%\ \text{confidence}\right) = 89.85 \cdot \frac{\chi_{w,\text{blend}}}{\chi_{w,\text{magnet}}} \pm 10.8 \qquad (5)$$

The uncertainty of predictions may be further decreased if more data is added to the existing model or if a new model is established based on data for a specific combustion plant with a specific bed material. If in this way a new simple linear regression model is established that has a higher coefficient of determination than the model established here, i.e., R^2>0.931, the uncertainty will be lower.

Claims

1. A method for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler, **characterized by** the steps of:

   a. measuring magnetic susceptibility of a particulate ash stream from an ash outlet of the boiler;
   b. magnetic separation of this ash stream into a magnetizable and non-magnetizable fraction;
   c. measuring magnetic susceptibility of the magnetic fraction;
   d. calculating the weight specific magnetic susceptibility of the particulate ash stream and the magnetizable fraction;
   e. calculating the normalized magnetic susceptibility by dividing the weight specific magnetic susceptibility of the particulate ash stream through the weight specific magnetic susceptibility of the magnetizable fraction;
   f. using this normalized magnetic susceptibility as an indicator of the content of iron containing materials in the ash stream.

2. A method for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler, **characterized by** the steps of:

a. measuring magnetic susceptibility χ_{blend} and density ρ_{blend} of a particulate ash stream from an ash outlet of the boiler;
b. magnetic separation of this ash stream into a magnetizable and non-magnetizable fraction
c. measuring magnetic susceptibility χ_{magnet} and density ρ_{magnet} of the magnetizable fraction;
d. calculating the content f_{active} of iron containing materials in the particulate ash stream using the formula

$$f_{\text{active}} = k \cdot \frac{\chi_{\text{blend}}}{\chi_{\text{magnet}}} \cdot \frac{\rho_{\text{magnet}}}{\rho_{\text{blend}}}$$

with k being a proportionality constant.

3. The method of claims 1 or 2, **characterized in that** it further comprises a pre-classification step, in which the particles in the ash stream are pre-classified before step a.; wherein preferably the pre-classification comprises mechanical particle classification and/or fluid driven particle classification, more preferably sieving and/or gas driven particle classification; and wherein the fine fraction is fed into step a.

4. The method of claim 3, **characterized in that** the mechanical particle classification comprises sieving with a mesh size from 500 to 1,000 μm, preferably 500 to 800 μm, further preferred 650 to 750 μm; wherein preferably a rotary sieve is used.

5. The method of any one of claims 1 to 4, **characterized in that** the separation includes a step of using a magnetic separator comprising a field strength of 2,000 Gauss or more, preferably 4,500 Gauss or more.

6. The method of any of the claims 1 to 5, **characterized in that** the magnetic separator (12) comprises a rare earth roll (RER) or rare earth drum (RED) magnet.

7. The method of any one of claims 1 to 6, **characterized in that** the magnetic field is axial or radial.

8. The method of any one of claims 1 to 7, **characterized in that** the iron containing material comprises ilmenite, preferably selected from the group consisting of rock ilmenite and sand ilmenite.

9. The method of any one of claims 1 to 8, **characterized in that** the measurement of magnetic susceptibility is carried out at a defined temperature, preferably a defined temperature between 20 and 40°C.

10. A system for monitoring the content of iron containing materials in a particulate ash stream of a fluidized bed boiler, **characterized in that** it comprises:

a. means for measuring magnetic susceptibility of a particulate ash stream from an ash outlet of the boiler;
b. means for magnetic separation of this ash stream into a magnetizable and non-magnetizable fraction;
c. means for measuring magnetic susceptibility of the magnetizable fraction.

11. The system of claim 10, **characterized in that** it further comprises means for measuring the density of the particulate ash stream from an ash outlet of the boiler; and means for measuring the density of the magnetizable fraction.

12. A fluidized bed boiler, characterized that it comprises a system according to claim 10 or 11.

13. The boiler of claim 11, **characterized in that** it is a circulating fluidized bed boiler (CFB) or a bubbling fluidized bed boiler (BFB).

14. The boiler of claim 12 or 13, characterized that it comprises a nominal thermal power of 1 MW or more.

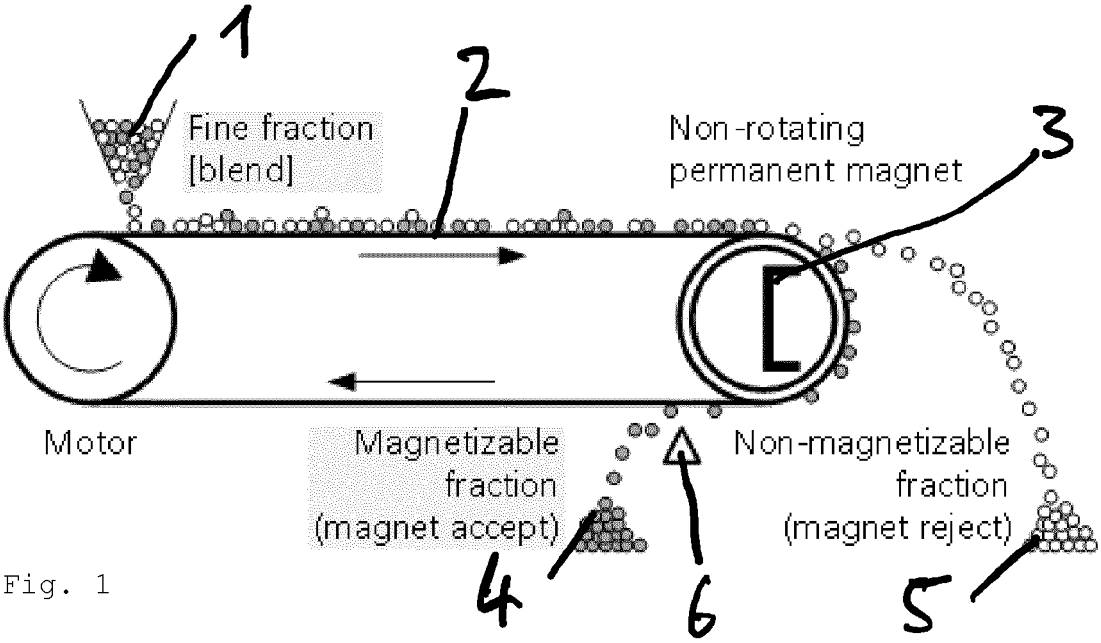

Fig. 1

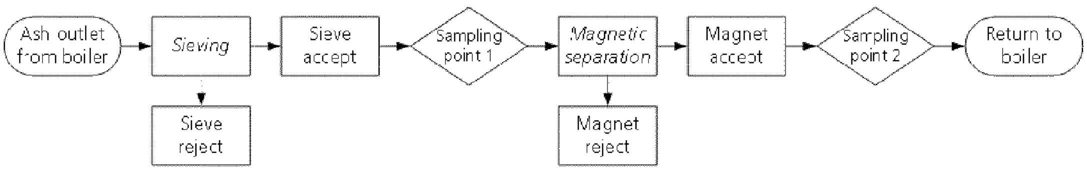

Fig. 2

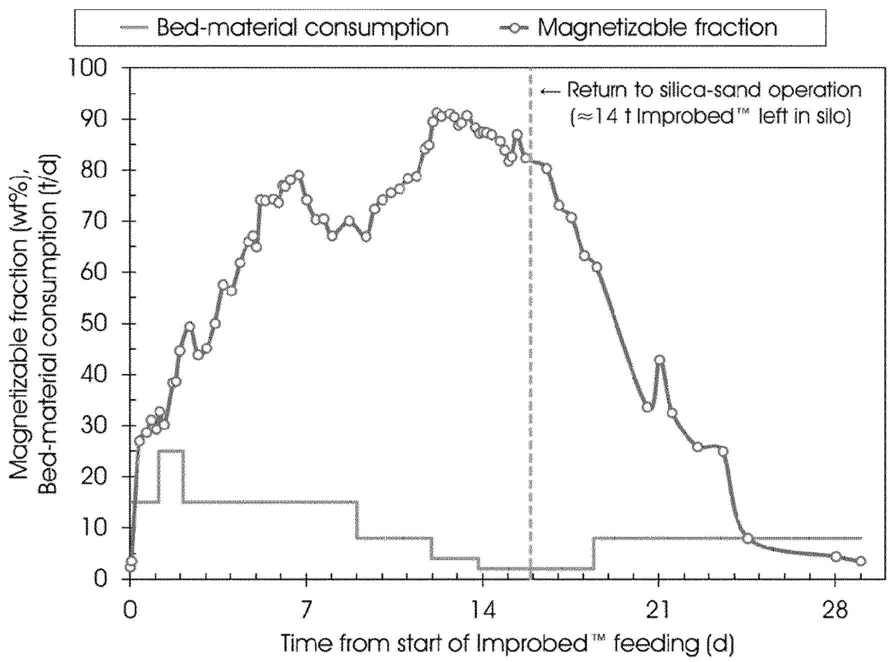

Fig. 3

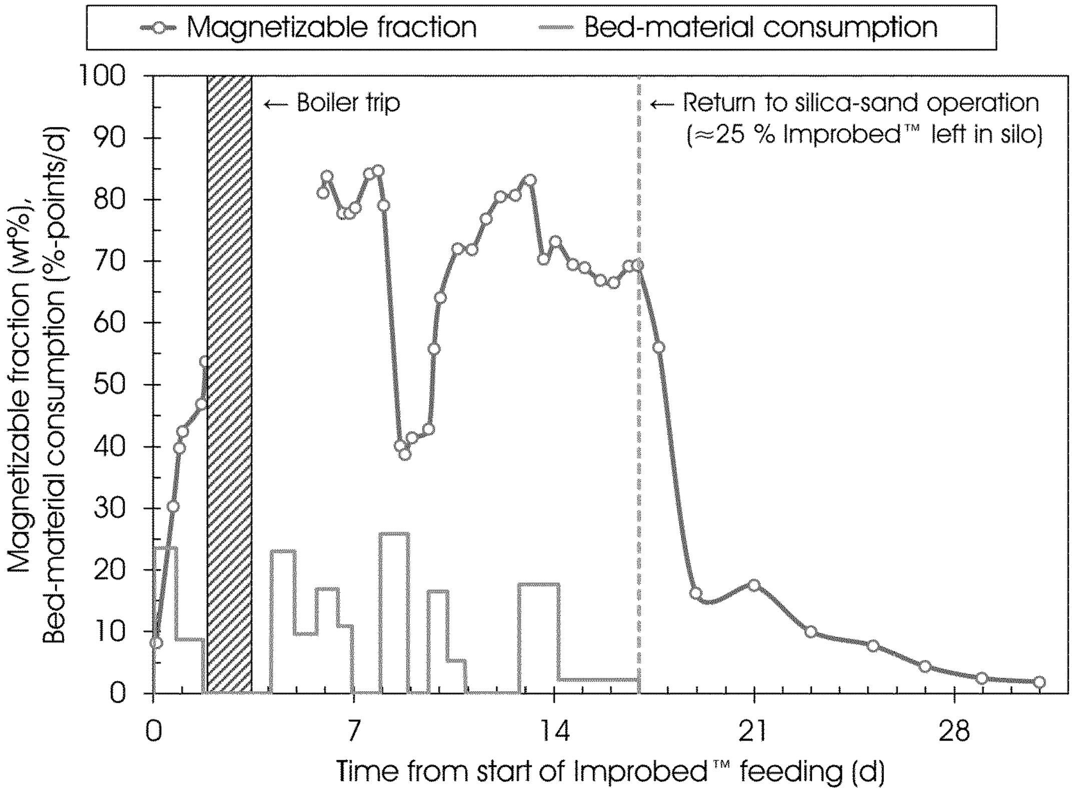
Magnetizable fraction
Bed-material consumption
← Boiler trip
← Return to silica-sand operation
(≈25 % Improbed™ left in silo)
Magnetizable fraction (wt%),
Bed-material consumption (%-points/d)
100
90
80
70
60
50
40
30
20
10
0
0
7
14
21
28
Time from start of Improbed™ feeding (d)

Fig. 4

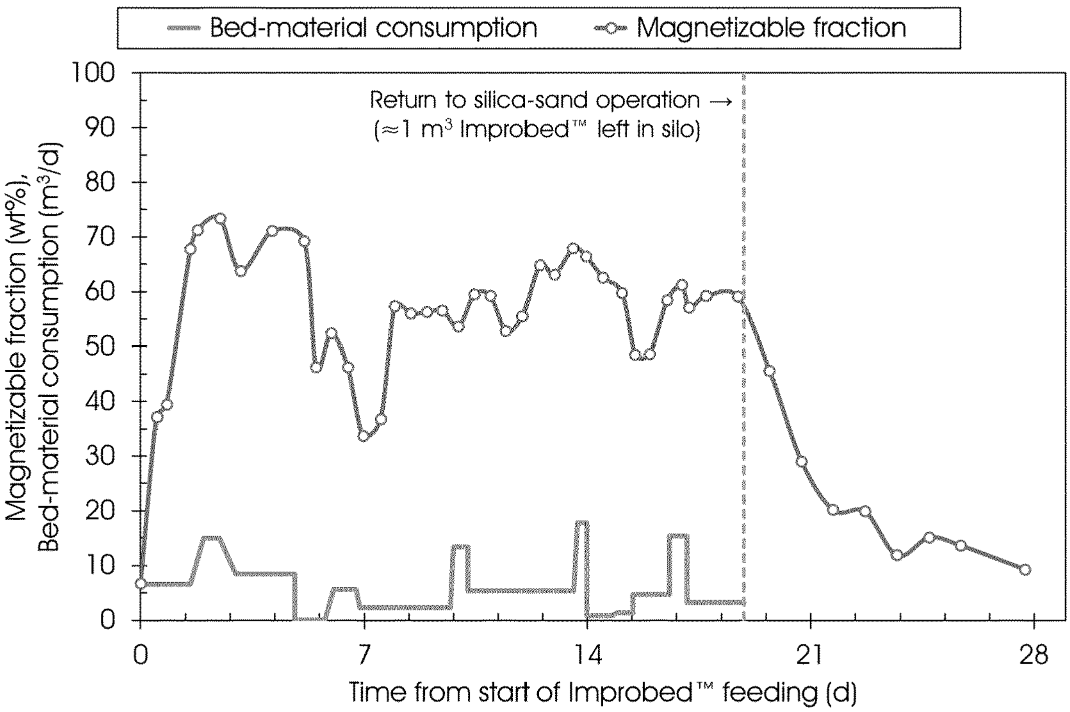
Bed-material consumption
Magnetizable fraction
Return to silica-sand operation →
(≈1 m³ Improbed™ left in silo)
Magnetizable fraction (wt%),
Bed-material consumption (m³/d)
100
90
80
70
60
50
40
30
20
10
0
0
7
14
21
28
Time from start of Improbed™ feeding (d)

Fig. 5

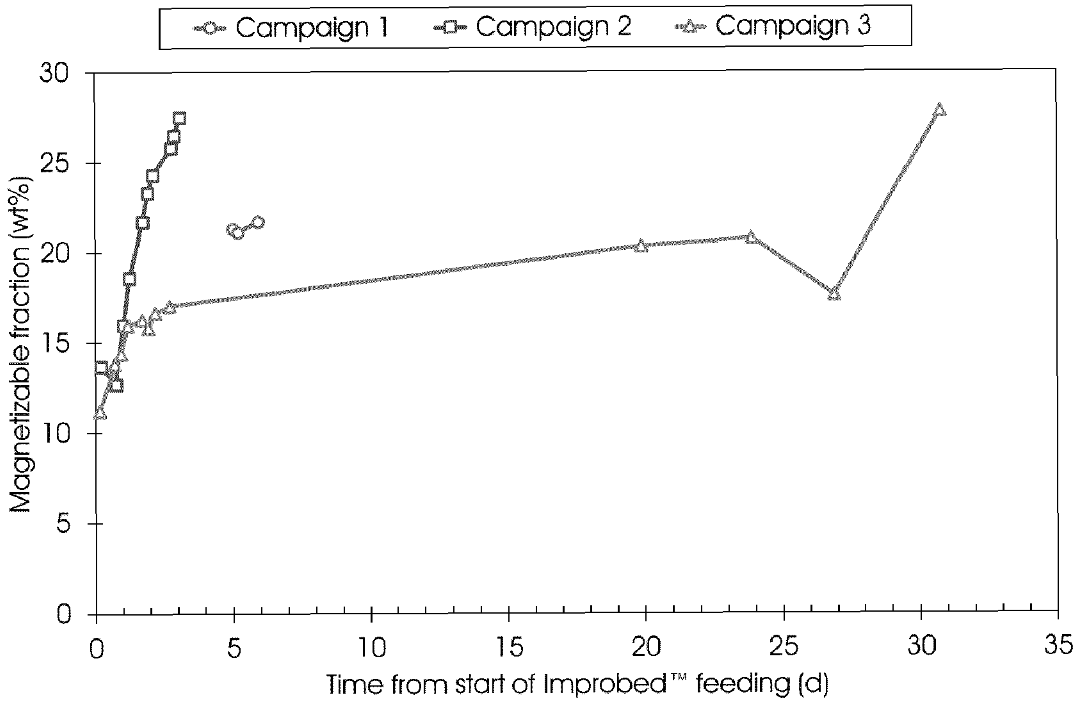
Campaign 1
Campaign 2
Campaign 3
Magnetizable fraction (wt%)
Time from start of Improbed™ feeding (d)

Fig. 6

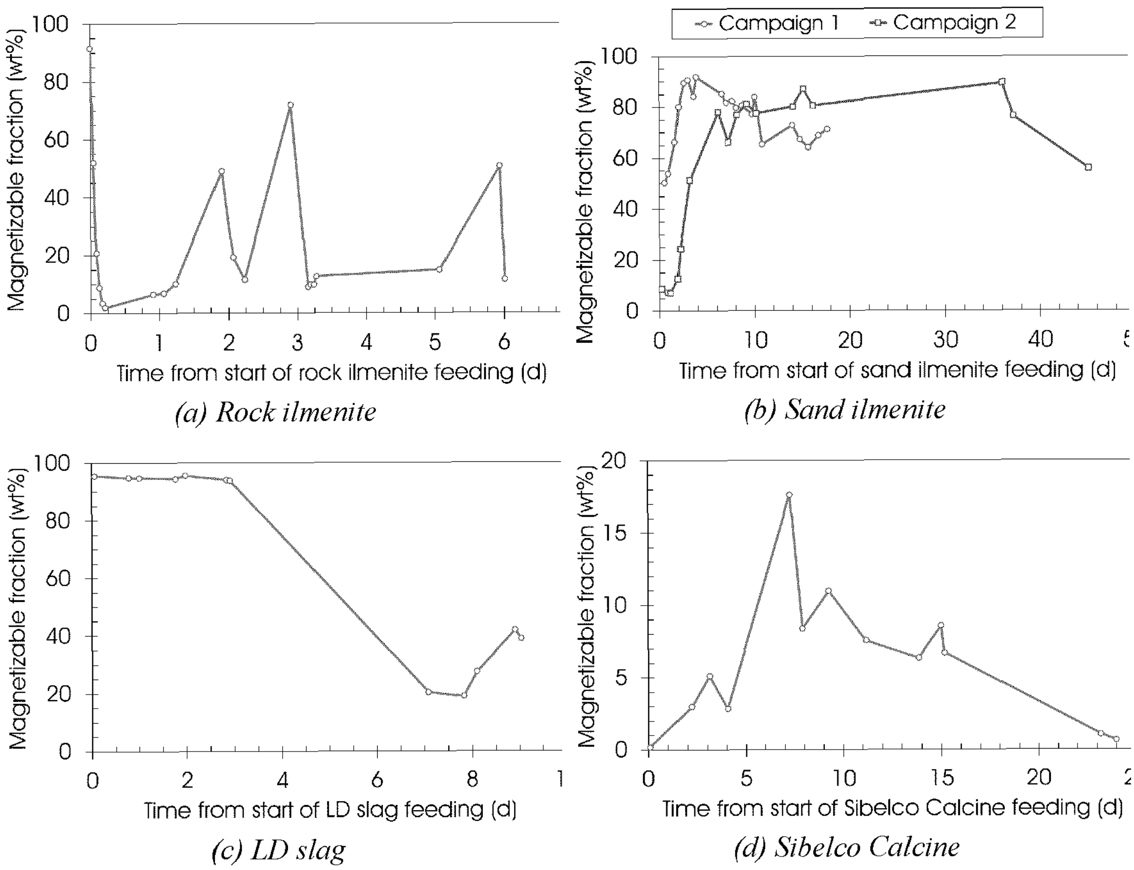
Magnetizable fraction (wt%)
Time from start of rock ilmenite feeding (d)
(a) Rock ilmenite
Campaign 1
Campaign 2
Time from start of sand ilmenite feeding (d)
(b) Sand ilmenite
Time from start of LD slag feeding (d)
(c) LD slag
Time from start of Sibelco Calcine feeding (d)
(d) Sibelco Calcine

Fig. 7

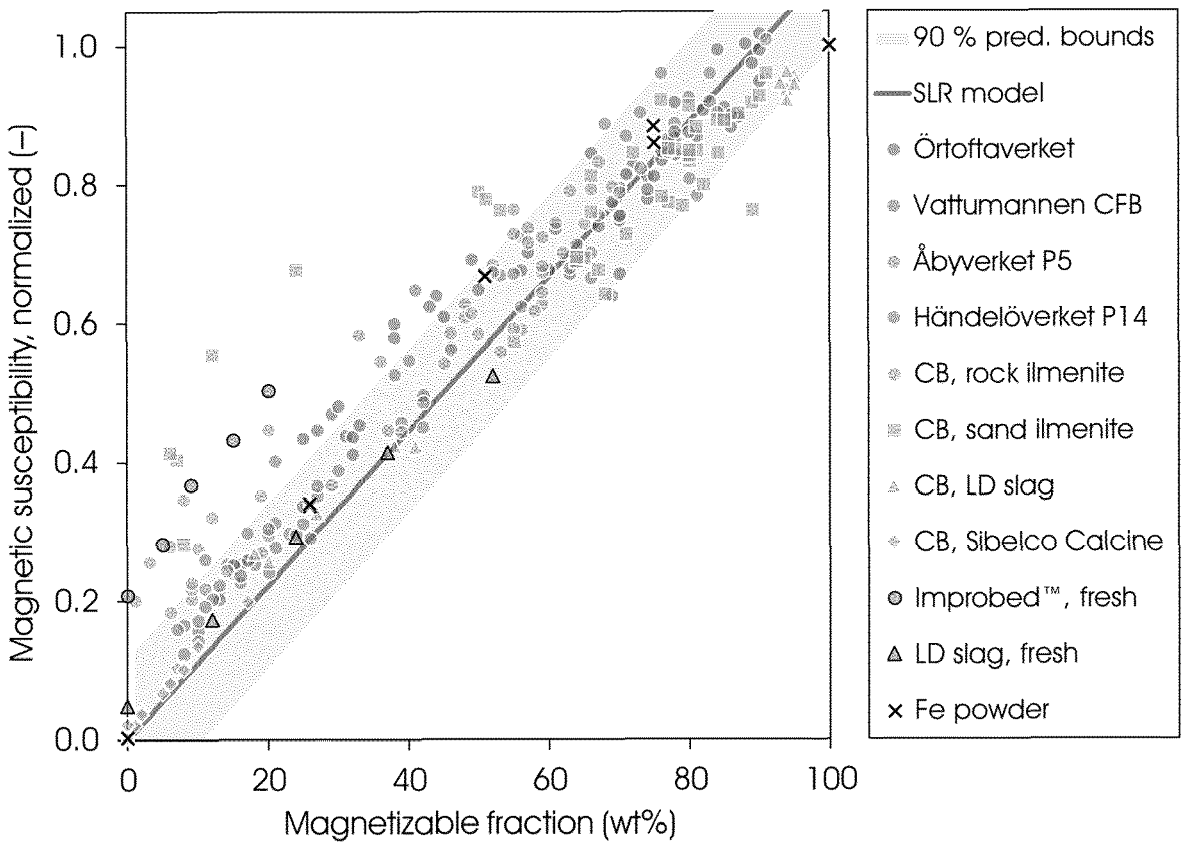
1.0
0.8
0.6
0.4
0.2
0.0
Magnetic susceptibility, normalized (–)
0
20
40
60
80
100
Magnetizable fraction (wt%)
90 % pred. bounds
SLR model
Örtoftaverket
Vattumannen CFB
Åbyverket P5
Händelöverket P14
CB, rock ilmenite
CB, sand ilmenite
CB, LD slag
CB, Sibelco Calcine
Improbed™, fresh
LD slag, fresh
Fe powder

Fig. 8

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EUROPEAN SEARCH REPORT

Application Number
EP 20 18 9964

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	CN 109 402 404 B (UNIV BEIJING SCIENCE & TECH) 12 May 2020 (2020-05-12) * claims 1, 2; figure 1 * -----	1,2	INV. F23J1/02 B03C1/02 F23C10/26
A	US 2019/330720 A1 (ALBRECHT EDWARD W [US] ET AL) 31 October 2019 (2019-10-31) * paragraphs [0135] - [0138] * * figures 1A, 1B * -----	1,2	
A	US 2019/256949 A1 (ALBRECHT EDWARD W [US] ET AL) 22 August 2019 (2019-08-22) * paragraphs [0074] - [0077] * * figures 1A, 1B * -----	1,2	

TECHNICAL FIELDS SEARCHED (IPC)

F23J
B03C

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	21 April 2021	Vogl, Paul

CATEGORY OF CITED DOCUMENTS

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EPO FORM 1503 03.82 (P04C01)

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21-04-2021

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		WO 2020222859 A1	05-11-2020
US 2019256949 A1	22-08-2019	NONE	

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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