(54) Title of the Invention: Soft sensor for online estimation of the steel bath temperature in an electric arc furnace (EAF)

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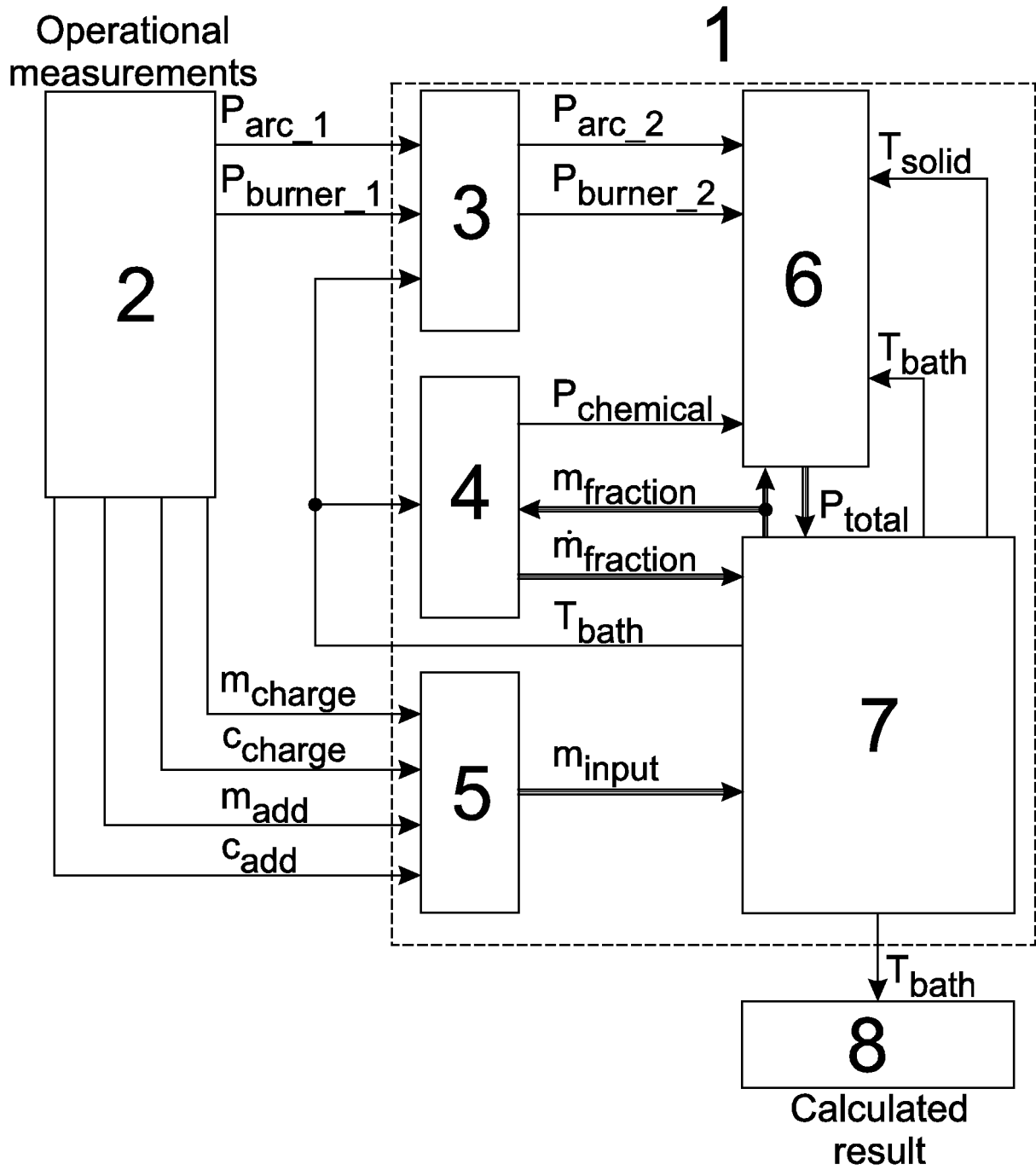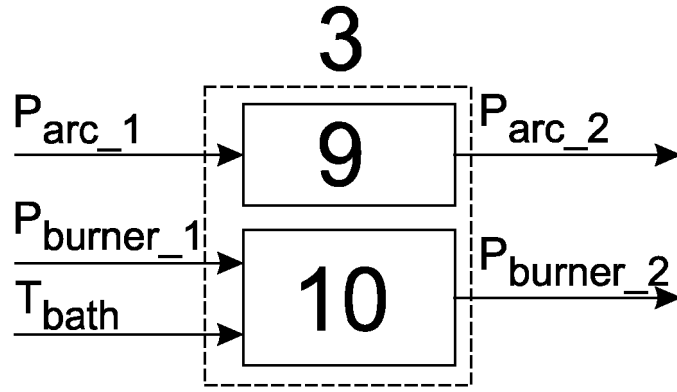
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DRAWINGS

Operational
measurements

1

P_{arc_1} → P_{arc_2} →

P_{burner_1} → P_{burner_2} →

T_{solid}

2

3

6

$P_{chemical}$ →

$m_{fraction}$ ←

T_{bath}

4

$\dot{m}_{fraction}$ →

P_{total}

T_{bath}

14 11 12

m_{charge}

c_{charge}

m_{add}

c_{add}

5

m_{input} →

7

T_{bath}

8

Calculated
result

Figure 1

3

P_{arc_1}

9

P_{arc_2}

P_{burner_1}

T_{bath}

10

P_{burner_2}

Figure 2

5

14 11 12

m_{charge}

c_{charge}

11

| Fe | Si | C | Mn | Cu | .... | Al |

$m_{elements}$

m_{add}

c_{add}

12

| FeO | CaO | MnO | .... | C | O₂ |

m_{input}

$m_{compounds}$

Figure 3

4

$m_{elements}$ 4.1 $\dot{m}_{elements}$

$m_{fraction}$

T_{bath}

4.n

$\dot{m}_{fraction}$

$P_{chemical}$

Figure 4

14 11 12

4.x

T_{bath}

$m_{elements}$

13

14

15

16

17

$P_{element}$

$\dot{m}_{elements}$
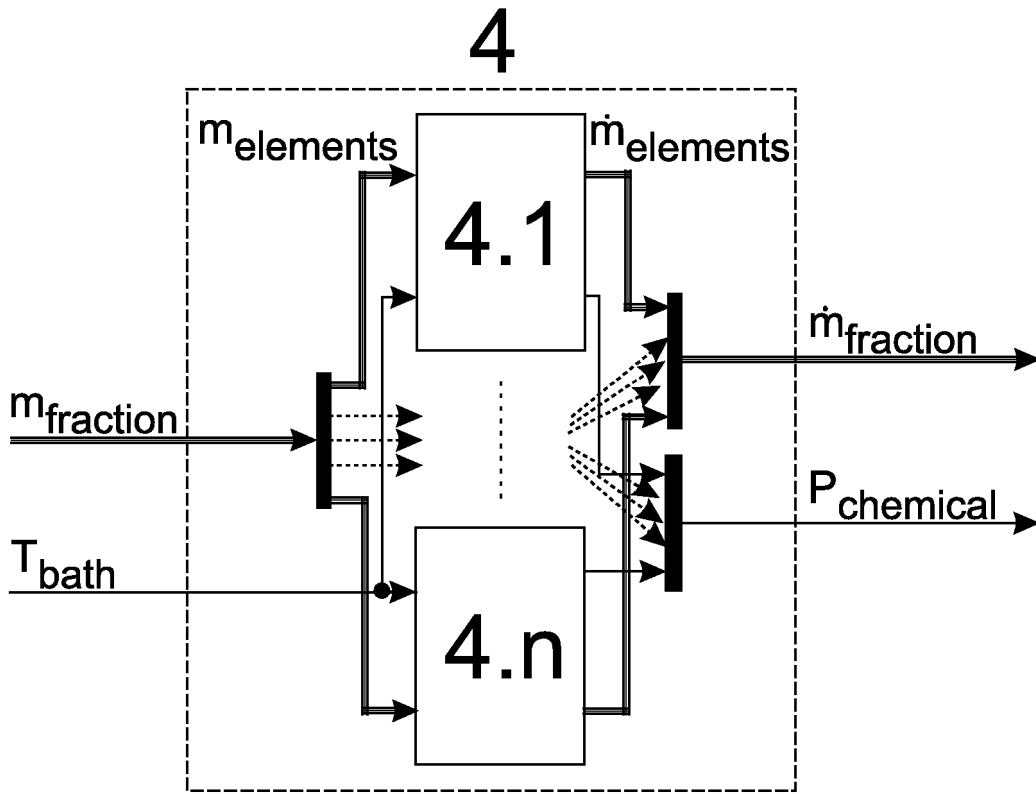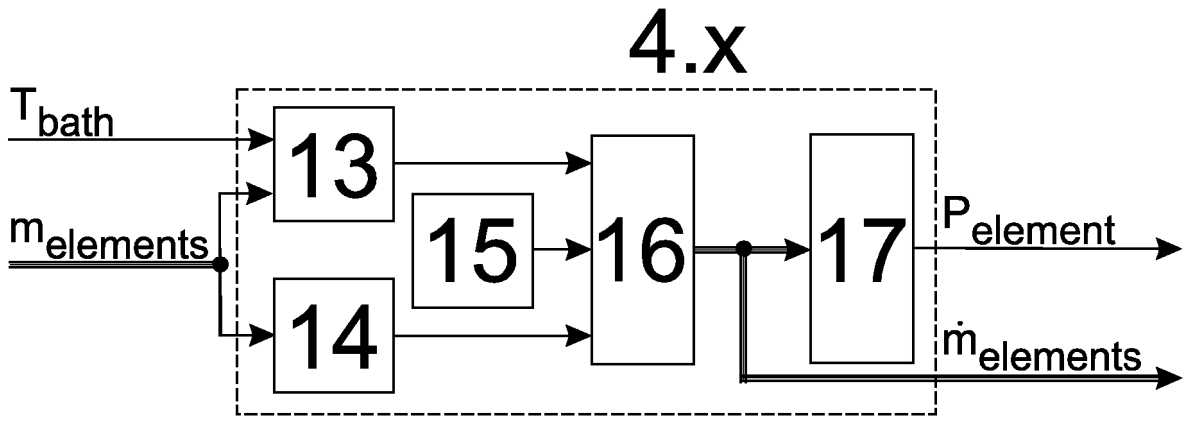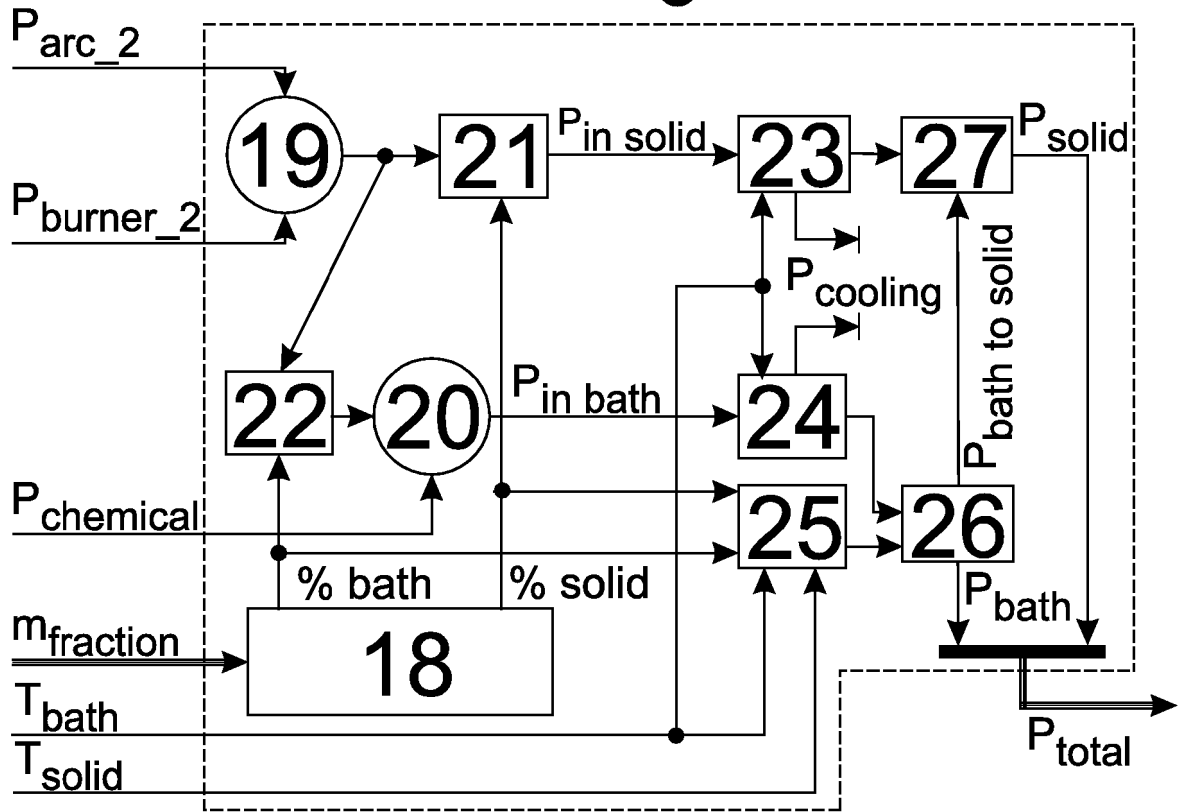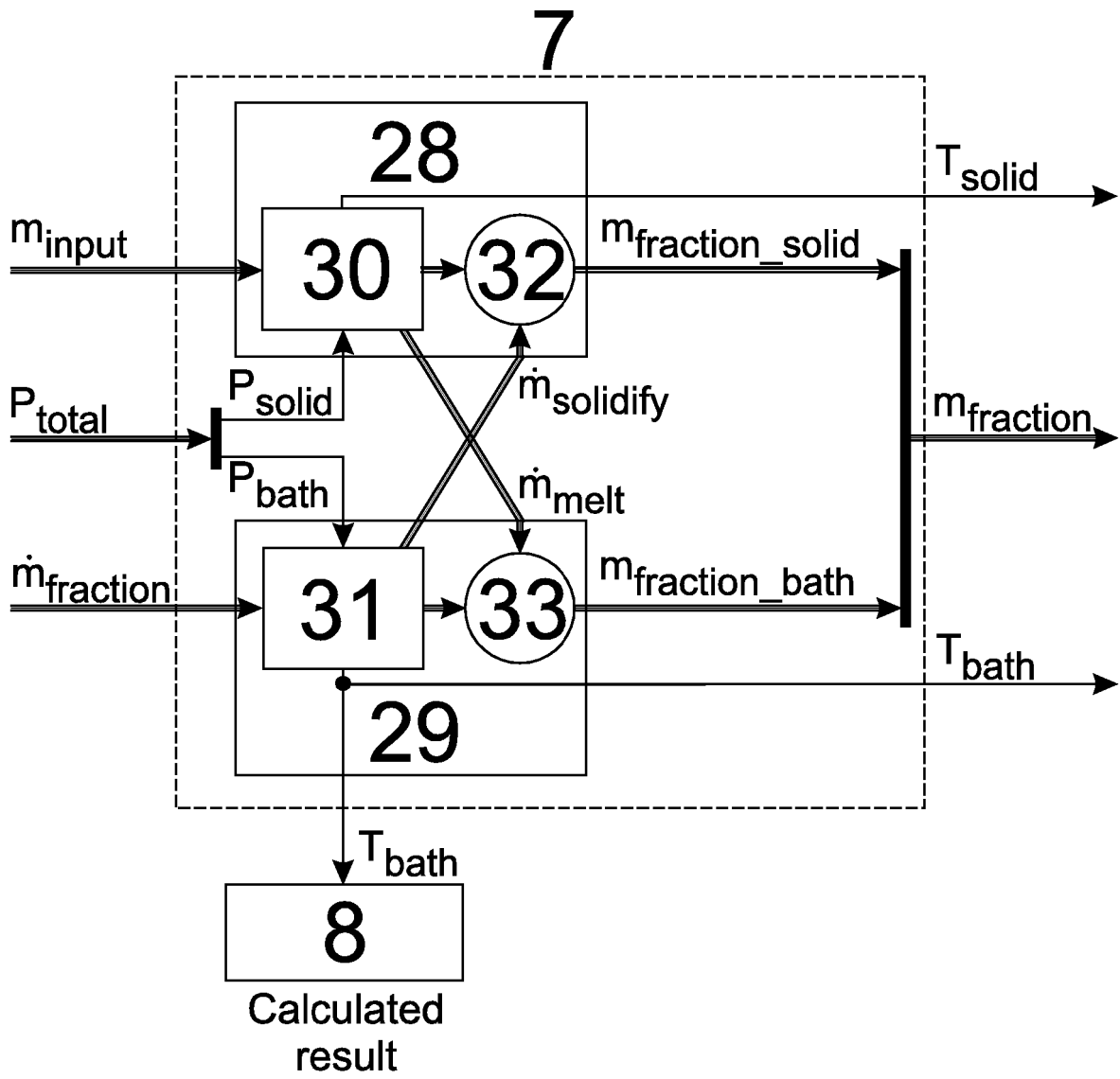
Figure 5

6

Figure 6

Figure 7

Title: Soft sensor for online estimation of the steel bath temperature in an electric arc furnace (EAF)

Background of the invention

Recycling of the steel scrap using electric arc furnaces (EAF) nowadays roughly represents 1/3 of the annual steel production. The EAF melting process of gaining steel from metal scrap is composed of several steps, such as: loading the furnace and additional buckets with metal scrap, preheating of the scrap, melting the scrap, tapping of the steel bath and further treatment (for further reading and state of the art in EAF steelmaking see e.g. R. J. Fruehan, *The Making, Shaping and Treating of Steel*, The AISE Steel Foundation, Pittsburgh, USA, 1998; E. T. Turkdogan, *Fundamentals of Steelmaking*, Institute of Materials, London, UK, 1996).

Considering the EAF operation, several factors influence the technological procedure of the steel melting regarding the produced steel quality/grade, steel bath temperature being one of them. Both, current and endpoint bath temperatures represent an important factor, while acquiring appropriate structural properties of the steel, as they influence several chemical (reaction courses, rates and equilibria) and mass-transfer (melting and solidification) processes and also determine the timeline of the physical operation of the furnace (furnace power, scrap loading, addition of slag-forming elements, burner operation, carbon injection, oxygen lancing, etc.). Moreover, appropriate bath temperature ensures sufficient conditions for triggering/performing most of the chemical reactions, prevents reverting of the oxidized elements from the slag to the steel and allows further steel treatment in secondary processes (end-point or tap temperature). Whether the bath temperature during the melting is to high it significantly increases the furnace wear (bottom, lining, panels, etc.), which shortens its life and also increases the operational costs (unnecessary electrical energy input). On the other hand, whether the bath temperature is to low it causes improper triggering of the chemical processes and other product-quality related issues.

Due to the nature of the steel-melting process (high temperatures, high electrical voltages, molten metal, etc.), direct online measurements of the bath temperature are difficult. Usually, the bath temperature is measured only before the tap (endpoint measurement before steel pouring) using a manual or an automated lance with disposable card-board thermocouple tip. Whether the tap temperature is too low, more energy is added to the bath in order to increase the temperature and allow proper secondary treatment of the steel. In practice, optimal tap temperature should be contained in a rather narrow interval around the optimal temperature, depending on the steel grade produced. Most of the today's furnaces operate without online bath temperature measurement system during the melting process, which was introduced in the past few years. Therefore, bath temperature is estimated by operators according to the charged steel and slag weight, power-on time, electrical energy input, added oxygen and carbon, burners operation, etc. to that point. Such estimations requires extensive knowledge of the process and are as successful as the operator is experienced. Usually, such methods yield suboptimal results. Further deviations from the ideal temperature levels arise in the case of furnace operation failures or difficulties, such as arc extinguishes, electrode breakage, etc., when it is after the furnace power-off harder to determine the actual temperature levels according to the prior operation parameters. Each deviation from the ideal temperature interval either causes longer production times, excessive consumption of the electrical energy or excessive furnace wear.

For this reason it is desirable to provide an efficient system for online estimation of the steel bath temperature, which supports the operator made decisions about the EAF technological procedure, overcomes the drawbacks of the EAF assembly without the online bath temperature measurement and can be installed to any EAF assembly without major interventions to the same

assembly. The system for such online estimation is based on a calculation model as a soft sensor, embodying the necessary mathematical equations to replicate the course of the steel bath temperature.

Summary of the invention

The invention relates to the soft sensor based on the calculation model for online estimation of the steel bath temperature in an electric arc furnace during the steel melting process. The presented soft sensor uses model-based approach and the measurable process values, which affect the steel bath temperature, which is otherwise not measured, in order to obtain the steel bath temperature

The invention is based on the realization that by using mathematical equations for modelling the parts of the EAF, and by using EAF operational measurements to fit the model parameters, a usable modelling method for estimation of the steel bath temperature is achieved.

According to the object of invention, the soft sensor and the calculation model are based on the physical laws of thermodynamics and thermochemistry, embodying the necessary mathematical equations, describing thermal, chemical and mass related processes.

According to the object of invention, to obtain an applicable soft sensor and a calculation model, the EAF processes should be modelled with appropriate model parameters, whose values need to correspond to the real EAF. The model parameters should be be adjusted to meet the real EAF conditions either numerically, analytically, experimentally or using a combination of the previous. Some parameters, which are not EAF-specific, such as: common thermal and chemical constants, should be found in any publication covering such topics.

In order for the soft sensor to fulfill its purpose, i.e. estimate steel bath temperature, it should run in a simulation mode simultaneously with the real EAF process using the necessary measured EAF operational data as its inputs.

The presented invention can be used in any EAF assembly with accessible operational measurements; however, it is reasonable to use it with the EAF assemblies, which do not incorporate an online steel bath temperature measurement system, but do possess a measurement system for all other process values needed by the calculation model.

Brief description of the drawings

In the following, the object of the invention will be explained in detail on the basis of the accompanying drawings. For all drawings applies that doubled lines represent a multiple-value data flow, while single lines represent a single-value data flow.

The list of figures:

Figure 1: A block diagram illustrating the structure of the soft sensor for online estimation of the steel bath temperature in an EAF using the presented calculation model **1**.

Figure 2: A detailed view of the block diagram illustrating the efficiency calculation module **3** of the main calculation model **1.**

Figure 3: A detailed view of the block diagram illustrating the input mass-fraction calculation module **5** of the main calculation model **1.**

Figure 4: A detailed view of the block diagram illustrating the chemical reaction module **4** of the main calculation model **1.**

Figure 5: A detailed view of the block diagram illustrating the submodules **4.x** of the chemical reaction module **4.**

Figure 6: A detailed view of the block diagram illustrating the energy distribution module **6** of the main calculation model **1.**

Figure 7: A detailed view of the block diagram illustrating melting and temperature calculation module **7** of the main calculation model **1.**

Detailed description of the invention

Here we present a detailed description of the invention. Referring to Fig. 1, a model-based soft sensor for online estimation of the steel bath temperature in an EAF, as the object of invention can be composed of several modules which should contain mathematical relations describing the physical properties of the EAF steel melting process and the corresponding model parameters. In the present embodiment of the invention the following estimation procedure is assumed: the calculation model **1** (representing the necessary EAF processes), which can be composed of several submodels **3-7**, takes the real-time EAF operational measurements **2** as its inputs to different modules in order to obtain the estimated steel bath temperature **8** as its calculated result. In order to estimate the steel bath temperature **8**, the EAF operational measurements **2** should include at least the following real-time measured process values: the sum of the current arc powers (P_{arc_1}), the sum of the current oxygen-fuel burners powers (P_{burner_1}), current amount of the steel mass charged (m_{charge}), current composition of the steel charged (c_{charge}), current amount of the additions mass charged (m_{add}) and current composition of the additions charged (c_{add}). The steel charged into the EAF can, beside the iron (Fe), include other chemical elements in smaller amount, which define the structural properties of the steel, such as: carbon (C), manganese (Mn), silicon (Si), chromium (Cr), sulfur (S), phosphorus (P), nickel (Ni), copper (Cu), aluminium (Al) and others. Referring to Fig. 1, variable c_{charge} should define the amount (in %) of each element contained in the charged steel, where the percentages of at least the main elements performing in EAF processes, such as: iron (Fe), carbon (C), silicon (Si) and manganese (Mn) should be included. Moreover, c_{charge} may include the information about the percentages of more elements appearing in the steelmaking processes. Furtheron, the additions charged into the EAF can include slag-forming elements (CaO, SiO_2, MgO, Al_2O_3, etc.), carbon (C) or oxygen (O_2). The variable c_{add} should define the amount (in %) of each addition present in the added mass (m_{add}) and should include at least the information about the main additions to the EAF, such as: slag-forming elements (CaO, MgO), carbon injection (C) and oxygen (O_2) lancing.

According to the accompanying drawings a detailed description of each module of the calculation model **1** shall be given in the following.

Referring to Fig. 2, a detailed description of the efficiency calculation module **3** shall be given. Efficiency calculation module **3** should be connected in a manner to receive the inputs such as the measured sum of arc powers (P_{arc_1}) and the sum of oxy-fuel burners powers (P_{burner_1}) from the EAF operational measurements module **2** and the estimated steel bath temperature (T_{bath}) from the melting and temperature calculation module **7**. The efficiency calculation module **3** is characterized in that it comprises of mathematical equations defining the relations between the thermal conditions in the furnace (bath temperature) and the useful arc or burner power (arc and burner efficiency). Efficiency calculation module **3** of the main calculation model **1** should reduce the sum of the arc powers **9** on its output (P_{arc_2}) for approximately 5% in comparison to the input arc powers (P_{arc_1}), as a consequence of the energy lost to electrode oxidation and heating. The 5% energy loss is an estimation which should suit most of the EAF assemblies and can be replaced to other percentage if needed. Efficiency calculation module **3** should also reduce the sum of the burner powers **10** on its ouput (P_{burner_2}) from 30% to 80% in comparison to the input burner powers (P_{burner_1}), depending on the estimated temperature of the steel bath (T_{bath}). Burner efficiency, which determines the useful

power of the burners transferred to the steel and the power lost can be described by different mathematical equations, characteristic curves or other methods defining the relations between the thermal conditions in an EAF and the burner efficiency. Here the relation between the steel bath temperature (T_{bath}) and the burner efficiency (in %) is characterized as a nonlinear function, where at temperature 300°C the efficiency is 70% and decreases to 20% at 1500°C (for further background in oxy-fuel burner efficiency see: J. A. T. Jones, B. Bowman and P. A. Lefrank, *The Making, Shaping and Treating of Steel*; 10th ed., *Chapter 10: Electric Furnace Steelmaking*, The AISE Steel Foundation, Pittsburgh, USA, 1998, pp. 600). The described relation between the input burner power (P_{burner_1}) and the steel bath temperature (T_{bath}) on one hand and the output burner power (P_{burner_2}) on the other can be obtained using a lookup table, where to each steel bath temperature level (T_{bath}) corresponds an appropriate multiplier (gain), with which the input burner power (P_{burner_1}) is multiplied in order to obtain the output burner power (P_{burner_2}). Output burner power (P_{burner_2}) is the value which should then be used for further calculations in the energy distribution module **6**.

Referring to Fig. 1, other inputs to the calculation model **1**, such as the mass of the steel charge (m_{charge}), its composition (c_{charge}), mass of other additions (m_{add}) and their composition (c_{add}) enter the input mass-fraction calculation module **5**.

Detailed description of the input mass-fraction calculation module **5** shall be given in the following according to Fig. 3. As has been mentioned, the composition of the steel charge (c_{charge}) should define the percentage of at least the following elements: Fe, Si, C and Mn, which appear in the steel mass (m_{charge}) added to the furnace. Similarly, the composition of other additions (c_{add}) should define the percentage of the certain compound in the total addition of the added mass (m_{add}). The additions which are added at certain times to the furnace during the melting process should include at least the following: slag-forming elements (CaO, MgO), carbon injection (C) and oxygen (O_2) lancing. Input mass-fraction calculation module **5** should, using the input data (m_{charge}, c_{charge}, m_{add} and c_{add}) and the mathematical operations calculate the masses of the individual elements **11** ($m_{elements}$) and compounds **12** ($m_{compounds}$), which are to be added to the total mass in the EAF. Obtained masses can then be combined and outputed (m_{input}) from the module. The added masses of the elements or compounds should be when entering the EAF through this module **5** considered as solids (except the lanced oxygen which is considered as gas) and should in such form enter the melting and temperature calculation module **7**.

According to Fig. 1, the melting and temperature calculation module **7** should use the input mass (m_{input}) obtained from the input mass-fraction calculation module **5**, total power input (P_{total}) from the energy distribution module **6** and the element/compound mass fraction change ($\dot{m}_{fraction}$) from the chemical reaction module **4** in order to calculate the steel melting ratio and the corresponding fractions ($m_{fraction}$) of the present elements/compunds and to calculate the temperature of the steel bath (T_{bath}).

At this point a detailed description of the chemical reactions module **4** shall be given in the following according to Fig. 4 and Fig. 5. According to Fig. 1, the chemical reactions module **4** should use the calculated bath temperature (T_{bath}) and the current mass conditions in the furnace ($m_{fraction}$) from the melting and temperature calculation module **7** in order to compute the change of masses ($\dot{m}_{fraction}$) in the furnace due to the chemical reactions and the corresponding power of chemical reactions ($P_{chemical}$). The chemical reactions module **4** should operate with masses which are already in a liquid or gaseous (O_2) state, since chemical reactions do not appear when the elements or compounds are still in a solid state. It is known that chemical reactions contribute a substantial amount of energy, which is added to the total energy provided by the arcs and the burners and influence the temperature conditions in an EAF. The chemical reactions which appear in the EAF steelmaking processes include oxidation of the elements and reduction of the compounds. In order to estimate the appropriate release of the energy, which affects the steel bath temperature at least the fundamental chemical reactions should be modelled (for further information on EAF steelmaking

thermochemistry see e.g. R. J. Fruehan, *The Making, Shaping and Treating of Steel*, The AISE Steel Foundation, Pittsburgh, USA, 1998;). The reactions which can be considered as fundamental are the following:

- oxidation of iron: $Fe + 1/2O_2 \rightarrow FeO$
- oxidation of silicon: $Si + O_2 \rightarrow SiO_2$
- partial oxidation of carbon: $C + 1/2O_2 \rightarrow CO$
- oxidation of carbon monoxide: $CO + 1/2O_2 \rightarrow CO_2$
- reduction of iron oxide: $FeO + C \rightarrow CO + Fe$
- reduction of iron oxide: $FeO + Mn \rightarrow MnO + Fe$
- reduction of manganese oxide: $MnO + C \rightarrow Mn + CO$

To estimate the chemical energy, other less important reactions (from the energy point of view) may be considered, such as

- oxidation of phosphorus
- oxidation of chromium
- reduction of sulfur
- etc.

In general, the course of each chemical reaction appearing in the chemical reactions module **4** can be described by three values, which can be either constant or obtainable from the current mass and temperature conditions in the steel bath. These are: reaction rate, molar fraction of the element/compound in the bath and molar fraction of the element/fraction at equilibrium. The reaction rate determines the speed of the chemical reaction and is defined as constant for each reaction. To fulfill the purpose of the module, the values of the reaction rates for each reaction should be obtained from an appropriate publication dealing with the EAF chemistry. On the other hand molar fractions (current and at equilibrium) define whether the conditions for the reaction to start/stop are met and beside the reaction rate also determine the speed of the reaction (the greater the difference between the current and the equilibrium molar fraction the faster the reaction). Both molar fractions are dependent on several factors such as the chemical balance of the elements/compounds that affect the particular reaction and the current temperature of the bath. For all fundamental chemical reactions a common mathematical equation for the change of mass of element/compound can be applied, i.e:

$$\dot{m}_{el} = -k_{el}(\%el - \%el_{eq}), \qquad \text{Eq. 1}$$

where the $\dot{m}_{el}$ represents the change of the element/compound mass, k_{el} represents the reaction rate, $\%el$ represents the current molar fraction of the element/compound in the steel bath and $\%el_{eq}$ represents the molar fraction of the element/compound at equilibrium for the given chemical reaction. The molar fractions of the elements/compounds at equilibrium for all appearing reactions should be obtained according to the mathematical equations, which are accessible from publications dealing with the EAF chemistry.

Each of the chemical reactions appearing in the steel bath either releases (exothermic reactions) or consumes (endothermic reactions) the energy. The rule applies, that the energy is released in the case of oxidative reactions, while in the case of reductive reactions the energy is consumed in order to carry out the reaction. According to Eq. 1, for each chemical reaction and the corresponding mass change there is a subsequent release/consumption of the energy, which can be described by the following equation:

$$\Delta H_T^{\circ} = \sum \Delta H_{298}^{\circ}(\text{products}) - \sum H_{298}^{\circ}(\text{reactants}) + \int_{298}^{T} [\sum C_p(\text{products}) - \sum C_p(\text{reactants})] dT, \quad \text{Eq.2}$$

where ΔH_T° represents the enthalpy change for the given reaction. Eq. 2 defines that the change of the enthalpy of the reaction is given by the difference between the enthalpies of the products and

those of the reactants and by the integral (from the initial to the actual temperature) of the difference between the specific heat capacities of the products and the reactants.

Referring to Fig. 4 and according to the implementation of the invention, the chemical reaction module **4** can include several submodules, i.e. from **4.1** to **4.n**. Each submodule should correspond to one fundamental chemical reaction, meaning that the total number of submodules **n** should correspond to the number of chemical reactions included in the chemical reaction module **4**. The number of each submodule **4.1** to **4.n** inputs is dependent on the specific reaction, meaning that elements/compounds relevant for the given reaction specify the number of submodule inputs. The input values (beside the steel bath temperature T_{bath}) are the masses of the corresponding elements/compounds significant for the specific reaction. According to the mathematical equations Eq. 1 and Eq. 2 in each submodule **4.1** to **4.n**, appropriate change of masses and the corresponding chemical power of the chemical reactions can be obtained and sent to the output ($\dot{m}_{fraction}$, $P_{chemical}$). A more detailed view of the calculations in each submodule is given in Fig. 5, which represents a detailed block diagram of each submodule **4.1** to **4.n**, here represented as **4.x**. According to Eq. 1 and Eq. 2 and the corresponding elements/compounds performing in the particular reaction (a subset of values in $m_{elements}$) and the current temperature of the steel bath (T_{bath}), the submodule **4.x** should calculate the current molar fractions of the element/compounds **14** and equilibrium molar fractions of the element/compounds **13**, which together with the reaction rate **15** define the change of masses of the elements/compounds performing in the specific reaction **16** ($\dot{m}_{elements}$). For each change of mass of the element/compound a corresponding yield of chemical power **17** can furtheron be calculated. All partial chemical powers should be summed up to obtain the total power of a separate chemical reaction ($P_{element}$). The change of mass fractions ($\dot{m}_{fraction}$) exiting the chemical reactions module **4** should be used as an input to the melting and temperature calculation module **7**, where the change of masses due to chemical reactions should be accounted for in a total mass balance. The power of the chemical reactions ($P_{element}$) exiting the chemical reactions module **4** should be used as an input to the energy distribution module **6.**

According to Fig. 1, the energy distribution module **6** uses the current arc (P_{arc_2}) and burner (P_{burner_2}) powers from the efficiency calculation module **3**, chemical powers ($P_{chemical}$) from the chemical reaction module **4** and the current mass conditions in the EAF ($m_{fraction}$) from the melting and temperature calculation module **7** as it's inputs.

Referring to Fig. 6 a detailed description of the energy distribution **6** module shall be given. According to the mass conditions ($m_{fraction}$) calculated by the melting and temperature calculation module **7**, the percentage of the solid and the bath masses can be determined using a bath/solid phase detection submodule **18**, which should from the amounts of separate items of the $m_{fraction}$ determine the total percentage of the solid and bath masses. This percentage (% bath, % solid) can be used to determine the amount of the summed arc and burner powers **19** transfered either to the solid **21** or to the bath **22** phase, respectively. Total amounts of the arc and burner powers transferred to the bath and solid phase are directly dependent on the percentage of the bath and solid masses, i.e. % bath = % total arc/burner power to bath. Other mechanisms of power transfer to phases can also be used. Due to the fact, that the chemical reactions only appear in the bath phase, chemical power ($P_{chemical}$) should be transfered **20** to the bath phase only. In this manner, distributed input powers to both phases ($P_{in\,solid}$, $P_{in\,bath}$) can be obtained. Furtheron, both input powers should be reduced for the amount of the energy losses, i.e. solid phase energy losses **23** and bath phase losses **24**, which occur due to the cooling of the furnace vessel. The loss of the powers due to the EAF vessel cooling should either be assumed constant for each phase or as here computed by knowing the EAF-specific cooling-water flows, EAF dimensions, surface temperatures and thermal constants. Cooling losses of the furnace may also be described by other appropriate heat transfer mechanisms. The values of the thermal coefficients and constants, which correspond to the specific EAF should be found in appropriate publications dealing with the EAF heat transfer topics. Using the calculated

percentage of the solid and bath phase masses and the temperature of the bath phase, the percentage of the power transferred from the liquid to the solid phase can be obtained 25. The power to the bath should therefore further be reduced **26** by the power, transfered from the bath to solid phase ($P_{bath\ to\ solid}$) and occurs due to the temperature difference between the bath and the solid phases. Consequently, the power to the solid phase is increased **27** by the power transfered from the bath phase. Similarly to cooling losses, power from the bath to solid phase can also be obtained using standard heat-transfer equations between two materials with appropriate EAF-specific coefficients or any other appropriate heat transfer mechanism considering the mass percentages of the bath and solid phases and their temperatures (T_{bath}, T_{solid}). The reduced power to bath (P_{bath}) represents the output of the submodule and can be together with the increased power to solid (P_{solid}) combined to form one output (P_{total}) of the energy distribution module **6**. P_{total} should represent one of the inputs to the melting and temperature calculation module **7**.

According to Fig. 1, the melting and temperature calculation module **7** uses input mass (m_{input}) calculated by input mass-fraction calculation module **5**, change of mass conditions ($\dot{m}_{fraction}$) due to the chemical reactions module **4** and the distributed total powers (P_{total}).

Referring to Fig. 7 a detailed description of the melting and temperature module **7** shall be given. The input mass (m_{input}) should directly enter the solid phase mass and temperature change calculation submodule **28**, since the m_{input}, which enters the EAF should be considered as being in a solid form and should be melted first. On the other hand $\dot{m}_{fraction}$ should directly enter the bath phase mass and temperature change calculation submodule **29**, as the $\dot{m}_{fraction}$ as received from the chemical reactions module **4** should be considered as already being in a liquid form. Both the input mass (m_{input}) and the mass change ($\dot{m}_{fraction}$) should be added to the existing solid or bath masses, i.e. to solid phase mass in submodule **30** and to bath phase massin submodule **31**. The total input powers (P_{total}) should also represent one of the inputs to both submodules **30** and **31** (P_{solid}, P_{bath}) for mass and temperature change calculation. Each of the submodules should incorporate mathematical equations which describe the processes of temperature change, material melting and solidification. These equations should be found in publications dealing with the fundamentals of thermodynamics and the parameters should be set to appropriate values, which ensure proper process description. Both modules **30** and **31** should calculate the change of masses for each phase ($\dot{m}_{fraction\_solid}$, $\dot{m}_{fraction\_bath}$) and the corresponding mass transfer from one phase to another due to melting and solidification ($\dot{m}_{melt}$, $\dot{m}_{solidify}$), which should be added to the existing phase masses to obtain the current mass for each phase ($m_{fraction\_solid}$, $m_{fraction\_bath}$). In the case of the solid phase the addition is made in **32** and in the case of the bath phase the addition is made in **33**. Both calculated values combined in $m_{fraction}$ should appear as output from the module **7** and can be used as inputs to other modules. Moreover, the submodules **30** and **31** should also include the calculation of the current temperatures of the steel according to the standard thermodynamical equations (solid phase - T_{solid}, bath phase - T_{bath}), of which the steel bath temperature T_{bath} appears as the calculated result **8** of the presented model.

List of reference symbols

m_{charge} – the mass of charged metal
m_{add} – the mass of additions
m_{input} – the set of masses of input elements (Fe, Si, C, Mn, ...) and additions (slag, C, O_2) in solid form
$m_{fraction}$ – the set of masses of elements and compounds in solid and bath forms
$\dot{m}_{fraction}$ – the set of mass changes of elements and compounds in solid and bath forms
$m_{elements}$ – the set of masses of input elements (Fe, Si, C, Mn, ...) in solid form
$m_{compounds}$ – the set of masses of input compounds (FeO, CaO, MgO, ...) in solid form
$\dot{m}_{solidify}$ – the change of mass due to the solidification of the metal

$\dot{m}_{melt}$ – the change of mass due to the melting of the metal

$\dot{m}_{el\_i}$ – the change of a separate element/compound mass due to chemical reactions

$\dot{m}_{fraction\_solid}$ – the change of solid metal mass

$m_{fraction\_solid}$ – the mass of the solid metal

$\dot{m}_{fraction\_bath}$ – the change of bath metal mass

$m_{fraction\_bath}$ – the mass of the bath metal

c_{charge} – the set of percentages defining the composition of the charged metal

c_{add} – the set of percentages defining the composition of the charged additions

P_{arc_1} – the sum of the input arc powers

P_{arc_2} – the sum of the reduced arc powers (considering arc efficiency)

P_{burner_1} – the sum of the input burner powers

P_{burner_2} – the sum of the reduced burner powers (considering burner efficiency)

$P_{chemical}$ – the sum of chemical powers

P_{el_i} – chemical power of a separate element reaction

$P_{element}$ – the sum of separate element reaction powers

P_{total} – the set of total powers for each phase (P_{solid}, P_{bath})

P_{in_solid} - power to solid phase without considering the losses

P_{in_bath} – power to liquid phase without considering the losses

P_{solid} – total power to solid phase considering the losses and the power received from the bath

P_{bath} – total power to bath phase considering the losses and the power lost to the solid metal

T_{solid} – solid steel temperature

T_{bath} – steel bath temperature

Amendment to the claims

1. A soft sensor for continuous estimation of the steel bath temperature in an electric arc furnace during the entire steel melting process comprising:
- a calculation model comprising mathematical equations based on thermodynamic and thermochemical laws and parameterized to correspond to the real EAF processes;
- acquisition of continuous EAF measurements, used as calculation model inputs, comprising arc powers, oxygen-fuel burner powers, charged steel mass, charged steel composition including the percentages of materials: iron, carbon, silicon and manganese, charged additions mass, charged additions composition including the percentages of slag-forming materials (CaO, MgO), carbon and oxygen;
- wherein the model comprises mathematical equations to calculate: arc power efficiency, burner power efficiency, masses of iron, carbon, silicon and manganese obtained from the steel and additions composition, mass transfers due to steel and slag-forming materials charging, mass transfers due to steel and slag-forming materials melting, power distribution to solid and bath phases, power losses due to cooling of the furnace vessel, solid phase melting rate, solid and bath phase temperatures;
- wherein the model also comprises mathematical equations to calculate: chemical powers and mass transfers due to the following chemical reactions: $Fe + 1/2O_2 \rightarrow FeO$, $Si + O_2 \rightarrow SiO_2$, $C + 1/2O_2 \rightarrow CO$, $CO + 1/2O_2 \rightarrow CO_2$, $FeO + C \rightarrow CO + Fe$, $FeO + Mn \rightarrow MnO + Fe$, $MnO + C \rightarrow Mn + CO$.

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