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Material Balance Model for Steel Production in Electric Arc Furnace - Reduction Period

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ABSTRACT

The reduction period is the third, last, part during the production of the so-called electric steel. The period, as well as the melting and oxidation periods is based on an electric arc method, feasible in a three-phase furnace. Through formulated dependencies forming the present material balance model, as well as their calculation, results (presented in tabular form) were obtained for the quantities of charge materials used to produce liquid metal, slag and gases, as well as the composition of these phases.

Keywords: steelmaking in an electric arc furnace, reduction period.

INTRODUCTION

The model used certain assumptions that are approved by metallurgical practice or are described in the specialized literature [1 - 8]. During the period, it is necessary to carry out deoxidation, as a mandatory procedure after the oxidation period, under the so-called carbide slag, and the treatment with it should be about 80 min. It is important that the slag has a basicity of about 2.00 - 2.50 in the reduction period with a content of FeO $\leq$ 0.5 %, and CaC_2 should be about 4 % at the beginning of the reduction period and about 1 % at the end of the reduction period. The total amount of the reduction slag should be from 2 to 4 % of the weight of the metal. The values obtained, after calculating the formulated dependencies, are based on 100 kg of starting charge (or approximately 100 kg of metal) [1, 3 - 6].

EXPERIMENTAL

Determination of the amount of slag [3]

This amount is determined by the task of carrying out the desulfurization of steel. We set the goal to separate so much sulfur from the metal that at the end of the period we get about 0.012 % S, which is approximately 0.012 kg ($m_{red.-end}^{[S]}$) [1], according to the weight of the metal at the end of the oxidation period - 98.150 kg [2]. At the end of the oxidation period the metal contains 0.020 kg S ($m_{oxid.-end}^{[S]}$) [2]. Thus, the amount of sulfur that must be separated into the slag ($m_{red.-end}^{(S)}$) during the reduction period will be:

$$m_{red.-end}^{(S)} = m_{oxid.-end}^{[S]} - m_{red.-end}^{[S]}, \text{ kg}, \qquad (1)$$

where: $m_{oxid.-end}^{[S]}$ - amount of sulfur dissolved in the metal at the end of the oxidation period, kg;

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$m_{red.-end}^{[S]}$ - amount of sulfur dissolved in the metal at the end of the reduction period, kg.

For industrial furnaces, it is assumed that the sulfur distribution coefficient (L_S) between the slag and the metal is:

$$L_S = \frac{\%(S)_{red.-end}}{m_{red.-end}^{[S]}} = 30, \qquad (2)$$

where: $\%(S)_{red.-end}$ - percentage amount of sulfur that should be contained in the slag at the end of the reduction period, %.

Then $\%(S)_{red.-end}$ will be:

$$\%(S)_{red.-end} = L_S \, . \, m_{red.-end}^{[S]}, \text{ kg} \qquad (3)$$

Then the amount of the so-called first (oxidative) slag for the reduction period ($m_{red.}^{slag1}$) will be:

$$m_{red.}^{slag1} = \frac{m_{red.-end}^{(S)}}{\%(S)_{red.-end}}, \text{ kg} \qquad (4)$$

The slag from the reduction period is formed from:

- From the oxidation slag - $m_{oxid.}^{slag\text{-}total}$ [2]. It is assumed that 95 % of the slag at the end of the oxidation period is removed, and 5 % of it remains in the furnace. Thus, the amount of slag from the oxidation period for the reduction period ($m_{oxid.}^{slag\text{-}red.}$) will be:

$$m_{oxid.}^{slag-red.} = m_{oxid.}^{slag-total} \frac{5}{100}, \text{ kg} \qquad (5)$$

- From the furnace vault - it is assumed that for every 100 kg of metal, during the reduction process from the dinas vault 0.40 kg ($m_{red.}^{dinas\text{-}slag}$) enters the furnace;
- From the furnace floor and walls - it is assumed that for every 100 kg of metal, during the reduction process, 0.50 kg ($m_{red.}^{magnesite\text{-}slag}$) enters the furnace from the magnesite floor and walls;
- From the furnace electrodes - it is assumed that for every 100 kg of metal, during the reduction process, 0.14 kg ($m_{red.}^{electrodes}$) enters the furnace from the electrodes [1], and the ash from them is about 1 % and passes completely into the slag, i.e. it represents 0.0014 kg ($m_{red.}^{ash\text{-}electrodes\text{-}slag}$).
- From the added lime, fluxspar and sand - their total quantity ($m_{red.}^{lime,fluxspar,sand\text{-}slag}$) is obtained by the formula:

$$m_{red.}^{lime,fluxspar,sand-slag} = m_{red.}^{slag1} - (m_{oxid.}^{slag-red.} + $$
$$+ m_{red.}^{dinas-slag} + m_{red.}^{magnesite-slag} + m_{red.}^{electrodes-slag}), \text{ kg} \qquad (6)$$

It is assumed that the amounts of lime ($m_{red.}^{lime\text{-}slag}$), fluxspar ($m_{red.}^{fluxspar\text{-}slag}$) and sand ($m_{red.}^{sand\text{-}slag}$) are added in a ratio of 75 % : 20 % : 5 %, respectively. This results in:

$$m_{red.}^{lime-slag} = m_{red.}^{lime,fluxspar,sand-slag} \frac{75}{100}, \text{ kg} \qquad (7)$$

$$m_{red.}^{fluxspar-slag} = m_{red.}^{lime,fluxspar,sand-slag} \frac{20}{100}, \text{ kg} \qquad (8)$$

$$m_{red.}^{sand-slag} = m_{red.}^{lime,fluxspar,sand-slag} \frac{5}{100}, \text{kg} \qquad (9)$$

The amount of $m_{red.}^{lime,fluxspar,sand\text{-}slag}$ is part of the first slag mixture and represents about 1 % of the weight of the metal. About 10 min. after formation, the first slag is melted and then the so-called carbide mixture, which is ground electrode waste, is fed into the furnace. The amount of the carbide mixture is about 30 - 35 % (33 %) of $m_{red.}^{lime,fluxspar,sand\text{-}slag}$. This gives:

$$m_{red.}^{electrode\ waste-slag} = m_{red.}^{lime,fluxspar,sand-slag} \frac{33}{100}, \text{ kg.} \qquad (10)$$

Calculation of metal additives in the form of ferroalloys [3]

For the current low-alloyed bearing steel, it is assumed that the metal losses with the discharged slag and for laboratory analysis will be covered by the imported ferroalloys. Therefore, when calculating the additives, the amount of metal ($m_{oxid.\rightarrow red.}^{metal}$) is taken as 98 kg.

To accelerate the formation of carbide slag on the metal mirror, 75 % ferrosilicon in pieces ($m_{red.}^{FeSi\text{-}slag}$) is added in an amount of 0.05 % of the metal or:

$$m_{red.}^{FeSi-slag} = \frac{m_{oxid.\to red.}^{metal} \,.\, 0.05}{100 \,.\, \frac{72}{100}} \text{ , kg,} \tag{11}$$

where: 100 - coefficient for transition from % to kg; 72 - % of Si in 75 % FeSi [1], %.

This ferrosilicon brings silicon at the beginning of the process in the amount ($m_{red.}^{Si\text{-}slag}$), as follows:

$$m_{red.}^{Si-slag} = m_{red.}^{FeSi-slag} \frac{72}{100} \text{ , kg,} \tag{12}$$

and as a percentage of the metal the same silicon ($\%Si_{red.}^{Si\text{-}slag}$) will be:

$$\%Si_{red.}^{Si-slag} = \frac{m_{red.}^{Si-slag} \,.\, 100}{m_{oxid.\to red.}^{metal}} \text{ ,\%.} \tag{13}$$

A part of this silicon will be spent on deoxidation of the metal, forming SiO_2, which passes into the slag. Due to the treatment of the metal with carbide slag for about 80 min., the carbon from it will reduce part of this amount of silicon dioxide to silicon, which returns to the metal. The rate of this reduction is taken as 0.05 % / 60 min. Thus, the percentage of silicon from the slag to the metal will be:

$$\%Si_{red.}^{Si-slag\to metal} = 0.05 \frac{80}{60} \text{ , \%,} \tag{14}$$

and the weight:

$$m_{red.}^{Si-slag\to metal} = \\ = m_{oxid.\to red.}^{metal} \frac{\%Si_{red.}^{Si-slag\to metal}}{100} \text{ , kg.} \tag{15}$$

One hour after the start of the reduction period, ferrochrome is introduced into the furnace in order to reach about 1.50 % Cr in the metal (according to the chemical composition of the steel grade [1]. It is assumed that 3 % of the chromium in this ferroalloy is oxidized and passes into the slag. The amount of ferrochrome required ($m_{red.}^{FeCr\text{-}metal}$) will be:

$$m_{red.}^{FeCr-metal} = \frac{m_{oxid.\to red.}^{metal} \,.\, 1.50}{100 \,.\, \frac{70}{100}} \text{ , kg} \tag{16}$$

where: 70 - % of participation (or 70/100 in weight ratio) of Cr in ferrochrome (Table 1), %.

Ferrochrome contains 2 % Si [1], which will be introduced into the process. Its weight quantity ($m_{red.}^{FeCr\to Si\text{-}metal}$) is:

$$m_{red.}^{FeCr\to Si-metal} = m_{red.}^{FeCr-metal} \frac{2}{100} \text{ , kg,} \tag{17}$$

and the %:

$$\%Si_{red.}^{FeCr\to Si-metal} = \frac{m_{red.}^{FeCr\to Si-metal} \,.\, 100}{m_{oxid.\to red.}^{metal}} \text{ , \%.} \tag{18}$$

The finished metal should contain 0.30 % Si (according to the chemical composition of the steel grade [1]. Thus, silicon should be added in an amount ($\%Si_{red.}^{Si\text{-}add.\text{-}metal}$), calculated by the formula:

$$\%Sire_{d.}^{Si-add.-metal} = 0.30 - (\%Si_{red.}^{Si-slag} + \\ + \%Si_{red.}^{Si-slag\to metal} + \%Si_{red.}^{FeCr\to Si-metal} + \%Si_{oxid.\_end}^{metal}) \tag{19}$$

where: $\%Si_{oxid.\text{-}end}^{metal}$ - percentage content of silicon in the metal at the end of the oxidation period [2], %.

Silicon is introduced into the slag for about 35 min. before the metal is discharged, as ground 75 % FeSi, of which 70 % (or 70/100 by weight) of silicon, iron and other elements in this ferroalloy, with the exception of aluminum (which passes 100 % into the slag, as Al_2O_3), are absorbed by the metal, and the remaining 30 % pass into the slag, as SiO_2, etc. Thus, the amount of ferrosilicon required ($m_{red.}^{FeSi\text{-}add.\text{-}metal}$) to bring the missing amount of silicon into the metal is:

$$m_{red.}^{FeSi-add.-metal} =$$

$$= \frac{m_{oxid.\to red.}^{metal} \,.\, \%Si_{red.}^{Si-add.-metal}}{100 \,.\, \frac{70}{100} \cdot \frac{72}{100}} \text{, kg.} \qquad (20)$$

Preliminary composition and mass of slag [3]

So far, the computational structure allows us to determine the preliminary chemical composition and mass of the reduction slag. As mentioned above, it is a set of several components, the amount of which is determined according to the following relationships:

- For the amount of chemical compounds ($m_{red.}^{RxOy-slag}$) in the slag remaining from the oxidation period:

$$m_{red.}^{RxOy-slag} = m_{oxid.}^{slag-red.} \frac{\%RxOy_{oxid.}^{slag-red.}}{100}$$

kg, (21)

where: $\%RxOy_{oxid.}^{slag-red}$ - percentage of the desired substance in the slag remaining from the oxidation period (Table 5) [2], kg;

- For the amount of chemical compounds ($m_{red.}^{RxOy-lime}$) in the added lime:

$$m_{red.}^{RxOy-lime} = m_{red.}^{lime-slag} \frac{\%RxOy_{red.}^{lime-slag}}{100}$$

kg, (22)

where: $\%RxOy_{red.}^{lime-slag}$ - percentage of the desired substance in the lime (Table 2) [1], kg;

- For the amount of chemical compounds ($m_{red.}^{RxOy-fluxspar}$) in the added fluxspar:

$$m_{red.}^{RxOy-fluxspar} =$$

$$= m_{red.}^{fluxspar-slag} \frac{\%RxOy_{red.}^{fluxspar-slag}}{100} \text{, kg} \qquad (23)$$

where: $\%RxOy_{red.}^{fluxspar-slag}$ - percentage of the desired substance in the fluxspar [1], kg;

- For the amount of chemical compounds ($m_{red.}^{RxOy-sand}$) in the added sand:

$$m_{red.}^{RxOy-sand} = m_{red.}^{sand-slag} \frac{\%RxOy_{red.}^{sand-slag}}{100} \text{,}$$

kg, (24)

where: $\%RxOy_{red.}^{sand-slag}$ - percentage of the desired substance in the sand (Table 2) [1], kg;

- For the amount of chemical compounds ($m_{red.}^{RxOy-dinas}$) from the dinas vault of the furnace:

$$m_{red.}^{RxOy-dinas} = m_{red.}^{dinas-slag} \frac{\%RxOy_{red.}^{dinas-slag}}{100}$$

kg, (25)

where: $\%RxOy_{red.}^{dinas-slag}$ - percentage of the desired substance in the dinas [1], kg;

- For the amount of chemical compounds ($m_{red.}^{RxOy-magnesite}$) from the magnesite floor and walls of the furnace:

$$m_{red.}^{RxOy-magnesite} =$$

$$= m_{red.}^{magnesite-slag} \frac{\%RxOy_{red.}^{magnesite-slag}}{100} \text{,}$$

kg, (26)

where: $\%RxOy_{red.}^{magnesite-slag}$ - percentage of the desired substance in magnesite [1], kg;

- For the amount of chemical compounds ($m_{red.}^{RxOy-ash-electrodes,electrode\ waste}$) from the ash of the furnace electrodes and the ash of the electrode waste from the carbide mixture for the slag:

$$m_{red.}^{RxOy-ash-electrodes,electrode\ waste} =$$

$$= \left(m_{red.}^{ash-electrodes-slag} + m_{red.}^{ash-electrode\ waste-slag}\right)$$

$$\frac{\%RxOy_{red.}^{ash-electrodes,electrode\ waste-slag}}{100} \text{, kg,} \qquad (27)$$

where: $\%RxOy_{red.}^{ash-electrode,electrode\ waste-slag}$ - percentage of the desired substance in the slag [1], kg; $m_{red.}^{ash-electrode\ waste-slag}$ - amount of ash from electrode waste ($m_{red.}^{ash-electrode\ waste-slag} = m_{red.}^{electrode\ waste-slag}$. 0.01, kg, [1]);

- The silicon from the imported mill ferrosilicon to provide the missing silicon and the silicon from the imported pieces ferrosilicon to support the formation of the carbide slag ($m_{red.}^{Si-FeSi-metal,slag}$) is in the amount:

$$m_{red.}^{Si-FeSi-metal,slag} =$$

$$= \left(m_{red.}^{FeSi-add.-metal} \frac{72}{100} \frac{30}{100}\right) \cdot \left(m_{red.}^{FeSi-slag} \frac{72}{100}\right)$$

, kg. (28)

From the formula it can be seen that this silicon is oxidized by 30 % to silicon dioxide ($m_{red.}^{SiO2\text{-}FeSi\text{-}metal,slag}$). Thus, it passes into the slag in the amount:

$$m_{red.}^{SiO2-FeSi-metal,slag} = m_{red.}^{Si-FeSi-add.-metal,slag} \frac{M_{SiO2}}{A_{Si}}$$

kg, (29)

where: M_{SiO2} and A_{Si} - molecular and atomic weight, respectively, of SiO_2 and Si;

- The used quantities of ferrosilicon contain aluminum ($m_{red.}^{Al\text{-}FeSi\text{-}metal,slag}$), the amount of which is:

$$m_{red.}^{Al-FeSi-metal,slag} =$$

$$= \left(m_{red.}^{FeSi-add.-metal} + m_{red.}^{FeSi-slag}\right) \frac{2.5}{100}\text{, kg,}$$

(30)

where: 2.5/100- weight content of aluminium in 75 % FeSi [1].

As mentioned above, it will be oxidized to 100 % and as Al_2O_3 ($m_{red.}^{Al2O3\text{-}FeSi\text{-}metal,slag}$) passes into the slag according to the dependence:

$$m_{red.}^{Al2O3-FeSi-metal,slag} =$$

$$= m_{red.}^{Al-FeSi-add.-metal,slag} \frac{M_{Al2O3}}{M_{2Al}}\text{, kg,}$$

(31)

where: M_{Al2O3} and M_{2Al} - molecular weight, respectively, of Al_2O_3 and 2Al;

- The amounts of ferrosilicon used also contain some manganese ($m_{red.}^{Mn\text{-}FeSi\text{-}metal,slag}$), which is oxidized to 30 % to MnO. The amount of manganese is:

$$m_{red.}^{Mn-FeSi-metal,slag} =$$

$$= \left(m_{red.}^{FeSi-add.-metal} \frac{0.4}{100} \frac{30}{100}\right) . \left(m_{red.}^{FeSi-slag} \frac{0.4}{100}\right)$$

kg, (32)

where: 0.4/100 - weight content of manganese in 75 % FeSi (Table 1) [1].

The resulting MnO ($m_{red.}^{MnO\text{-}FeSi\text{-}metal,slag}$) passes into the slag according to the dependence:

$$m_{red.}^{MnO-FeSi-metal,slag} = m_{red.}^{Mn-FeSi-add.-metal,slag} \frac{M_{MnO}}{A_{Mn}},$$

kg, (33)

where: M_{MnO} and A_{Mn} - molecular and atomic weight, respectively, of MnO and Mn;

- As mentioned, 3 % of the chromium from ferrochrome passes into the slag, as Cr_2O_3. The amount of chromium ($m_{red.}^{Cr\text{-}FeCr\text{-}metal,slag}$) is calculated by:

$$m_{red.}^{Cr-FeCr-metal,slag} = \left(m_{red.}^{FeCr-metal} \frac{30}{100} \frac{70}{100}\right)$$

kg, (34)

where: 70/100 - weight content of chromium in ferrochrome [1].

The resulting Cr_2O_3 ($m_{red.}^{Cr2O3\text{-}metal,slag}$) passes into the slag according to the relationship:

$$m_{red.}^{Cr2O3-FeCr-metal,slag} = m_{red.}^{Cr-FeCr-metal,slag} \frac{M_{Cr2O3}}{M_{Cr2}}$$

kg, (35)

where: M_{Cr2O3} and M_{2Cr} - molecular weight, respectively, of Cr_2O_3 and 2Cr.

Deacidification of the liquid metal [3]

Deoxidation is a mandatory part of the reduction period, which aims to remove as much oxygen from the metal юas possible.

For carbon tool steels, such as the current bearing steel, the following order of reduction of metal and slag from oxygen is assumed, shown in Table 1.

At the beginning of the reduction period, Al pieces are added to the FeSi pieces for deep (precipitation) initial deoxidation. At the end of the oxidation period, SiMn is introduced, the effect of which on the metal and slag is shown in [2]. At the end of the oxidation period, the metal contains oxygen in the form of FeO ($m_{oxid.\text{-}end}^{FeO\rightarrow O2}$), the amount of which is:

$$m_{oxid.-end}^{FeO\rightarrow O2} = \frac{m_{oxid.\rightarrow red.}^{metal} . \%[FeO]_{oxid.}^{TD} . A_O}{100 . M_{FeO}}$$

kg O_2, (36)

where: $\%[FeO]_{oxid.}^{TD}$ - concentration of FeO (0.126 %), respectively oxygen, in the metal of the oxidation period, necessary to reach 0.8 % C at the end of the oxidation period [2], %; A_O - atomic mass of oxygen in FeO; M_{FeO} - molecular mass of FeO.

A part of this oxygen ($m_{red.}^{FeO+Mn\rightarrow O2}$) during

Table 1. Percentages of oxygen removal from metal and slag using deoxidizing elements.

Deoxidizer	From the metal, %	From the slag, %
Mn from SiMn on pieces	10	-
Si from FeSi on pieces	10	-
C from electrode wastes and CaC_2	30	90
Si from mill FeSi	25	3
Al from Al on pieces	15	-
Total	90	93

deoxidation, through manganese, is combined according to the equation FeO + Mn = MnO + Fe with manganese in the amount:

$$m_{red.}^{FeO+Mn\rightarrow O2} = \frac{m_{oxid.\rightarrow red.}^{metal} \cdot m_{oxid.-end}^{FeO\rightarrow O2} \cdot \frac{10}{100}}{100}$$

, kg O_2, (37)

where: 10/100 s- percentage of oxygen taken from the metal, through manganese (Table 1).

Thus, the metal is reduced to iron in the amount $m_{red.}^{FeO+Mn\rightarrow Fe}$ according to the formula:

$$m_{red.}^{FeO+Mn\rightarrow Fe} = m_{red.}^{FeO+Mn\rightarrow O2} \frac{A_{Fe}}{A_O}\text{, kg Fe,} \quad (38)$$

where: A_{Fe} - atomic mass of iron.

The amount of MnO formed ($m_{red.}^{FeO+Mn\rightarrow MnO}$) is calculated by the formula:

$$m_{red.}^{FeO+Mn\rightarrow MnO} = m_{red.}^{FeO+Mn\rightarrow O2} \frac{M_{MnO}}{A_O}\text{, kg,} \quad (39)$$

where: M_{MnO} - molecular mass of manganese oxide.

The mass of manganese consumed ($m_{red.}^{FeO\rightarrow Mn}$) is:

$$m_{red.}^{FeO\rightarrow Mn} = m_{red.}^{FeO+Mn\rightarrow O2} \frac{A_{Mn}}{A_O}\text{, kg,} \quad (40)$$

where: A_{Mn} - atomic mass of manganese.

During the deoxidation of the metal with ferrosilicon in pieces, another part of the oxygen ($m_{red.}^{FeO+Si(pieces)\rightarrow O2}$) combines with silicon:

$$m_{red.}^{FeO+Si(pieces)\rightarrow O2} =$$

$$= \frac{m_{oxid.\rightarrow red.}^{metal} \cdot m_{oxid.-end}^{FeO\rightarrow O2} \cdot \frac{10}{100}}{100}\text{, kg } O_2\text{,} \quad (41)$$

where: 10/100 - % of oxygen removed from the metal by silicon (Table 1).

Thus, the metal is reduced to iron in an amount of $m_{red.}^{FeO+Si(pieces)\rightarrow Fe}$ according to the formula:

$$m_{red.}^{FeO+Si(pieces)\rightarrow Fe} = m_{red.}^{FeO+Si(pieces)\rightarrow O2} \frac{A_{Fe}}{A_O}$$

kg Fe, (42)

The amount of SiO_2 formed ($m_{red.}^{FeO+Si(pieces)\rightarrow SiO2}$) is calculated according to the formula:

$$m_{red.}^{FeO+Si(pieces)\rightarrow Fe} = m_{red.}^{FeO+Si(pieces)\rightarrow O2} \frac{A_{Fe}}{A_O}$$

kg, (43)

where: M_{SiO2} - molecular mass of silicon dioxide; M_{O2} - molecular mass of oxygen.

The mass of silicon consumed ($m_{red.}^{FeO\rightarrow Si(pieces)}$) is:

$$m_{red.}^{FeO\rightarrow Si(pieces)} = m_{red.}^{FeO+Si(pieces)\rightarrow O2} \frac{A_{Si}}{M_{O2}},$$

kg, (44)

where: A_{Si} - atomic mass of silicon.

At this stage of the process, during the deoxidation of the metal with aluminum in pieces, another part of the oxygen ($m_{red.}^{FeO+Al(pieces)\rightarrow O2}$) combines with aluminum:

$$m_{red.}^{FeO+Al(pieces)\rightarrow O2} =$$

$$= \frac{m_{oxid.\rightarrow red.}^{metal} \cdot m_{oxid.-end}^{FeO\rightarrow O2} \cdot \frac{15}{100}}{100},$$

kg O_2, (45)

where: 15/100 - percentage of oxygen taken from the metal by aluminium (Table 1).

Thus, the metal is reduced to iron in an amount of $m_{red.}^{FeO+Al(pieces)\rightarrow Fe}$ according to the formula:

$$m_{red.}^{FeO+Al(pieces)\rightarrow Fe} = m_{red.}^{FeO+Al(pieces)\rightarrow O2} \frac{A_{Fe}}{A_O}$$

kg Fe. (46)

The amount of Al_2O_3 formed ($m_{red.}^{FeO+Al(pieces)\rightarrow Al2O3}$) is calculated according to the formula:

$$m_{red.}^{FeO+Al(pieces)\rightarrow Al2O3} =$$

$$= m_{red.}^{FeO+Al(pieces)\rightarrow O2} \frac{M_{Al2O3}}{M_{O3}}, \text{ kg}, \quad (47)$$

where: M_{Al2O3} - molecular mass of dialuminium trioxide. The mass of the spent aluminium ($m_{red.}^{FeO\rightarrow Al(pieces)}$) is:

$$m_{red.}^{FeO\rightarrow Al(pieces)} = m_{red.}^{FeO+Al(pieces)\rightarrow O2} \frac{A_{2Al}}{M_{O3}}$$

kg, (48)

where: A_{2Al} - atomic mass of aluminium.

Around the middle of the reduction period, desulfurization of sulfur in the amount of $m_{red.-end}^{(S)}$ begins, by CaO from the slag. As a result of the desulfurization reaction CaO + FeS = CaS + FeO, iron is consumed ($m_{red.}^{FeS\rightarrow Fe}$) in the amount of:

$$m_{red.}^{FeS\rightarrow Fe} = m_{red.-end}^{(S)} \frac{A_{Fe}}{A_S}, \text{ kg}, \quad (49)$$

where: A_S - atomic mass of sulfur.

Thus, FeO is obtained in the amount of $m_{red.}^{FeS+CaO\rightarrow FeO}$ according to the formula:

$$m_{red.}^{FeS+CaO\rightarrow FeO} = m_{red.}^{FeS\rightarrow Fe} \frac{M_{FeO}}{A_{Fe}}, \text{ kg}. \quad (50)$$

Furthermore, deoxidation continues through the ground electrodes and ferrosilicon by diffusion under carbide slag. According to Table 1, when the metal is exposed to such slag, 30 % of the oxygen (or 30/100 by weight) in it will be removed, thus reducing FeO in the amount ($m_{red.}^{FeO+C\rightarrow Fe}$):

$$m_{red.}^{FeO+C\rightarrow Fe} = \frac{m_{oxid.\rightarrow red.}^{metal} \cdot \%[FeO]_{oxid.}^{TD} \cdot \frac{30}{100}}{100}$$

kg. (51)

Also according to Table 1, 90 % of the oxygen will be removed from the slag by carbon, which makes it possible to completely (or 100/100 = 1.00 in weight ratio) reduce MnO, Fe_2O_3 and P_2O_5, as well as up to 80 % (or 80/100 = 0.8 in weight ratio) of FeO and Cr_2O_3. Thus, the corresponding amounts reduced by the slag ($m_{red.}^{MnO+C}$, $m_{red.}^{Fe2O3+C}$, $m_{red.}^{P2O5+C}$, $m_{red.}^{FeO+C}$, $m_{red.}^{Cr2O3+C}$) of the indicated oxides are determined by the formulas:

$$m_{red.}^{MnO+C} = (m_{red.}^{FeO+Mn\rightarrow MnO} + m_{red.}^{MnO\text{-}tab.1}) \cdot 1.00, \text{ kg}, \quad (52)$$

where: $m_{red.}^{MnO\text{-}tab.1}$ - amount of manganese oxide in the pre-calculated reduction slag (Table 4 below), kg;

$$m_{red.}^{Fe2O3+C} = m_{red.}^{Fe2O3\text{-}tab.1} \cdot 1.00, \text{ kg}, \quad (53)$$

where: $m_{red.}^{Fe2O3\text{-}tab.1}$ - amount of diiron trioxide in the pre-calculated reduction slag (Table 4), kg;

$$m_{red.}^{P2O5+C} = m_{red.}^{P2O5\text{-}tab.1} \cdot 1.00, \text{ kg}, \quad (54)$$

where: $m_{red.}^{P2O5\text{-}tab.1}$ - amount of diphosphorus pentoxide in the pre-calculated reduction slag (Table 4), kg;

$$m_{red.}^{FeO+C} = (m_{red.}^{FeS+CaO\rightarrow FeO} + m_{red.}^{FeO\text{-}tab.1}) \cdot 0.8, \text{ kg} \quad (55)$$

where: $m_{red.}^{FeO\text{-}tab.1}$ - amount of iron oxide in the previously calculated reduction slag (Table 4), kg;

$$m_{red.}^{Cr2O3+C} = m_{red.}^{Cr2O3\text{-}tab.1} \cdot 0.8, \text{ kg}, \quad (56)$$

where: $m_{red.}^{Cr2O3\text{-}tab.1}$ - amount of dichromium trioxide in the previously calculated reduction slag (Table 4), kg.

The calculations of dependencies from 52 to 56, the reduction reactions of the indicated oxides by carbon and the mass of the products that passed into the metal are shown in Table 2. Further deoxidation continues to be carried out by diffusion, with the help of silicon from the ground FeSi, which additionally deoxidizes 25 % (or 25/100 in weight parts, Table 1) of FeO from the metal. For this amount of FeO ($m_{red.}^{FeO+Si\rightarrow Fe}$)

$$m_{red.}^{FeO+Si\rightarrow Fe} = \frac{m_{oxid.\rightarrow red.}^{metal} \cdot \%[FeO]_{oxid.}^{TD} \cdot \frac{25}{100}}{100}$$

kg. (57)

Of the remaining 20 %, unreduced by carbon amounts of FeO and Cr_2O_3 in the slag, silicon reduces FeO to a residual content in it of about 0.3 % (between 0.1 and 0.5 % [3]). This FeO ($m_{red.}^{FeO\rightarrow 0.3\text{-}slag}$) is determined by:

$$m_{red.}^{FeO+Si\rightarrow 0.3\text{-}slag+Fe} = (0.038 + m_{red.}^{FeS+CaO\rightarrow FeO}) - \\ - (m_{red.}^{FeO+C} + 2.490 \frac{0{,}3}{100}), \text{ kg}, \quad (58)$$

where: 0.038 - amount of FeO from the previously calculated slag (Table 4), kg; 2.490 - total amount of the previously calculated slag (Table 4), kg.

The mass of Cr_2O_3 ($m_{red.}^{Cr2O3+Si\rightarrow Cr}$) is found by the expression:

Table 2. Reduced oxides of carbon from carbide slag.

Oxide	Mass, kg	Reaction	Expenditure of carbon, kg	Pass in the metal, kg
FeO	0.037*+0.045=0.082	FeO+C=Fe+CO	$0.082\frac{12}{72}=0.013$	$0.082\frac{56}{72}=0.064$ Fe
Fe_2O_3	0.042	$Fe_2O_3+3C=2Fe+3CO$	$0.042\frac{36}{160}=0.010$	$0.042\frac{112}{160}=0.029$ Fe
MnO	0.034	MnO+C=Mn+CO	$0.034\frac{12}{71}=0.006$	$0.034\frac{55}{72}=0.026$ Mn
Cr_2O_3	0.051	$Cr_2O_3+3C=2Cr+3CO$	$0.051\frac{36}{152}=0.012$	$0.051\frac{104}{152}=0.035$ Cr
P_2O_5	0.007	$P_2O_5+5C=2P+5CO$	$0.007\frac{60}{142}=0.003$	$0.007\frac{62}{142}=0.003$ P
		Total	0.044 C	

*Note: * - this quantity is obtained after calculating (51).*

Table 3. Reduced silicon oxides from mill FeSi.

Oxide	Mass, kg	Reaction	Expenditure of silicon, kg	Pass in the metal, kg
FeO	0.031+0.00 = 0.034	$2FeO+Si = 2Fe+SiO_2$	$0.034\frac{28}{144}=0.007$	$0.034\frac{56}{72}=0.029$ Fe
Cr_2O_3	0.013	$2Cr_2O_3+3Si=2Cr+3SiO_2$	$0.013\frac{84}{304}=0.004$	$0.013\frac{104}{152}=0.009$ Cr
		Total	0.011 Si	

$$m_{red.}^{Cr2O3+Si\rightarrow Cr}=\frac{0{,}20}{100}\,0.064,\ \text{kg}, \qquad (59)$$

where: 0.064 - amount of Cr_2O_3 from the previously calculated slag, kg (Table 4).

The calculations of dependencies from 57 to 59, the reduction reactions of the indicated oxides of silicon and the mass of the products passed into the metal are shown in Table 3.

As can be seen from Table 3, the silicon consumption for the reduction of the indicated oxides is 0.011 kg, from which the following amount of SiO_2 will be obtained ($m_{red.}^{FeO,Cr2O3+Si\rightarrow SiO2}$):

$$m_{red.}^{FeO,Cr2O3+Si\rightarrow SiO2}=0.011\,\frac{M_{SiO2}}{A_{Si}},\ \text{kg}, \qquad (60)$$

where: M_{SiO2} - molecular mass of SiO_2.

The metal remains 10 % (or 10/100 by weight) of the FeO dissolved at the end of the oxidation period, which amount ($m_{red.}^{FeO\text{-}metal\text{-}oxid.}$) in kilograms is calculated by the expression:

$$m_{red.}^{FeO-metal-oxid.}=$$

$$=\frac{m_{oxid.-end}^{FeO-metal}\cdot m_{oxid.\rightarrow red.}^{metal}\cdot\frac{10}{100}}{100},\ \text{kg}, \qquad (61)$$

where: $m_{oxid.\text{-}end}^{FeO\text{-}metal}$ - amount of iron oxide in the metal at the end of the oxidation period [2], kg.

The last part of the deoxidation is carried out again by deep (precipitation) deoxidation with aluminum. This is done by introducing aluminum into the furnace at the end of the reduction period. Its consumption is assumed to be from 0.03 to 0.05 kg / 100 kg of metal (average 0.04 kg) [3]. Thus, according to the chemical composition of the aluminum used (Table 1), its amount ($m_{red.}^{FeO\rightarrow Al(final\ deoxidation)}$) is:

$$m_{red.}^{FeO\rightarrow Al(final\ deoxidation)}=0.04\frac{98}{100},\ \text{kg}, \qquad (62)$$

where: 98 - content of the chemical element aluminum in the aluminum introduced into the deoxidation process, %.

It is assumed that half (or 50/100) of this aluminum, as a result of the previous deoxidation procedures and the reduction of the amount of oxygen in the metal, is oxidized to Al_2O_3, which passes into the slag. This amount of Al_2O_3 ($m_{red.}^{FeO+Al(final\ deoxidation)\to Al2O3}$) is calculated by:

$$m_{red.}^{FeO+Al(final\ deoxidation)\to Al2O3} =$$

$$= m_{red.}^{FeO\to Al(final\ deoxidation)}\ \frac{50}{100}\,\frac{M_{Al2O3}}{M_{Al2}}\ ,\ kg. \qquad (63)$$

The other half of the aluminum ($m_{red.}^{Al(final\ deoxidation)-metal}$) passes into the metal:

$$m_{red.}^{Al(final\ deoxidation)-metal} =$$

$$= m_{red.}^{FeO\to Al(final\ deoxidation)}\ \frac{50}{100},\ kg. \qquad (64)$$

Iron from aluminum (2 %, [1]) passes completely into the metal in an amount ($m_{red.}^{Al(final\ deoxidation)-Fe-metal}$):

$$m_{red.}^{Al(final\ deoxidation)-Fe-metal} =$$

$$= m_{red.}^{FeO\to Al(final\ deoxidation)}\ \frac{2}{100}\ ,kg. \qquad (65)$$

Final composition and quantity of metal and slag from the reduction period [3]

The slag composition during about 2/3 of the period contains about 4 % CaC_2, and at the end of the reduction period the slag is brought to a low-carbide content, containing about 1 % CaC_2 ($m_{red.}^{slag-CaC2}$). This amount is calculated by the formula:

$$m_{red.}^{slag-CaC2} = 2.490\ \frac{1}{100},\ kg, \qquad (66)$$

where: 2.490 - total amount of slag at the beginning of the reduction period, see tab. 4.

To form this carbide, the reaction $CaO + 3C =$ $= CaC_2 + CO$ is in effect, and calcium oxide is required in the amount ($m_{red.}^{CaO\to CaC2}$):

$$m_{red.}^{CaO\to CaC2} = 2.490\ \frac{M_{CaO}}{M_{CaC2}},\ kg, \qquad (67)$$

where: M_{CaO} and M_{CaC2} - molecular masses, respectively, of CaO and CaC_2.

For this, carbon with a mass ($m_{red.}^{C\to CaC2}$) is also required:

$$m_{red.}^{C\to CaC2} = 2.490\ \frac{A_{2C}}{M_{CaC2}},\ kg. \qquad (68)$$

About 1/2 of the CaF_2, which is introduced in the middle of the reduction period, through fluxspar, reacts with SiO_2 by the reaction $2CaF_2 + SiO_2 = SiF_4 + 2CaO$. Silicon fluoride is volatile and passes into the gas phase. For its formation, SiO_2 is required in an amount ($m_{red.}^{SiF4\to SiO2}$):

$$m_{red.}^{SiF4\to SiO2} = \frac{1}{2}\ 0.171\ \frac{M_{SiO2}}{M_{2CaF2}}\ ,\ kg, \qquad (69)$$

where: M_{SiO2} and M_{2CaF2} - molecular masses, respectively, of SiO_2 and $2CaF_2$; 0.171 - amount of CaF_2 in the fluxspar (Table 4), kg.

As mentioned, silicon fluoride is formed ($m_{red.}^{CaF2+SiO2\to SiF4}$):

$$m_{red.}^{CaF2+SiO2\to SiF4} = \frac{1}{2}\ 0.171\ \frac{M_{SiF4}}{M_{2CaF2}},\ kg, \qquad (70)$$

where: M_{SiF4} - molecular mass of SiF_4.

Calcium oxide is also formed ($m_{red.}^{CaF2+SiO2\to CaO}$):

$$m_{red.}^{CaF2+SiO2\to CaO} = \frac{1}{2}\ 0.171\ \frac{M_{2CaO}}{M_{2CaF2}},\ kg, \qquad (71)$$

where: M_{2CaO} - molecular mass of 2CaO.

As a result of the desulfurization reaction $CaO + FeS = CaS + FeO$, for the separation of sulfur from the metal in an amount of $m_{red.-end}^{(S)} =$ 0.008 kg (Table 5), CaS is formed ($m_{red.}^{CaO+FeS\to CaS}$) according to the formula:

$$m_{red.}^{CaO+FeS\to CaS} = m_{red.-end}^{(S)}\ \frac{M_{CaS}}{A_S}\ ,\ kg, \qquad (72)$$

where: M_{CaS} - molecular mass of CaS. For this, CaO is required in an amount of ($m_{red.}^{CaS\to CaO}$):

$$m_{red.}^{CaS\to CaO} = m_{red.}^{CaO+FeS\to CaS}\ \frac{M_{CaO}}{M_{CaS}}\ ,kg \qquad (73)$$

During this period, silicon is reduced from the slag with a mass $m_{red.}^{\text{Si-slag}\to\text{metal}}$ according to the equation $SiO_2 + 2C = Si + 2CO$. This requires silicon dioxide in the amount ($m_{red.}^{\text{Si-metal}\to\text{SiO2-slag}}$):

$$m_{red.}^{\text{Si-metal}\to\text{SiO2-slag}} = m_{red.}^{\text{Si-slag}\to\text{metal}}\frac{M_{SiO2}}{A_{Si}}$$

kg, (74)

as well as carbon in the amount $m_{red.}^{\text{SiO2-slag}\to\text{C}}$ according to the formula:

$$m_{red.}^{\text{SiO2-slag}\to\text{C}} = m_{red.}^{\text{Si-slag}\to\text{metal}}\frac{A_{2C}}{A_{Si}}\text{, kg} \qquad (75)$$

Composition and quantity of the gas phase from the reduction period [3]

As mentioned above, during the reduction period of 100 kg of metal, graphite electrodes in the amount of $m_{red.}^{\text{electrodes}}$ are consumed. From the melting period, we know that the carbon in them is 99 % (or 90/100 by weight). Thus, its mass ($m_{red.}^{\text{electrodes-C}}$) is:

$$m_{red.}^{\text{electrodes-C}} = m_{red.}^{\text{electrodes}}\frac{90}{100}\text{, kg.} \qquad (76)$$

From the mill electrode waste, especially from its fine fraction (in them carbon is also 99 %), which are introduced into the slag after the first slag mixture to form carbide slag, carbon is oxidized in an amount ($m_{red.}^{\text{electrode waste-C}}$) according to the formula:

$$m_{red.}^{\text{electrode waste-C}} = \left(m_{red.}^{\text{electrode waste-slag}}\frac{90}{100}\right) -$$

$$- \left(0.044 + 0.128 + m_{red.}^{\text{C}\to\text{CaC2}} + m_{red.}^{\text{SiO2-slag}\to\text{C}}\right)\text{, kg,} \qquad (77)$$

where: 0.044 - total amount of carbon for reduction, see table 3, kg; 0.128 - amount of carbon passing from the slag to the metal, Table 5, kg.

When working under carbide slag, the carbon from the electrodes and the excess of ground electrode waste is oxidized by the air to CO, burning carbon in an amount $m_{red.}^{\text{electrodes-C,electrode waste-C}\to\text{CO}}$ according to:

$$m_{red.}^{\text{electrodes-C,electrode waste-C}\to\text{CO}} = m_{red.}^{\text{electrodes-C}} + m_{red.}^{\text{electrode waste-C}}\text{, kg.} \qquad (78)$$

This forms carbon monoxide with a weight ($m_{red.}^{\text{electrodes,electrode waste}\to\text{CO}}$) calculated by the formula:

$$m_{red.}^{\text{electrodes,electrode waste}\to\text{CO}} = m_{red.}^{\text{electrodes-C,electrode waste-C}\to\text{CO}}\frac{M_{CO}}{A_C}\text{, kg.} \qquad (79)$$

This carbon monoxide will consume oxygen ($m_{red.}^{\text{electrodes-C,electrode waste-C-O2}\to\text{CO}}$):

$$m_{red.}^{\text{electrodes-C,electrode waste-C-O2}\to\text{CO}} = m_{red.}^{\text{electrodes,electrode waste}\to\text{CO}} - m_{red.}^{\text{electrodes-C,electrode waste-C}\to\text{CO}}\text{, kg.} \qquad (80)$$

During deoxidation, silicon is oxidized (from the ground ferrosilicon, where silicon is 72 % or 0.72 by weight) by the reaction $Si + O_2 = SiO_2$. As mentioned above, 30 % or 0.30 by weight of this silicon is oxidized and passes into the slag. The amount of oxidized silicon ($m_{red.}^{\text{FeSi-mill-Si}\to\text{SiO2}}$) is:

$$m_{red.}^{\text{FeSi-mill-Si}\to\text{SiO2}} = \left(m_{red.}^{\text{FeSi-add.-metal}} \cdot 0.72 \cdot 0.30 - 0.011\right) + \left(m_{red.}^{\text{Si-slag}} - 0.003\right)\text{, kg,} \qquad (81)$$

where: 0.011 - total silicon consumption for the reduction of FeO and Cr_2O_3, Table 3, kg; 0.003 - weight amount (or about 0.3 %) of silicon in the finished metal by condition [1], kg.

For the oxidation of this silicon, oxygen will be required $m_{red.}^{\text{FeSi-mill-O2}\to\text{SiO2}}$:

$$m_{red.}^{\text{FeSi-mill-O2}\to\text{SiO2}} = m_{red.}^{\text{FeSi-mill-Si}\to\text{SiO2}}\frac{M_{O2}}{A_{Si}}\text{, kg} \qquad (82)$$

In the final deoxidation with aluminum according to the reaction: $2Al + 3FeO = 3Fe + Al_2O_3$, as mentioned above, 50 % (or 0.50 by weight) of aluminum is oxidized in the amount $m_{red.}^{\text{FeO}\to\text{Al(final deoxidation)}}$ according to the formula:

$$m_{red.}^{\text{Al(final deoxidation)}\to\text{Al2O3}} = m_{red.}^{\text{FeO}\to\text{Al(final deoxidation)}} \cdot 0.50\text{, kg,} \qquad (83)$$

where: $m_{red.}^{\text{Al(final deoxidation)}\to\text{Al2O3}}$ - amount of oxidized aluminum passing into the slag, kg.

For this oxidation, oxygen is required ($m_{red.}^{Al(final\ deoxidation)\rightarrow O2\rightarrow Al2O3}$):

$$m_{red.}^{Al(final\ deoxidation)\rightarrow O2\rightarrow Al2O3} = m_{red.}^{Al(final\ deoxidation)\rightarrow Al2O3}\ \frac{M_{O3}}{M_{Al2}}\ \text{, kg.} \qquad (84)$$

Thus, the total oxygen required from the air is $m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2}$ and is calculated by:

$$m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2} = m_{red.}^{electrodes\text{-}C,electrode\ waste\text{-}C\text{-}O2\rightarrow CO} + m_{red.}^{FeSi\text{-}mill\text{-}O2\rightarrow SiO2} + m_{red.}^{Al(final\ deoxidation)\rightarrow O2\rightarrow Al2O3}\text{, kg.} \qquad (85)$$

This oxygen corresponds to a volume ($V_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2}$):

$$V_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2} = m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2}\ \frac{1 mol\ o2}{M_{O2}}\text{, m}^3\text{,} \qquad (86)$$

where: 1mol O_2 - 22.4 l.

Oxygen is accompanied by nitrogen with a mass $m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2\rightarrow N2}$:

$$m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2\rightarrow N2} = m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2}\ \frac{77}{23}\text{, kg,} \qquad (87)$$

where: 77/23 - approximate weight ratio of nitrogen to oxygen in the air.

This nitrogen corresponds to a volume ($V_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2\rightarrow N2}$) by the expression:

$$V_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2\rightarrow N2} = V_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2}\ \frac{79}{21}\text{, m}^3\text{,} \qquad (88)$$

where: 79/21 - approximate volume ratio of nitrogen to oxygen in the air.

Thus, the mass of air ($m_{red.}^{air}$) will be:

$$m_{red.}^{air} = m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2\rightarrow N2} + m_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2}\text{, kg.} \qquad (89)$$

Atmospheric air is used in the process and in order to obtain its volume ($V_{red.}^{atm.air}$) it is necessary to take into account a certain amount of impurities in it, for which a coefficient of 1.09 is assumed [3]. Thus, it is obtained:

$$V_{red.}^{atm.air} = (V_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2} + V_{red.}^{C,Si,Al\text{-}oxidation\rightarrow O2\rightarrow N2})\ .\ 1.09\text{, m}^3\text{.} \qquad (90)$$

It is assumed that the mass of moisture in 1 m^3 of atmospheric air ($m_{H2O}^{1m3\text{-}atm.air}$) is 0.012 kg. Then the used volume of atmospheric air, according to (90) will bring into the process moisture with mass $m_{red.}^{air\rightarrow H2O}$ according to:

$$m_{red.}^{air\rightarrow H2O} = V_{red.}^{atm.air}\ .\ m_{H2O}^{1m3\text{-}atm.air}\text{, kg.} \qquad (91)$$

The amount of moisture brought with lime ($m_{red.}^{lime\rightarrow H2O}$) is:

$$m_{red.}^{lime\rightarrow H2O} = 0.676\ .\ 0.002\text{, kg,} \qquad (92)$$

where: 0.676 - amount of lime in the slag from the reduction period (see Table 6), kg; 0.002 - weight amount of H_2O in the lime [1], kg.

Thus, the mass of the total moisture introduced $m_{red.}^{atm.air,lime\rightarrow H2O}$ is:

$$m_{red.}^{atm.air,lime\rightarrow H2O} = m_{red.}^{air\rightarrow H2O} + m_{red.}^{lime\rightarrow H2O}\text{, kg} \qquad (93)$$

The total amount of water vapor will be reduced by carbon monoxide by the reaction $H_2O + CO = H_2 + CO_2$. The hydrogen that will be formed ($m_{red.}^{H2O\rightarrow H2}$) will be:

$$m_{red.}^{H2O\rightarrow H2} = m_{red.}^{atm.air,lime\rightarrow H2O}\ \frac{M_{H2}}{M_{H2O}}\text{, kg,} \qquad (94)$$

where: M_{H2} and M_{H2O} - molecular weight, respectively, of hydrogen and water.

The carbon monoxide required for this reduction ($m_{red.}^{H2O+CO}$) is:

$$m_{red.}^{H2O+CO} = m_{red.}^{atm.air,lime\rightarrow H2O}\ \frac{M_{CO}}{M_{H2O}}\text{, kg.} \qquad (95)$$

In this way, CO_2 will be formed in the amount ($m_{red.}^{H2O\rightarrow CO2}$):

$$m_{red.}^{H2O\rightarrow CO2} = m_{red.}^{H2O+CO}\ \frac{M_{CO2}}{M_{CO}}\text{, kg.} \qquad (96)$$

At the temperatures of the reduction process, the lime used is heated, while the carbon dioxide contained in it is released into the gas phase with a mass $m_{red.}^{lime\rightarrow CO2}$, which is 0.20 % or 0.002 kg [1]:

$$m_{red.}^{lime\rightarrow CO2} = 0.676 \; . \; 0.002, \text{ kg.} \qquad (97)$$

Another amount of carbon monoxide ($m_{red.}^{CaO\rightarrow CO}$) passes into the gas phase after the formation of calcium carbide by the reaction 3C + CaO = CaC_2 + CO, by the formula:

$$m_{red.}^{CaO\rightarrow CO} = m_{red.}^{slag\text{-}CaC2} \frac{M_{CO}}{M_{CaC2}}, \text{ kg.} \qquad (98)$$

When reducing SiO_2 from the slag with its carbon by the reaction $SiO_2 + 2C = Si + 2CO$, carbon monoxide is also produced, for whose mass $m_{red.}^{SiO2\rightarrow 2CO}$ the formula is valid:

$$m_{red.}^{CaO\rightarrow CO} = m_{red.}^{slag\text{-}CaC2} \frac{M_{CO}}{M_{CaC2}}, \text{ kg.} \qquad (99)$$

When deoxidizing oxides with carbon according to the reactions presented in Table 2, carbon monoxide ($m_{red.}^{RxOy\rightarrow CO}$) is released in the amount:

$$m_{red.}^{RxOy\rightarrow CO} = 0.044 \frac{M_{CO}}{A_C}, \text{ kg,} \qquad (100)$$

where: 0.044 - total amount of carbon required for the reductions, Table 2, kg.

According to equation (70), silicon fluoride with a mass $m_{red.}^{CaF2+SiO2\rightarrow SiF4}$ is formed, which passes completely to the gas phase.

RESULTS AND DISCUSSION

After substitution with the values of the various components and calculation using dependencies from (1) to (35), the preliminary composition and quantity of the slag is obtained, presented in Table 4.

From the composition thus calculated, it can be easily calculated that the basicity of the slag at the initial stage of the reduction period is about 2. Further, with the formation of carbide slag, as described in the model, the basicity will increase slightly. After calculating the dependencies from (36) to (75), the values for the composition of the metal and slag at the end of the reduction period were obtained in Tables 5 and 6. For the formation of these tables, the formulas from the notes below them were also taken into account.

The results for the gas phase are based on formulas (76) to (100). Thus, its composition is shown in Table 7.

Table 4. Preliminary composition and mass (kg) of the reduction slag.

Oxide	Slag from the oxid. period	Lime	Flux spar	Sand	Dinas from the vault	Floor and walls	Electrodes ash and electrodes waste ash	From FeSi	From FeCr	Sum	
										kg	%
CaO	0.208	0.622	0.001	-	0.002	0.018	0.0005	-	-	0.852	34.22
SiO_2	0.054	0.017	0.006	0.043	0.387	0.017	0.0023	0.189	-	0.715	28.72
MgO	0.067	0.022	-	-	-	0.451	-	-	-	0.540	21.69
Al_2O_3	0.008	0.007	0.001	0.001	0.003	0.004	0.0013	0.011	-	0.036	1.45
FeO	0.038	-	-	-	-	-	-	-	-	0.038	1.53
Fe_2O_3	0.021	0.004	0.001	0.001	0.005	0.010	-	-	-	0.042	1.67
MnO	0.020	-	-	-	-	-	-	0.001	-	0.021	0.84
CaF_2	-	-	0.171	-	-	-	-	-	-	0.171	6.87
P_2O_5	0.003	0.001	-	-	0.003	-	-	-	-	0.007	0.28
Cr_2O_3	-	-	-	-	-	-	-	-	0.064	0.064	2.57
S	0.001	0.001	0.001	-	-	-	-	-	-	0.003	0.12
H_2O	-	0.001	-	-	-	-	-	-	-	0.001	0.04
Total	0.420	0.676	0.180	0.045	0.400	0.500	0.004	0.201	0.064	2.490	100

Table 5. Mass and composition of the metal at the end of the reduction period, kg.

Element	Metal at the beginning of the red. period[*]	Imported with FeSi-pieces[**]	Imported with FeCr[***]	It is reduced from FeO in the metal during initial deoxidation with Mn, FeSi-pieces, Al-pieces	Passes from the slag upon reduction with C from the slag or Si from FeSi-mill	Imported from mill FeSi[*****]	Imported by Al at initial and final deoxidation	Expenditure from deoxidation or desulphurization (the values presented are subtracted from the sum)	Sum	
									kg	%
C	0.779	0.00008	0.084	-	0.128[****]	0.0002	-	-	0.991	0.985
Mn	0.291	0.0003	0.008	-	0.026, see tab. 3	0.001	-	0.010, see (40)	0.316	0.308
Si	0.047	-	0.042	-	0.066, see (15)	0.092	-	-	0.247	0.248
P	0.014	0.00003	0.001	-	-	0.00005	-	-	0.015	0.015
S	0.020	0.00002	0.001	-	-	0.00004	-	0.008, see (1)	0.013	0.013
Cr	-	-	1.426	-	0.035+0.009, see tab. 3 and tab. 4	-	-	-	1.470	1.451
FeO	0.123	-	-	-	-	-	-	0.123.0.9[******] = 0.111	0.012	0.012
Al	-	-	-	-	-	0.005	0.005+0.040, see (48) and (62)	0.005+0.020, see (48) and (62)	0.025	0.025
Fe	96.876	0.017	0.494	0.011+0.011+0.014, see (38), (42), (46)	0.064+0.029+0.026, see tab. 3 and tab. 4	0.031	0.0008	0.014, see (49)	97.560	96.931
Total	98.150	0.017	2.056	0.036	0.383	0.129	0.046	0.168	100.649	100

*Note: * - [2];*

** - *the values are calculated using the formula:* $m_{red.}^{R-FeSi-metal} = m_{red.}^{FeSi-slag} \frac{\%R_{FeSi}^{pieces/mill}}{100}$, *kg, where:* $m_{red.}^{R-FeSi-metal}$ *- elements from FeSi-pieces passing into the metal, kg;* $\%R_{FeSi}^{pieces/mill}$ *- percentage content of elements in FeSi-pieces [1], %.* (101)

*** - *the values are calculated using the formula:* $m_{red.}^{R-FeCr-metal} = m_{red.}^{FeCr-metal} \frac{\%R_{FeCr}^{pieces}}{100}$ *(only for chromium, the formula takes into account 3 % Cr passing into the slag), kg, where:* $m_{red.}^{R-FeCr-metal}$ *- elements from FeCr passing into the metal, kg;* $\%R_{FeCr}^{pieces}$ *- percentage content of elements in FeCr [1], %.* (102)

**** - *in 80 minutes under carbide slag, about 10 % (or 10/100 = 0.1) carbon passes from the slag into the metal in percentage* ($\%C_{red.}^{slag\to metal}$): $\%C_{red.}^{slag\to metal} = 0.1\ 80/60$, *%.* (103)

or in weight ($m_{red.}^{C-slag\to metal}$): $m_{red.}^{C-slag\to metal} = m_{oxid.\to red.}^{metal} \frac{\%C_{red.}^{slag\to metal}}{100}$, *kg.* (104)

***** - *the values are calculated by the formula:* $m_{red.}^{R-FeSi-add.-metal} = m_{red.}^{FeSi-add.-metal} \frac{\%R_{FeSi}^{pieces/mill}}{100}$ *70/100, kg, where:* $m_{red.}^{R-FeSi-add.-metal}$ *- elements from FeSi-mill, passing into the metal, kg; 70/100 - percentage, in weight ratio, of absorption by the metal of the elements C, Mn, Si, P, S, Fe from FeSi-mill (only aluminum from FeSi-mill passes completely into the metal), kg.* (105)

****** - *0.9 - percentage of passage in weight ratio (90/100) of FeO from the metal to the slag (61), kg..*

Table 6. Mass and composition of slag at the end of the reduction period, kg.

Oxide	From oxidation	Lime	Ash from electrodes	Vault	Floor, wals	Flux spar	Sand	From FeSi	From FeCr	Deoxida-tion	Reduction from red. slag	Desulphuri-zation	Formation of SiF_4	Formation of CaC_2	Sum, kg	Sum, %
1	2**	3**	4**	5**	6**	7**	8**	9**	10**	11***	12****	13*****	14******	15*******	16	17
CaO	0.208	0.622	0.001	0.002	0.018	0.001	-	-	-	-	-	0.021*	0.071	0.022*	0.880	39.59
SiO_2	0.054	0.017	0.002	0.387	0.017	0.006	0.043	0.189	-	0.006 0.023	0.141*	-	0.033*	-	0.570	25.64
MgO	0.067	0.022	-	-	0.451	-	-	-	-	-	-	-	-	-	0.540	24.29
Al_2O_3	0.008	0.007	0.001	0.003	0.004	0.001	0.001	0.011	-	0.009 0.038	-	-	-	-	0.083	3.73
FeO	0.038	-	-	-	-	-	-	-	-	-	0.045* 0.003*	0.018	-	-	0.008	0.36
Fe_2O_3	0.021	0.004	-	0.005	0.010	0.001	0.001	-	-	-	0.042*	-	-	-	-	-
MnO	0.020	-	-	-	-	-	-	0.001	-	0.013	0.034*	-	-	-	-	-
CaF_2	-	-	-	-	-	0.171	-	-	-	-	-	-	0.086*	-	0.086	3.87
P_2O_5	0.003	0.001	-	0.003	-	-	-	-	-	-	0.007*	-	-	-	-	-
CaS	-	-	-	-	-	-	-	-	-	-	-	0.027	-	-	0.027	1.22
CaC_2	-	-	-	-	-	-	-	-	-	-	-	-	-	0.025	0.025	1.13
Cr_2O_3	-	-	-	-	-	-	-	-	0.064	-	0.051* 0.013*	-	-	-	-	-
H_2O	-	0.001	-	-	-	-	-	-	-	-	-	-	-	-	0.001	0.05
S	0.001	0.001	-	-	-	0.001	-	-	-	-	-	-	-	-	0.003	0.14
Total	0.420	0.676	0.004	0.400	0.500	0.180	0.045	0.201	0.064	0.089	0.336*	0.045 0.021*	0.071 0.119*	0.025 0.022*	2.223	100

Note: * - *the values presented are subtracted from the sum*

** - *the values from columns 2 to 10 are presented from Table 1*

*** - *the values from column 11 are calculated by (43), (60), (47), (63), (39)*

**** - *the values from column 12 are calculated by (74), (55), (58), Table 3, Table 4*

***** - *the values from column 13 are calculated by (73), (50), (72)*

****** - *the values from column 14 are calculated by (71), (69), Table 1*

******* - *the values from column 15 are calculated by (67), (66)* The result for carbon monoxide is the basis for optimal implementation of the reduction process. Although nitrogen has the highest percentage of participation in the gas phase, it does not play a role in the development of the reduction process, because it is an inert gas. Based on the created modeling for technological implementation of the reduction process, as well as with the help of data from tables 5, 6 and 7, table 8 presents the final results of the material balance for the period.

Table 7. Composition and quantity of the gas phase from the reduction period.

Gas	kg	%
CO	0.662	34.50
CO_2	0.040	2.08
H_2	0.002	0.10
N_2	1.158	60.35
SiF_4	0.057	2.97
Total	1.919	100

Table 8. Material balance of the reduction period.

Expenditure	kg	Income	kg
Metal from oxidation period	98.150	Metal	100.649
Lime	0.676	Slag	2.309
Fluxspar	0.180	Gases	1.919
Sand	0.450		
Mill electrode wastes	0.297		
Ferrosilicon - pieces	0.068		
Ferrochrome	2.100		
Ferrosilicon - mill	0.179		
Aluminum	0.045		
Electrodes	0.140		
Slag from oxidation period	0.420		
Vault	0.400		
Floor and wals	0.500		
Air	1.504		
Unattached	0.272		
Total	104.877		104.877

According to the calculation procedures of the present reduction period, as well as the results obtained from the melting period and the oxidation period [1, 2], Table 9 shows the summarized results for the entire electric arc process in the production of bearing steel.

Fig. 1 shows the ratio between the total amount of the three product phases according to the balance models of the three periods (melting, oxidation, reduction) for the production of bearing steel.

The final amount of steel represents 76.55 % of the amount of all cost components for its production. In terms of slag and gases, this indicator is 12.64 % and 10.81 %, respectively.

Table 9. Material balance of the electric steelmaking process for producing bearing steel.

Expenditure	kg	Income	kg
Iron scrap	98.200	Metal	100.649
Ferromanganese	0.490	Slag from periods of melting and oxidation	14.306
Silicomanganese	0.250	Slag from the reduction period	2.309
Ferrosilicon 75 %	0.247	Gases	12.572
Ferrochrome	2.100	Iron losses with gases	1.650
Aluminum	0.040		
Electrodes	0.700		
Electrode wastes	1.607		
Lime	7.246		
Fluxspar	0.180		
Sand	0.045		
Iron ore	3.770		
Magnesite – wals, floor	2.500		
Dinas - vault	1.200		
Air	9.591		
Unattached	3.320		
Total	131.486		131.486

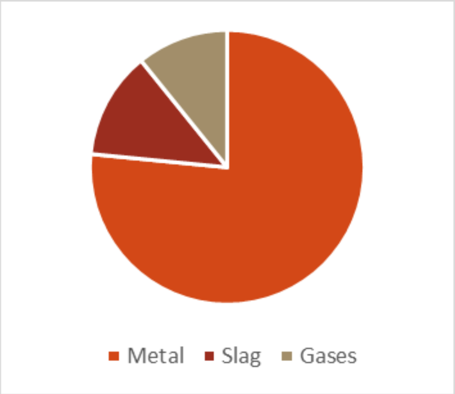

Fig. 1. Relationship between metal, slag and gas phases in a completed model

CONLUSIONS

The article presents a mathematical balance modelling of the last, third, stage in the electric steelmaking production of bearing steel. The entire reduction period is structured by a series of formulas. On their basis, as well as with the help of the information obtained from the melting and oxidation periods, the final values of all accompanying components of the material balance for the studied period are calculated and presented in a ready-made form.

A summary of the entire process has been made, including the determination of the quantities of the batch components necessary for the three technological periods for the production of the steel in question - melting, oxidation, reduction. The material models created for these periods allow, in a relatively easy way, to reach the structure and composition of the final metal, slag and gas phase, as products of the metallurgical process, especially if it is necessary to use starting raw materials with different chemical composition.

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