ABSTRACT

The modern steel industry is characterized by continual improving the quality of the produced steel with constantly increasing range and quantity of deoxidation and alloying alloys. Among them falls SiCa with vanadium. Consider the absence in the Republic of Bulgaria of raw materials containing vanadium for example, the needs of metallurgy are provided mainly by imports of ferro-alloys. At the same time our country has an active chemical and metallurgical industries where significant polluting quantities of vanadium catalyst drop from production of sulfuric acid, which contains Si and V.

Both material and heat balance models are developed for carbothermal producing of SiCa with a high content of vanadium. Vanadium waste, metallurgical lime and metallurgical coke are the raw material. The elements in the alloy after the carbothermal reduction are: \( V – 9.09 \% \), \( Fe – 9.06 \% \), \( Si – 66.45 \% \), \( Ca – 12.26 \% \), \( P – 0.02 \% \), \( S – 0.04 \% \), \( C – 0.21 \% \), \( Al – 2.83 \% \) u \( Mn – 0.03 \% \). The main contributor into the alloy of \( V \), \( Si \) and \( Fe \) is the waste vanadium catalyst. The relative consumption of electricity according to the heat balance model is 11505 kWh/ton alloy.

Keywords: vanadium catalyst, lime, coke, SiCa alloy.

INTRODUCTION

SiCa is used for modification and deoxidation of iron, steel and alloys. In separate studies it was prepared SiCa with the elements vanadium, zirconium, titanium, aluminum and others [1 - 5]. When alloying SiCa with vanadium and subsequent alloying of the steel, its strength at reduced temperatures increases without reducing the impact toughness. Currently, SiCa is produced mainly in the Russian Federation in accordace with the requirements of GOST 4762-71 [6]. The purpose of this study is to make material and heat balance model for producing SiCa alloy with higher content of vanadium using vanadium waste, lime and metallurgical coke.

THEORETICAL CONSIDERATION AND RESULTS

A material balance model of carbothermal producing SiCa with increased content of vanadium from vanadium waste.

The composition of the charge materials is given in the Table. 1. Main raw material for the alloy is a waste vanadium catalyst [6, 7] and secondary – the metallurgical lime. Metallurgical coke is used as a reducer.

According to [7 - 10]: 98 % of \( V_2O_5 \) is reduced and \( V \) passes into the alloy, 1% non-reduced \( V_2O_5 \) goes into the slag, and 1% non-reduced \( V_2O_5 \) - in the gas phase; \( Fe_2O_3 \) is reduced 100% to Fe, and then passes in the alloy, 88 % of MnO is reduced by the carbon from the coal, and 16 % of the resultant Mn passes into the gas phase and
Table 1. Chemical composition of the charge materials.

<table>
<thead>
<tr>
<th>Charge materials</th>
<th>Chemical composition, %</th>
<th>Chemical composition, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V₂O₅</td>
<td>Fe₂O₃</td>
</tr>
<tr>
<td>1. V catalyst</td>
<td>4,81</td>
<td>3,98</td>
</tr>
<tr>
<td>2. Met. lime</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3. Coke</td>
<td>-</td>
<td>1,10</td>
</tr>
</tbody>
</table>

72 % - in the alloy. The remaining 12 % non-reduced MnO passes in the slag; Al of 90 % reduced Al₂O₃ passes in the alloy, the non-reduced Al₂O₃ is 10 % and it goes into the slag; 90 % of SiO₂ is reduced and Si goes to the alloy. 6 % of SiO₂ is reduced to SiO, passing into the gas phase, and 4 % of SiO₂ is not reduced at all and goes into the slag. Part of the Si alloy joins 99.95 % of the sulfur from the vanadium catalyst and 100 % of the sulfur from the coke and pass into the gas phase; CaO from the coke is reduced 85 %, and passes into the metal. In the slag passes 15 % non-reduced CaO; P₂O₅ from the coke is reduced 100 %, and 50 % of the obtained P goes into the metal and 50 % - in the gas phase, Na₂O and K₂O are not reduced, and 95 % of them pass into the gas phase while the rest 5 % - in the slag; the volatile components pass 100 % in the gas phase; S in the alloy – up to 0.05 % of its composition; P in the alloy – up to 0.10 %; the amount of carbon oxidized 100 % passes into the gas phase; 0.2 % of the alloy is saturated with carbon during reduction process. Calcium in alloy - 12 %. The calculations are made on the basis of 100.00 kg of vanadium catalyst.

The following rounded atomic (A) and molecular (M) masses are used:

- Ac - 12; Aᵥ - 51; Aᵥ₅ - 56; Aₛ₅ - 28;
- Aᵥ₂O₅ - 16; Aᵥ₅₅ - 55; Aₛ - 32; Aₚ - 31;
- Aᵥ₅₅ - 27; Aᵥ₅₅ - 40; V₂O₅ - 182;
- Fe₂O₃ - 160; Mₐl₂O₃ - 142; MₛiO₂ - 60;
- Mₐl₅O₅ - 102; Mₚ₅O₅ - 61; Mₙ₅O₅ - 56.

### 1. Amount of oxygen taken away

The amount of oxygen abstracted by reduction is calculated by the formula:

\[ m_{\text{O}_2} = \frac{91\% \text{RxO}_y \text{cat}. m_{\text{cat}} \cdot \eta^{L}}{100 \cdot \frac{M_{\text{O}_2}}{M_{\text{RxO}_y}}} \text{, kg} \]  \hspace{1cm} (1)

where: \( m_{\text{O}_2} \) is the amount of oxygen released from an oxide RxOₙ of vanadium catalyst at the reduction, kg; \% RxOₙ - participation rate of the oxide RxOₙ in the vanadium catalyst, %; \( m_{\text{cat}} \cdot \) amount of vanadium catalyst - 100, kg; 100 - coefficient of transition from rate per kilogram; \( \eta^{L} \text{RxO}_y \rightarrow \text{R} \) - reduction factor of the oxide RxOₙ to the element R, passing in the alloy; \( M_{\text{O}_2} \text{RxO}_y \) - molecular weight of the oxygen from corresponding oxide RxOₙ; \( M_{\text{RxO}_y} \) - molecular weight of corresponding oxide RxOₙ.

Then:

\[ V₂O₅ \rightarrow 2V + \frac{5}{2}O₂ \quad \text{SiO}_2 \rightarrow \text{SiO} + \frac{1}{2}O₂ \]

\[ m_{\text{V}_2\text{O}_5} = 2,07 \text{ kg.} \]

\[ m_{\text{SiO}_2} = 32,01 \text{ kg.} \]

### 2. Quantity of the reducer to connect the oxygen from the oxides of vanadium catalyst

The amount of reducer is determined according to:

\[ m_{\text{R}} = m_{\text{RxO}_y} \cdot \frac{M_{\text{C}}}{M_{\text{O}_2}} \text{, kg} \]  \hspace{1cm} (3)

where: \( m_{\text{R}} \) is the amount of reducing agent for the oxides of vanadium catalyst, kg; \( M_{\text{O}_2} \) - molecular mass.
of oxygen from formation of the molecule of CO; \( M_c \) - molecular mass of a carbon from formation of the molecule of CO.

To connect \( m_{R_xO_y}^{\text{O}_2} \) by the reaction

\[
2C + O_2 \rightarrow 2CO
\]
is needed C: \( m_{C} = 28.36 \text{ kg} \).

3. Quantity of \( O_2 \) from oxides of coke and determining the amount of C to reduce them

At the reduction a part of the carbon is consumed for reduction of the oxides of the coke. Its amount is calculated after determining the amount of oxygen in these oxides. The calculation is for 100 kg of coke. Then is calculated a predetermined amount of coke for reduction of the oxides of vanadium catalyst and coke (a coke ash):

\[
m_{1}^{\text{R}_xO_y}^{\text{O}_2} = \frac{\%R_xO_y^{\text{c}}.m_{\text{c}}.\frac{\eta_{\text{R}_xO_y}^{\text{c}}.M_{R_xO_y}^{\text{c}}}{M_{\text{O}_2}^{\text{c}}}}{100}, \text{ kg}.
\]

where: \( m_{1}^{\text{R}_xO_y}^{\text{O}_2} \) is the amount of oxygen released from \( R_xO_y \) oxide by reduction of coke, kg; \( \%R_xO_y^{\text{c}} \) - participation rate of the corresponding oxide \( R_xO_y \) in the coke, \%; \( m_{\text{c}} \) - quantity of the coke - 100, kg. Then:

\[
\begin{align*}
\text{Fe}_2O_3 & \rightarrow 2\text{Fe} + \frac{3}{2} \text{O}_2 \\
m_{2}^{\text{Fe}_2O_3} & = 0.33 \text{ kg}.
\end{align*}
\]

\[
\begin{align*}
\text{SiO}_2 & \rightarrow \text{Si} + \text{O}_2 \\
m_{2}^{\text{SiO}_2} & = 3.49 \text{ kg}.
\end{align*}
\]

\[
\begin{align*}
\text{Al}_2O_3 & \rightarrow 2\text{Al} + \frac{3}{2} \text{O}_2 \\
m_{2}^{\text{Al}_2O_3} & = 0.93 \text{ kg}.
\end{align*}
\]

The amount of \( O_2 \) is:

\[
\begin{align*}
m_{2}^{\text{R}_xO_y}^{\text{O}_2}^{\text{100c}} & = m_{2}^{\text{Fe}_2O_3} + m_{2}^{\text{SiO}_2} + m_{2}^{\text{Al}_2O_3} + m_{2}^{\text{MnO}_2} \\
& + m_{2}^{\text{SiO}_2 - \text{SiO}_2} + m_{2}^{\text{Al}_2O_3} + m_{2}^{\text{MnO}_2} \\
& + m_{2}^{\text{CaO}_2} + m_{2}^{\text{P}_2\text{O}_5} \text{, kg}.
\end{align*}
\]

4. Quantity of reducer to connect the oxygen from the oxides of the coke

For connecting \( m_{2}^{\text{R}_xO_y}^{\text{O}_2} \) kg \( O_2 \) in reaction

\[
2C + O_2 \rightarrow 2CO
\]
is required C according:

\[
m_{2}^{\text{R}_xO_y}^{\text{O}_2} = m_{2}^{\text{R}_xO_y}^{\text{O}_2}^{\text{100c}} \cdot \frac{M_{\text{C}}^{\text{CO}}}{M_{\text{O}_2}^{\text{c}}}, \text{ kg}, \quad (6)
\]

where: \( m_{2}^{\text{R}_xO_y}^{\text{O}_2} \) is the amount of reducing agent for the oxides of the vanadium catalyst, kg; \( M_{\text{O}_2}^{\text{c}} \) - molecular mass of oxygen for formation of the molecule CO; \( M_c \) - molecular weight of carbon for formation of the molecule CO. Or \( m_{2}^{\text{c}} = 3.84 \text{ kg} \) for the reduction of the oxides of 100 kg from coke, representing \( m_{1}^{\text{c}} \) %.

5. Calculation of advance amounts of coke

\[
m_{1}^{\text{c}} = m_{11}^{\text{c}} \cdot \frac{100}{\%\text{C}_{\text{c}}^{\text{c}} - m_{2}^{\text{c}}}, \text{ kg}.
\]

where: \( m_{1}^{\text{c}} \) is the quantity of coke for reduction of oxides of catalyst and coke, kg; 100 - coefficient of transition from rate per kilogram; \( \%\text{C}_{\text{c}}^{\text{c}} \) - participation rate of carbon in the coke.

Or \( m_{1}^{\text{c}} = 34.75 \text{ kg} \) coke.

6. Calculation of the quantity alloy

The amount of the resulting pure element in the reduction of the corresponding oxide was calculated by the formula:

\[
m_{1}^{\text{Me}} = \left( \frac{\%R_xO_y^{\text{cat}}.m_{\text{c}}.\eta_{\text{R}_xO_y}^{\text{c}}.M_{\text{Me}}^{\text{R}_xO_y}}{100} \cdot \frac{M_{\text{Me}}^{\text{R}_xO_y}}{M_{\text{R}_xO_y}} \right) + \left( \frac{\%R_xO_y^{\text{c}}.m_{\text{c}}^{\text{c}}.\eta_{\text{R}_xO_y}^{\text{c}}.M_{\text{Me}}^{\text{R}_xO_y}}{100} \cdot \frac{M_{\text{Me}}^{\text{R}_xO_y}}{M_{\text{R}_xO_y}} \right), \text{ kg}, \quad (8)
\]

where: \( m_{1}^{\text{Me}} \) is the quantity of pure single element in the alloy by oxide reduction, kg; \( M_{\text{Me}}^{\text{R}_xO_y} \) - molecular mass of the element from the corresponding oxide \( R_xO_y \). Then:

\[
\begin{align*}
\text{V}_2\text{O}_5 & \rightarrow 2\text{V} + \frac{5}{2} \text{O}_2 \\
m_{1}^{\text{V}} & = 2.64 \text{ kg}.
\end{align*}
\]

\[
\begin{align*}
\text{Fe}_2\text{O}_3 & \rightarrow 2\text{Fe} + \frac{3}{2} \text{O}_2 \\
m_{1}^{\text{Fe}} & = 2.63 \text{ kg}.
\end{align*}
\]

\[
\begin{align*}
\text{CaO} & \rightarrow \text{Ca} + \frac{1}{2} \text{O}_2 \\
m_{1}^{\text{Ca}} & = 0.09 \text{ kg}.
\end{align*}
\]

\[
\begin{align*}
\text{SiO}_2 & \rightarrow \text{Si} + \text{O}_2 \\
m_{1}^{\text{Si}} & = 29.07 \text{ kg}.
\end{align*}
\]

\[
\begin{align*}
2\text{MnO} & \rightarrow 2\text{Mn} + \text{O}_2 \\
m_{1}^{\text{Mn}} & = 0.82 \text{ kg}.
\end{align*}
\]

Provided by, 72 % from Mn from 88 % of the reduced Mn passes into the alloy.
Then:

\[ m_{\text{Mn}}^L = m_{\text{Mn}} \cdot \frac{\eta_{\text{Mn}}^L}{100}, \text{ kg.} \]  

(9)

Or \( m_{\text{Mn}}^L = 0.01 \text{ kg.} \)

\[ \text{P}_2\text{O}_5 \rightarrow 2\text{P} + \frac{5}{2}\text{O}_2 \]

Provided by, 50 % from P from 100 % of the reduced \( \text{P}_2\text{O}_5 \) passes into the alloy.

Then: \( m_{\text{P}}^L = m_{\text{P}} \cdot \frac{\eta_{\text{P}}^L}{100}, \text{ kg.} \)

(10)

Or \( m_{\text{P}}^L = 0.005 \text{ kg.} \)

Aggregate pre-amount alloy:

\[ m_1^L = m_{\text{V}}^L + m_{\text{Fe}}^L + m_{\text{Si}}^L + m_{\text{Al}}^L + m_{\text{Mn}}^L + m_{\text{Ca}}^L + m_{\text{P}}^L, \text{ kg.} \]

(11)

Or \( m_1^L = 35.27 \text{ kg.} \)

99.95 % of the sulfur from the vanadium catalyst and 100 % of the sulfur from the coke is associated with the silicon from alloy and passes into the gas phase according to the relation:

\[ m_{\text{Si}}^G = \left( \frac{\% \text{Si}_{\text{trans}} \cdot m_{\text{Si}}}{{\text{100}}} \right) + \left( \frac{\% \text{coker} \cdot m_{\text{coker}} \cdot \eta_{\text{SiS}}^G}{{\text{100}}} \right), \text{ kg,} \]

(12)

where: \( m_{\text{Si}}^G \) is the mass of sulfur passing into the gas phase, kg; \( \% \text{Si}_{\text{trans}} \) - participation rate of sulfur in the vanadium catalyst, kg; \% S_{\text{coker}} - participation rate of sulfur in the coke, kg; \( \eta_{\text{SiS}}^G \) - coefficient of the transfer of SiS from vanadium catalyst and coke in to gas phase, %. Or \( m_{\text{Si}}^G = 11.18 \text{ kg S for binding with Si. Then, according to the equation } \text{Si + S} \rightarrow \text{SiS} \text{ follows that:} \)

\[ m_{\text{Si-SiS}}^{\text{G}} = m_{\text{Si}} \cdot \frac{m_{\text{Si}}^{\text{SiS}}}{M_{\text{SiS}}}, \text{ kg,} \]

(13)

where: \( M_{\text{SiS}} \) is the molecular mass of the sulfur from SiS; \( M_{\text{Si}}^{\text{SiS}} \) - molecular mass of silicon from SiS.

Or \( m_{\text{Si-SiS}}^{\text{G}} = 9.78 \text{ kg Si. Then in the alloy will remain:} \)

\[ m_{\text{Si}}^L = m_{\text{Si}}^L - m_{\text{Si-SiS}}^{\text{G}}, \text{ kg} \]

(14)

Or \( m_{\text{Si}}^L = 19.29 \text{ kg.} \)

Intermediate mass of the alloy is:

\[ m_{\text{Si}}^L = m_{\text{Si}}^L - m_{\text{G-Si-SiS}}^{\text{G}}, \text{ kg} \]

(15)

0.05% S remain in the composition of the alloy. Or S in the alloy would be:

\[ m_{\text{S}}^L = \frac{m_{\text{S}}^L \cdot \eta_{\text{S}}^L}{100}, \text{ kg,} \]

(16)

where: \( \eta_{\text{S}}^L \) is the coefficient of passage of the sulfur in the alloy.

Or \( m_{\text{S}}^L = 0.01 \text{ kg.} \)

The amount of the alloy becomes:

\[ m_3^L = m_2^L + m_1^L, \text{ kg.} \]

(17)

Or \( m_3^L = 25.50 \text{ kg.} \)

Ca in the alloy should be 12 %. Other elements represent 88 %. But \( m_3^L \) kg alloy containing \( m_{\text{Ca}}^L \text{ kg} \)

\[ \text{Ca from metallurgical coke. The necessary additional amount of Ca alloy is:} \]

\[ m_{\text{Ca}}^L = \frac{m_{\text{Ca}}^L}{\text{88}} \cdot 12, \text{ kg.} \]

(18)

Or \( m_{\text{Ca}}^L = 3.47 \text{ kg.} \)

The Ca is provided by adding of CaO in amount:

\[ m_{\text{CaO}}^L = m_{\text{Ca}} \cdot \frac{M_{\text{CaO}}}{M_{\text{Ca}}}, \text{ kg} \]

(19)

where: \( M_{\text{CaO}} \) is the molecular mass of CaO; \( M_{\text{CaO}} \) - molecular mass of Ca from CaO.

Or \( m_{\text{CaO}}^L = 4.86 \text{ kg CaO secured by metallurgical lime, consisting of 99 % CaO (% CaO_{lime}). Or the required amount of lime is:} \)

\[ m_{\text{lime}}^L = \frac{m_{\text{CaO}}}{\% \text{CaO}_{lime}}, \text{ kg} \]

(20)

or \( m_{\text{lime}}^L = \frac{4.86}{99} = 4.91 \text{ kg.} \)

For reduction of CaO from the lime, additional quantity of further coke is introduced in the system. In order to determine its quantity it is necessary to calculate first the amount of oxygen by reduction of CaO, which is released by the reaction \( 2\text{CaO} \rightarrow 2\text{Ca} + \text{O}_2 \)

and represents: \( m_{\text{CaO}_{02}}^L = m_{\text{CaO}} \cdot \frac{M_{\text{CaO}}}{M_{\text{CaO}}}, \text{ kg} \)

(21)
Or $m_{CaO_{2}}^{\text{CO}} = 1.39$ kg. For connecting of $m_{CaO_{2}}^{\text{CO}}$ carbon is needed according to reaction $2C + O_2 \rightarrow 2CO$ and formula:

$$m_3 = m_{CaO_{2}}^{\text{CO}} \frac{M_{C}^{\text{CO}}}{M_{O_{2}}^{\text{CO}}}, \text{kg}$$  \hspace{1cm} (22)

Or $m_3 = 1.04$ kg.

The mass of the alloy becomes:

$$m_4^{L} = m_3^{L} + m_{C_{Ca}}^{L}, \text{kg}$$  \hspace{1cm} (23)

Or $m_4^{L} = 28.97$ kg.

For carburization - 0.2% C. Or C in the alloy would be:

$$m_{C}^{L} = \frac{m_4^{L} \cdot \eta_{C}^{L}}{100}, \text{kg}$$  \hspace{1cm} (24)

where: $\eta_{C}^{L}$ - ratio of transition of C in the alloy, %. Or $m_{C}^{L} = 0.06$ kg.

Final mass of the alloy:

$$m_5^{L} = m_4^{L} + m_{C}^{L}, \text{kg}.$$  \hspace{1cm} (25)

Or $m_5^{L} = 29.03$ kg.

### 7. Final amount of coke

The amount of coke required for carburization of the alloy and the amount of coke to provide carbon for reduction of the additional quantity introduced by the metallurgical lime CaO is:

$$m_{\text{coke}}^{\text{Coke}} = \left( m_{C}^{L} + m_3^{L} \right) \cdot \frac{100}{\% C_{\text{coke}}^{\text{Coke}} - m_2^{L}} \text{, kg coke}$$  \hspace{1cm} (26)

Or $m_{\text{coke}}^{\text{Coke}} = 1.35$ kg. The quantity of the coke needed $m_3^{\text{Coke}} = m_1^{\text{Coke}} + m_2^{\text{Coke}}, \text{kg}.$

Or $m_{\text{coke}}^{\text{Coke}} = 36.10$ kg. Taking into account the set-aside of the coke of 12% in the process, the final amount of the metallurgical coke becomes:

$$m_{\text{coke}}^{\text{Coke}} = \frac{m_3^{\text{Coke}}}{88/100}, \text{kg}$$  \hspace{1cm} (28)

Or $m_{\text{coke}}^{\text{Coke}} = 41.02$ kg.

The composition of the charge and chemical composition of the alloy are shown in Table 2.

### 8. Quantity and chemical composition of the slag

The amount of the corresponding oxide passing in the slag is given by:

$$m_{\text{slag}}^{\text{Oxide}} = \left( \% \text{RxO}_{y}^{\text{Coke}} \cdot m_{\text{Coke}} \cdot \eta_{\text{RxO}_{y}}^{\text{Slag}} \right) + \left( \% \text{RxO}_{y}^{\text{Coke}} \cdot m_{\text{Coke}} \cdot \eta_{\text{RxO}_{y}}^{\text{Slag}} \right), \text{kg}$$  \hspace{1cm} (29)

where: $m_{\text{slag}}^{\text{Oxide}}$ is the amount oxide passing into the slag, kg; $\eta_{\text{RxO}_{y}}^{\text{Slag}}$ - coefficient of passage of RxOy oxide in the slag.

Then:

- 1% of V$_2$O$_5$ passes into the slag. This represents the amount of:
  $$m_{1}^{\text{V2O5}} = 0.05 \text{ kg}.$$
  4% of SiO$_2$ passes into the slag. This represents the amount of:
  $$m_{2}^{\text{SiO2}} = 2.77 \text{ kg}.$$
  15% of CaO passes into the slag. This represents the amount of:
  $$m_{3}^{\text{CaO}} = 0.02 \text{ kg}.$$
  10% of Al$_2$O$_3$ passes into the slag. This represents the amount of:
  $$m_{4}^{\text{Al2O3}} = 2.83 \text{ kg}.$$
  5% of Na$_2$O passes into the slag. This represents the amount of:
  $$m_{5}^{\text{Na2O}} = 0.23 \text{ kg}.$$
  5% of K$_2$O passes into the slag. This represents the amount of:
  $$m_{6}^{\text{K2O}} = 0.39 \text{ kg}.$$

<table>
<thead>
<tr>
<th>Material</th>
<th>kg</th>
<th>%</th>
<th>Alloy</th>
<th>kg</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>V catalyst</td>
<td>100.00</td>
<td>70.92</td>
<td>V</td>
<td>2.64</td>
<td>9.09</td>
</tr>
<tr>
<td>Coke</td>
<td>36.10</td>
<td>25.60</td>
<td>Fe</td>
<td>2.63</td>
<td>9.06</td>
</tr>
<tr>
<td>Lime</td>
<td>4.91</td>
<td>3.48</td>
<td>Si</td>
<td>19.29</td>
<td>66.45</td>
</tr>
<tr>
<td>Al</td>
<td>0.82</td>
<td>2.83</td>
<td>Mn</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Ca</td>
<td>3.56</td>
<td>12.26</td>
<td>P</td>
<td>0.005</td>
<td>0.02</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
<td>0.04</td>
<td>C</td>
<td>0.06</td>
<td>0.21</td>
</tr>
<tr>
<td>Total</td>
<td>141.01</td>
<td>100.00</td>
<td>Total</td>
<td>29.03</td>
<td>100.00</td>
</tr>
</tbody>
</table>
The total amount of the components in the slag is:

\[ m^{S} = m^{S}_{V_2O_5} + m^{S}_{SiO_2} + m^{S}_{CaO} + m^{S}_{Al_2O_3} + m^{S}_{Na_2O} + m^{S}_{K_2O}, \text{ kg} \]

Or \( m^{S} = 3.64 \text{ kg} \).

The chemical composition of the slag is shown in Table 3.

### Table 3. Chemical composition of the slag.

<table>
<thead>
<tr>
<th>Oxides</th>
<th>kg</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_2O_5</td>
<td>0.05</td>
<td>1.37</td>
</tr>
<tr>
<td>SiO_2</td>
<td>2.77</td>
<td>76.10</td>
</tr>
<tr>
<td>Al_2O_3</td>
<td>0.18</td>
<td>4.95</td>
</tr>
<tr>
<td>CaO</td>
<td>0.02</td>
<td>0.55</td>
</tr>
<tr>
<td>Na_2O</td>
<td>0.23</td>
<td>6.32</td>
</tr>
<tr>
<td>K_2O</td>
<td>0.39</td>
<td>10.71</td>
</tr>
<tr>
<td>Total</td>
<td>3.64</td>
<td>100.00</td>
</tr>
</tbody>
</table>

The total amount of the components in the slag is:

\[ m^{S} = m^{S}_{V_2O_5} + m^{S}_{SiO_2} + m^{S}_{CaO} + m^{S}_{Al_2O_3} + m^{S}_{Na_2O} + m^{S}_{K_2O}, \text{ kg} \]

Or \( m^{S} = 3.64 \text{ kg} \).

The chemical composition of the slag is shown in Table 3.

### 9. Quantity and chemical composition of the gas phase

\[ m^{1}_{RxOy} \text{ of the oxides of vanadium catalyst, } m^{2}_{RxOy} \text{ of oxides of metallurgical coke and } m^{3}_{CaO} \text{ from the reduction of } CaO \text{ is associated with the } C \text{ in the reaction} \]

\[ 2C + O_2 \rightarrow 2CO \]

\[ m^{2}_{RxOy} = \frac{m^{2}_{RxOy, coke}}{100_{coke}} \cdot m^{3}_{coke}, \text{ kg} \]

where: \( m^{2}_{RxOy, coke} \) - oxygen, separated from the oxides of the ashes of coke required for the reduction in the amount \( m^{3}_{coke} \).

Or \( m^{2}_{RxOy, coke} = 1.85 \text{ kg} \).

The total amount of CO is:

\[ m^{G}_{CO} = (m^{1}_{RxOy} + m^{2}_{RxOy, coke} + m^{3}_{CaO}) \cdot \frac{M_{CO}}{M_{C}}, \text{ kg} \]

Or \( m^{G}_{CO} = 71.84 \text{ kg} \).

99.95 % of the sulfur from the vanadium catalyst, and 100 % of the sulfur from the coke is associated with Si from alloy and pass into the gas phase by the equation

\[ Si + S \rightarrow SiS. \]

According to (12):

\[ m^{G}_{Si} = \frac{\%S_{cat} \cdot m_{cat}}{100} \cdot \eta^{G}_{SiS} + \frac{\%S_{coke} \cdot m^{3}_{coke}}{100} \cdot \eta^{G}_{SiS}, \text{ kg} \]

kg, follow that:

\[ m^{G}_{Si} = 11.18 \text{ kg for connecting with Si}. \]

\[ m^{G}_{SiS} = m^{G}_{Si} \cdot \frac{M_{SiS}}{M_{Si}}, \text{ kg} \]

Or \( m^{G}_{SiS} = 20.96 \text{ kg} \).

The metallurgical coke and lime contain volatile components (VC) in amount of \( \% VC^{lime} \) and \( \% VC^{coke} \) respectively which also go 100% in the gas phase in an amount of:

\[ m^{G}_{VC^{lime}} = \frac{\% VC^{lime} \cdot m^{lime}}{100}, \text{ kg} \]

where: \( \% VC^{lime} \) is the participation rates of VC in the lime, %; 100 - coefficient of transition from rate per kilogram. Or \( m^{G}_{VC^{lime}} = 0.05 \text{ kg} \) and

\[ m^{G}_{VC^{coke}} = \frac{\% VC^{coke} \cdot m^{coke}}{100}, \text{ kg} \]

where: \( \% VC^{coke} \) is the participation rates of VC in the coke, %; 100 - coefficient of transition from rate per kilogram. Or \( m^{G}_{VC^{coke}} = 1.20 \text{ kg} \).

The amount of other oxides, passing in the gas phase was calculated by the formula:

\[ m^{G}_{RxOy} = \left( \frac{\% RxOy^{cat} \cdot m^{cat}}{100} \cdot \eta^{G}_{RxOy} \right) + \left( \frac{\% RxOy^{coke} \cdot m^{3}_{coke}}{100} \cdot \eta^{G}_{RxOy} \right), \text{ kg} \]

where: \( m^{G}_{RxOy} \) is the quantity of oxide passing in the gas phase, kg; \( \eta^{G}_{RxOy} \) - coefficient of transition of oxide \( RxOy \) in the gas phase. Then:

1% of \( V_2O_5 \) passes into the gas phase. This represents the amount of

\[ G^{cat.} V_2O_5 \rightarrow 0.05 \text{ kg}. \]

6% of \( SiO_2 \) passes into the gas phase as \( SiO \). This represents the following amount:

\[ G^{SI} SiO_2 \rightarrow SiO = 4.16 \text{ kg}, \text{ and the oxygen by reaction} \]

\[ SiO_2 \rightarrow SiO + \frac{1}{2} O_2 \]

is:

\[ m^{2}_{SiO_2 \rightarrow SiO +1/2 O_2} = m^{1}_{SiO_2 \rightarrow SiO} + \]

\[ + m^{2}_{SiO_2 \rightarrow SiO} = 2.36 \text{ kg} \]

Then:

\[ m^{G}_{SiO} = m^{G}_{SiO_2 \rightarrow SiO} - m^{2}_{SiO_2 \rightarrow SiO + 1/2 O_2}, \text{ kg} \]

where: \( m^{G}_{SiO} \) - is the SiO quantity of \( SiO_2 \) passing in gas phase, kg. Or \( m^{G}_{SiO} = 1.80 \text{ kg} \).

16 % Mn (\( \eta_{Mn}^{G} \)) from 88 % reduced MnO passes into the gas phase. This represents the following amount:

\[ m^{G}_{Mn} = m^{G}_{Mn} \cdot \frac{\eta_{Mn}^{G}}{100}, \text{ kg} \]
Or \( m_{\text{Mn}}^G = 0,003 \) kg.

16 % P (\( \eta_p^G \)) from 100% reduced \( \text{P}_2\text{O}_5 \) passes into the gas phase. This represents the following amount:

\[
m_p^G \cdot \frac{\eta_p^G}{100}, \text{kg.} \quad (40)
\]

Or \( m_p^G = 0,005 \) kg.

95 % of \( \text{Na}_2\text{O} \) passes into the gas phase. This represents the following amount: \( m_{\text{Na}_2\text{O}}^G = 4,36 \) kg.

95 % of \( \text{K}_2\text{O} \) passes into the gas phase. This represents the following amount: \( m_{\text{K}_2\text{O}}^G = 7,44 \) kg.

The total amount of the components in the gas phase is:

\[
\sum m_G = m_{\text{CO}}^G + m_{\text{SiS}}^G + m_{\text{vclime}}^G + m_{\text{vcoke}}^G + m_{\text{V}_2\text{O}_5}^G + m_{\text{SiO}}^G + m_{\text{Mn}}^G + m_{\text{Na}_2\text{O}}^G + m_{\text{K}_2\text{O}}^G, \text{kg}
\]

Or \( m_G = 107,71 \) kg.

The chemical composition of the gas phase is given in Table 4.

Summary of the material balance of the process of carbothermal producing of SiCa with increased content of vanadium is shown in Table 5. At properly calculated balance must be fulfilled the following equation:

\[
\sum \text{expenditure} = \sum \text{profit}, \text{kg} \quad (42)
\]

10. Relative fuel charge materials

Below is presented the relative expenditure of charge materials to produce one tone of the alloy. The consumption of the charge materials is calculated according to the relations:

\[
m_{\text{ch.m.}}^{L,1000} = m_p \cdot \frac{m_{\text{ch.m.}}^{L,1000}}{m_L}, \text{kg.} \quad (43)
\]

where: \( m_{\text{ch.m.}}^{L,1000} \) is the quantity of a charge material component for the preparation of an alloy in an amount of 1000 kg (respectively \( m_{\text{cat.}}^{L,1000}, m_{\text{coke}}^{L,1000}, m_{\text{lime}}^{L,1000} \)), kg; \( m_{\text{ch.m.}} \) - the quantity of a charge material component for the preparation of an alloy in an amount \( m_L \) (respectively \( m_{\text{cat.}}^L, m_{\text{coke}}^L, m_{\text{lime}}^L \)), kg; 1000 - 1000 kg of the alloy = 1 tone of the alloy.

Or \( \sum m_{\text{ch.m.}}^{L,1000} = 5026,87 \) kg. This yields to: \( \text{V catalyst} = 3444,71 \) kg/t alloy (68,53%), metallurgical coke = 1413,02 kg/t alloy (28,11%), lime = 169,14 kg/t alloy (3,37%).

A heat balance model of carbothermal production of SiCa with increased content of vanadium from vanadium waste

1. Income of heat
1.1. A heat from oxidation of carbon.

It is calculated according to the reaction

\[
C + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} \quad \text{and dependence:}
\]

\[
Q_a = m_c \cdot \Delta H_{\text{CO}}, \text{kJ} \quad (45)
\]

where: \( \Delta H_{\text{CO}} \) is the enthalpy of formation of CO = 9303 kJ/kg CO; \( m_c \) - mass of C necessary for reduction of the

Table 4. Composition of the gas phase.

<table>
<thead>
<tr>
<th>Oxides and elements</th>
<th>kg</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>71,84</td>
<td>66,70</td>
</tr>
<tr>
<td>SiS</td>
<td>20,96</td>
<td>19,46</td>
</tr>
<tr>
<td>SiO</td>
<td>1,80</td>
<td>1,67</td>
</tr>
<tr>
<td>VC-lime</td>
<td>0,05</td>
<td>0,05</td>
</tr>
<tr>
<td>VC-coke</td>
<td>1,20</td>
<td>1,11</td>
</tr>
<tr>
<td>( \text{V}_2\text{O}_5 )</td>
<td>0,05</td>
<td>0,05</td>
</tr>
<tr>
<td>P</td>
<td>0,005</td>
<td>0,005</td>
</tr>
<tr>
<td>Mn</td>
<td>0,003</td>
<td>0,003</td>
</tr>
<tr>
<td>( \text{Na}_2\text{O} )</td>
<td>4,36</td>
<td>4,05</td>
</tr>
<tr>
<td>( \text{K}_2\text{O} )</td>
<td>7,44</td>
<td>6,91</td>
</tr>
<tr>
<td>Total</td>
<td>107,71</td>
<td>100,00</td>
</tr>
</tbody>
</table>

Table 5. Material balance of the process.

<table>
<thead>
<tr>
<th></th>
<th>Expenditure</th>
<th>%</th>
<th>Products</th>
<th>%</th>
<th>Profit</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td>141,01</td>
<td>100,00</td>
<td>141,01</td>
<td>100,00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V catalyst</td>
<td>100,00</td>
<td>70,92</td>
<td>29,03</td>
<td>20,59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallurgical coke</td>
<td>36,10</td>
<td>25,60</td>
<td>3,64</td>
<td>2,58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime</td>
<td>4,91</td>
<td>3,48</td>
<td>Total (( \sum_{\text{exp}} ))</td>
<td>107,71</td>
<td>76,39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(rounding error)</td>
<td>0,63</td>
<td>0,45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (( \sum_{\text{exp}} ))</td>
<td>141,01</td>
<td>100,00</td>
<td>Total (( \sum_{\text{pr}} ))</td>
<td>141,01</td>
<td>100,00</td>
<td></td>
</tr>
</tbody>
</table>
corresponding oxide, kg. Then:

\[
\begin{align*}
\text{a) from } V_2O_5: & \quad C + \frac{1}{2} O_2^{V_2O_5} \to CO \\
O_2^{V_2O_5} &= 2.07 \text{ kg}; \quad C = 2.07 \frac{12}{16} = 1.55 \text{ kg} \\
Q_c &= 14443 \text{ kJ}.
\end{align*}
\]

\[
\begin{align*}
\text{b) from } Fe_2O_3: & \quad C + \frac{1}{2} O_2^{Fe_2O_3} \to CO \\
O_2^{Fe_2O_3} &= 1.52 \text{ kg}; \quad C = 1.52 \frac{12}{16} = 1.14 \text{ kg} \\
Q_c &= 10605 \text{ kJ}.
\end{align*}
\]

\[
\begin{align*}
\text{c) from } SiO_2: & \quad C + \frac{1}{2} O_2^{SiO_2} \to CO \\
O_2^{SiO_2} &= 35.50 \text{ kg}; \quad C = 35.50 \frac{12}{16} = 26.63 \text{ kg} \\
Q_c &= 247692 \text{ kJ}.
\end{align*}
\]

\[
\begin{align*}
\text{d) from } SiO_2: & \quad C + \frac{1}{2} O_2^{SiO_2} \to CO \\
O_2^{SiO_2} &= 2.36 \text{ kg}; \quad C = 2.36 \frac{12}{16} = 1.77 \text{ kg} \\
Q_c &= 16466 \text{ kJ}.
\end{align*}
\]

\[
\begin{align*}
\text{e) from } Al_2O_3: & \quad C + \frac{1}{2} O_2^{Al_2O_3} \to CO \\
O_2^{Al_2O_3} &= 1.34 \text{ kg}; \quad C = 0.41 \frac{12}{16} = 1.34 \text{ kg} \\
Q_c &= 12466 \text{ kJ}.
\end{align*}
\]

\[
\begin{align*}
\text{f) from } MnO: & \quad 2MnO \to 2Mn + O \\
Q_c &= 0.03 \text{ kg}; \quad q = 174 \text{ kJ}.
\end{align*}
\]

\[
\begin{align*}
\text{g) from } P_2O_5: & \quad 2P + O \\
Q_c &= 4.71 \text{ kg}; \quad q = 4.71 \times 5092.4 = 22305 \text{ kJ}.
\end{align*}
\]

\[
\begin{align*}
\text{h) from } CaO: & \quad Ca + O \\
Q_c &= 0.02 \text{ kg}; \quad q = 0.02 \times 0.015 = 0.015 \text{ kg} \\
Q_c &= 140 \text{ kJ}.
\end{align*}
\]

1.2. A heat from formation of CaO.SiO_2

Calculated according to:

\[
Q_b = m_{CaO} \Delta H_{CaO.SiO_2}, \text{ kJ},
\]

where: \( \Delta H_{CaO.SiO_2} \) is the enthalpy of formation of CaO.SiO_2.

1.3. A heat from the charge materials

The solid charge materials (vanadium catalyst, metallurgical coke and lime) have a temperature of 298 K and then import physical heat under:

\[
Q_c = m_{\text{cat. coke lime}} \cdot c_i \cdot t, \text{ kJ}
\]

where: \( t \) is temperature, K; \( m_{\text{cat. coke lime}} \) - mass of vanadium catalyst/coke/lime, kg; \( c_i \) - specific heat capacity of the component of the charge (vanadium catalyst/ coke/lime) kJ/kg.K. Its value is as follows: for vanadium catalyst \( c_{\text{cat.}} = 0.6 \text{ kJ/kg.K} \); for coke \( c_{\text{coke}} = 0.84 \text{ kJ/kg.K} \); for lime \( c_{\text{lime}} = 0.80 \text{ kJ/kg.K} \). The amount of physical heat introduced into the furnace of vanadium catalyst, metallurgical coke and lime would be:

\[
Q_{\text{cat. coke lime}} = 17880 \text{ kJ}; \quad Q_{\text{coke}} = 10268 \text{ kJ}; \quad Q_{\text{lime}} = 1171 \text{ kJ}. \quad \text{Then: } Q_{10} = 17880 + 10268 + 1171 = 29319 \text{ kJ}.
\]

The total income of heat is:

\[
Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7 + +Q_8 + Q_9 + Q_{10}, \text{ kJ}
\]

Or \( Q_i = 341699 \text{ kJ} \).

2. Expenditure of heat

2.1. Expenditure of heat from dissociation of oxides.

It is calculated by:

\[
q = \left( \frac{\%RxOy_{\text{cat.}} \cdot m_{\text{cat.}}}{100} \right) \cdot \frac{\eta^{+}_{R_{\text{RxOy} \to R}}}{100} \cdot \Delta H_{MeO} + \left( \frac{\%RxOy_{\text{coke}} \cdot m_{\text{coke}}}{100} \right) \cdot \frac{\eta^{-}_{\text{RxOy} \to R}}{100} \cdot \Delta H_{MeO}, \text{ kJ}
\]

where: \( q \) is the heat of a reaction, kJ; \( \%RxOy_{\text{cat.}} \) - participation rate of the corresponding oxide RxOy in vanadium catalyst, \%; \( m_{\text{cat.}} \) - amount of vanadium catalyst, kg; \( \%RxOy_{\text{coke}} \) - participation rate of the corresponding oxide RxOy in coke, \%; \( m_{\text{coke}} \) - amount of coke, kg; 100 - coefficient of transition from rate to kilogram; \( \eta^{+}_{R_{\text{RxOy} \to R}} \) - coefficient of transition of RxOy in the alloy; \( \Delta H_{R_{\text{RxOy}} \to R} \) - enthalpy of the respective compound RxOy, kJ/kg. Then:

\[
\text{a) from } V_2O_5: \quad V_2O_5 \to 2V + \frac{1}{2} O_2; \\
\Delta H = 8530 \text{ kJ/kg } V_2O_5; \\
V_2O_5 = 4.71 \text{ kg}; \quad q_1 = 4.71 \times 8530 = 40209 \text{ kJ}.
\]

\[
\text{b) from } Fe_2O_3: \quad Fe_2O_3 \to 2Fe + \frac{3}{2} O_2; \\
\Delta H = 5092.4 \text{ kJ/kg } Fe_2O_3; \\
Fe_2O_3 = 4.38 \text{ kg}; \quad q_2 = 4.38 \times 5092.4 = 22305 \text{ kJ}.
\]
c) from SiO₂: SiO₂ \rightarrow Si + O₂;
\Delta H = 14374 \text{ kJ/kg SiO₂};
SiO₂ = 62.37 kg; \ q₃ = 89656 \text{ kJ}.
d) from SiO₂ to SiO: SiO₂ \rightarrow SiO + \frac{1}{2} O₂;
\Delta H = 10200 \text{ kJ/kg SiO₂};
SiO₂ = 4.16 kg; \ q₄ = 42432 \text{ kJ}.
e) from Al₂O₃: Al₂O₃ \rightarrow 2Al + \frac{3}{2} O₂;
\Delta H = 16343 \text{ kJ/kg Al₂O₃};
Al₂O₃ = 1.58 kg; \ q₅ = 174 \text{ kJ}.
g) from P₂O₅: P₂O₅ \rightarrow 2P + \frac{5}{2} O₂;
\Delta H = 11067 \text{ kJ/kg P₂O₅};
P₂O₅ = 0.01 kg; \ q₆ = 111 \text{ kJ}.
h) from CaO: CaO \rightarrow Ca + \frac{1}{2} O₂;
\Delta H = 14250 \text{ kJ/kg CaO};
CaO = 4.98 kg; \ q₇ = 70965 \text{ kJ}.

2.2. From the heat content of the alloy
At casting the alloy exports heat as:

\[ q₉ = C_p_{\text{alloy}} \cdot m_{\text{alloy}} \cdot \frac{t - t_1}{C_p}, \text{ kJ} \]  

where: \ t is temperature of the alloy in casting = 1650° C; \ m_{\text{alloy}} - mass of the alloy = 29.03 kg; \ C_p_{\text{alloy}} - specific heat of the alloy = 0.7819 kJ/kg. Then: \ q₉ = 37453 \text{ kJ}.

2.3. From the heat content of the slag
At pouring the slag exports heat as:

\[ q_{10} = C_p_{\text{slag}} \cdot m_{\text{slag}} \cdot \frac{t - t_2}{C_p}, \text{ kJ} \]  

where: \ t is temperature of the slag in casting = 1900° C; \ m_{\text{slag}} - mass of slag = 3.64 kg; \ C_p_{\text{slag}} - specific heat of the alloy = 1.13 kJ/kg. Then: \ q_{10} = 7815 \text{ kJ}.

2.4. From the heat content of the gas phase
Gas phase exports heat as:

\[ q_{11} = C_p_{\text{g.f.}} \cdot m_{\text{g.f.}} \cdot \frac{t - t_3}{C_p}, \text{ kJ} \]  

where: \ t is flue gas temperature = 600° C; \ m_{\text{g.f.}} - mass of the gas phase = 113.24 kg; \ C_p_{\text{g.f.}} – specific heat capacity of the gas. For ease of calculation, it is assumed that the specific heat capacity of the effluent gases is equal to the specific heat capacity of the carbon oxide - \ c_{\text{CO}} = 1.13 \text{ kJ/kg}. Then: \ q_{11} = 76,777 \text{ kJ}.

2.5. From heating and evaporation
It is calculated in accordance with (48).

Table 6. Heat balance of the process.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Income</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>From oxidation of C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from V₂O₅</td>
<td>14443</td>
<td>4,23</td>
</tr>
<tr>
<td>from Fe₂O₃</td>
<td>10605</td>
<td>3,10</td>
</tr>
<tr>
<td>from SiO₂</td>
<td>247692</td>
<td>72,49</td>
</tr>
<tr>
<td>from SiO</td>
<td>16466</td>
<td>4,82</td>
</tr>
<tr>
<td>from Al₂O₃</td>
<td>12466</td>
<td>3,65</td>
</tr>
<tr>
<td>from MnO</td>
<td>140</td>
<td>0,04</td>
</tr>
<tr>
<td>from CaO</td>
<td>10396</td>
<td>3,04</td>
</tr>
<tr>
<td>from P₂O₅</td>
<td>140</td>
<td>0,04</td>
</tr>
<tr>
<td>From SiO₂ · SiO₂</td>
<td>32</td>
<td>0,01</td>
</tr>
<tr>
<td>From the charge:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from vanadium catal.</td>
<td>17880</td>
<td>5,23</td>
</tr>
<tr>
<td>from metallurg. coke</td>
<td>10268</td>
<td>3,01</td>
</tr>
<tr>
<td>from lime</td>
<td>1171</td>
<td>0,34</td>
</tr>
<tr>
<td>From Na₂O, K₂O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of heat content:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of the alloy</td>
<td>37453</td>
<td>2,66</td>
</tr>
<tr>
<td>of the slag</td>
<td>7815</td>
<td>0,55</td>
</tr>
<tr>
<td>of the gas phase</td>
<td>76777</td>
<td>5,45</td>
</tr>
<tr>
<td>of N₂O</td>
<td>2036</td>
<td>0,14</td>
</tr>
<tr>
<td>of K₂O</td>
<td>3475</td>
<td>0,25</td>
</tr>
<tr>
<td>Losses in masonry and throat</td>
<td>183912</td>
<td>13,04</td>
</tr>
<tr>
<td>Total</td>
<td>341699</td>
<td>100,0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials</th>
<th>Expenditure</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>From dissociation of the oxides</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from V₂O₅</td>
<td>40209</td>
<td>2,85</td>
</tr>
<tr>
<td>from Fe₂O₃</td>
<td>22305</td>
<td>1,58</td>
</tr>
<tr>
<td>from SiO₂</td>
<td>896506</td>
<td>63,58</td>
</tr>
<tr>
<td>from SiO</td>
<td>42432</td>
<td>3,01</td>
</tr>
<tr>
<td>from Al₂O₃</td>
<td>25822</td>
<td>1,83</td>
</tr>
<tr>
<td>from MnO</td>
<td>174</td>
<td>0,01</td>
</tr>
<tr>
<td>from CaO</td>
<td>111</td>
<td>0,01</td>
</tr>
<tr>
<td>from P₂O₅</td>
<td>70965</td>
<td>5,03</td>
</tr>
<tr>
<td>Of heat content:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of heat content:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of the alloy</td>
<td>37453</td>
<td>2,66</td>
</tr>
<tr>
<td>of the slag</td>
<td>7815</td>
<td>0,55</td>
</tr>
<tr>
<td>of the gas phase</td>
<td>76777</td>
<td>5,45</td>
</tr>
<tr>
<td>of N₂O</td>
<td>2036</td>
<td>0,14</td>
</tr>
<tr>
<td>of K₂O</td>
<td>3475</td>
<td>0,25</td>
</tr>
<tr>
<td>Losses in masonry and throat</td>
<td>183912</td>
<td>13,04</td>
</tr>
<tr>
<td>Total</td>
<td>1409992</td>
<td>100,0</td>
</tr>
</tbody>
</table>

| Shortage | 1068293 |   |
\[ \Delta H = 467 \text{ kJ/kg Na}_2\text{O}; \]
\[ m_{\text{Na}_2\text{O}}^G = 4.36 \text{ kg}; q_{12} = 2036 \text{ kJ}. \]

b) of K\text{O}:
\[ \Delta H = 467 \text{ kJ/kg K}_2\text{O}; \]
\[ m_{\text{K}_2\text{O}}^G = 7.44 \text{ kg}; q_{13} = 3475 \text{ kJ}. \]

The total expenditure of heat is:
\[ q_e = q_1 + q_2 + q_3 + q_4 + q_5 + q_6 + q_7 + q_8 + q_9 + q_{10} + q_{11} + q_{12} + q_{13}, \text{ kJ} \]
\[ \text{or } q_e = 1226080 \text{ kJ}. \]  

\section*{2.6. Losses in masonry and throat}

It is assumed that the losses in the masonry and the throat of the furnace is 15% of cumulative heat input.
\[ \text{or } q_{14} = m_p \cdot \frac{q_e}{100} \cdot 0.15, \text{ kJ} \]

Then: \[ q_{14} = 183912 \text{ kJ}. \]
The total expenditure becomes:
\[ q_{e1} = q_e + q_{14}, \text{ kJ} \]
\[ \text{or } q_{e1} = 1409992 \text{ kJ}. \]

The total quantity of heat of the process is:
\[ Q_\Sigma = Q_e - q_{e1}, \text{ kJ} \]
\[ \text{or } Q_\Sigma = -1068293 \text{ kJ}. \]

It is seen from relation (55) that the income of the heat is not sufficient to cover the heat expenditures. It is therefore necessary to introduce an additional power generation. It is assumed that:
\[ E = \frac{Q_\Sigma}{Q_e}, \text{ kWh} \]
\[ \text{or } E_1 = 297 \text{ kWh}. \]

The final expenditure of electricity would be:
\[ E_2 = \frac{E_1}{\cos \varphi}, \text{ kWh}. \]
\[ \text{or } E_2 = 334 \text{ kWh} \]

A relative expenditure of electricity:
\[ E_3 = \frac{T \cdot E_2}{\text{m}^2}, \text{ kWh}. \]

where: \( T \) is one ton weight = 1000 kg; \( \text{m}^2 \) - mass of the alloy (as calculated by the material balance), kg. Or \( E_3 = 11505 \text{ kWh} \) electricity to produce 1000 kg alloy.

The heat balance of the process of carbothermal production of SiCa alloy with increased content of vanadium is summarized in the Table. 6.

\section*{CONCLUSIONS}

- Material and heat balance models for producing SiCa alloy with high content of vanadium from waste vanadium catalyst, metallurgical coke and metallurgical lime are developed. The amount of the alloy is estimated as 29.03 kg. The main elements in the alloy after reduction are: \( \text{V} \) - 2.64 kg (9.09 %); \( \text{Fe} \) - 2.63 kg (9.06 %); \( \text{Si} \) - 19.29 kg (66.45 %); \( \text{Ca} \) - 3.56 kg (12.26 %); \( \text{Mn} \) - 0.01 kg (0.03 %); \( \text{Al} \) - 0.82 kg (2.83 %); \( \text{P} \) - 0.005 kg (0.02 %); \( \text{S} \) - 0.01 kg (0.04 %); \( \text{C} \) - 0.06 kg (0.21 %). For reduction coke with mass 40.96 kg is used. The components passed in the slag and gas phase are respectively: 3.64 kg and 107.71 kg. The predominant compound in the slag is \( \text{SiO}_2 \), while in the gas phase - \( \text{CO} \).
- Rate frequency of the slag is of limited value due to the optimum carbothermal reduction of the components of the charge materials.
- The estimated shortage of heat is 1068293 kJ and the energy required to compensate for the lack of heat is 11505 kWh for 1 ton alloy.
- The SiCa alloy with high content of vanadium obtained is closed to maximum extent to SiCa alloy of Russian factory standards TU 14-141-09-91. It is found an effective method for utilization of polluting waste product.

\section*{REFERENCES}

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