Density and surface tension of the systems CaO-FeO-Fe$_2$O$_3$-MgO, CaO-FeO-Fe$_2$O$_3$-ZnO, and CaO-Fe$_2$O$_3$-Cu$_2$O

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Abstract: The density and surface tension of melts of the systems CaO-FeO-Fe$_2$O$_3$-MgO at the temperature 1623 K, CaO-FeO-Fe$_2$O$_3$-ZnO at 1573 K, and CaO-Fe$_2$O$_3$-Cu$_2$O at 1573 K were determined using the maximum bubble pressure method. The molar volume, the excess molar volume, and the excess surface tension were calculated on the basis of the obtained data. From these properties information on the interactions of components and possible chemical reactions between them was obtained.

Due to the absence of silica and the low concentration of other network-forming oxides, only isolated FeO$_{\text{5-}}$ tetrahedra and the CaO-FeO ionic pairs are formed in these basic melts, the donor of the oxygen atoms being either CaO, FeO, or both CaO+FeO oxides. Even the observed ternary interactions may be attributed to the formation of the anions FeO$_{\text{5-}}$ only.

Keywords: Density, surface tension, pyrometallurgical slags, copper production

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1 Introduction

The study of the density and surface tension of melts of the CaO-FeO-Fe$_2$O$_3$-MgO, CaO-FeO-Fe$_2$O$_3$-ZnO, and CaO-Fe$_2$O$_3$-Cu$_2$O systems is a part of the investigation of the physico-chemical properties of calcium-ferritic slags used in the pyrometallurgical production of copper. From the theoretical point of view, such physico-chemical measurements may shed light on their structure, i.e. the ionic composition.

The present knowledge of the density and surface tension of the system CaO-FeO-Fe$_2$O$_3$-X is very limited. Most of the information may be obtained from papers dealing with steel slags; however, they concern mainly binary and a few ternary systems.

The density and surface tension in the systems Fe-O-CaO-MgO-SiO$_2$ and Fe-O-CaO-ZnO-SiO$_2$ at 1573 K was measured by Tomášek [1]. He found that magnesium oxide increases the surface tension a little more than Al$_2$O$_3$ and decreases the density. Zinc oxide increases both the density and surface tension. In all cases the dependencies of the molar volume on composition show deviations from additivity, which indicates structural changes in the melt with changing composition.

Tchizhikov and Deineka [2] measured density and surface tension in the system CaO-FeO-ZnO-SiO$_2$ with relatively high content of CaO and SiO$_2$. They found that on exchanging FeO for ZnO the molar volume of the melt increases and the dependence is not additive, while the surface tension is not substantially affected.

According to Vanjukov and Utkin [3], magnesium oxide increases the surface tension of ferro-silicate melts. It is due to the pronounced ability of MgO to modify the silicate network, especially in the presence of strong acidic oxides like SiO$_2$. In addition, Bakardzhiev [4] found that MgO increases the surface tension of melts of the system CaO-FeO-Al$_2$O$_3$-SiO$_2$ more than CaO and FeO and also ZnO has a positive effect on the surface tension increase.

The density and surface tension of the systems CaO-FeO-Fe$_2$O$_3$-SiO$_2$ and CaO-FeO-Fe$_2$O$_3$-Al$_2$O$_3$ was determined using the maximum bubble pressure method by Wadász et al. [5]. These authors found out that due to the low concentration of network forming oxides, isolated SiO$_4^{4-}$, AlO$_4^{5-}$ and FeO$_4^{5-}$ tetrahedrons are formed in these basic melts, the donor of the oxygen atoms being either CaO, FeO, or both CaO+FeO oxides. The observed ternary interactions may be most probably attributed to the formation of the anions SiFeO$_7^{7-}$ and FeAlO$_7^{7-}$, in which one Si atom is substituted by Fe and/or Al, forming two tetrahedrons linked by corner.

In the present work the density and the surface tension of the melts of the quaternary systems CaO-FeO-Fe$_2$O$_3$-MgO, CaO-FeO-Fe$_2$O$_3$-ZnO, and the ternary CaO-Fe$_2$O$_3$-Cu$_2$O one were determined using the maximum bubble pressure method. From these binary and ternary interactions, obtained from the dependence of the molar volume and the surface tension of the composition using multiple linear regression analysis, the information on the possible chemical reactions between the components and the probable structure, i.e. the ionic composition of the melts, was derived.
2 Experimental part

For the preparation of the synthetic slags, analytical grade chemicals were used. The mixtures with the required composition were melted in a PtRh10 crucible placed in an outer corundum crucible.

To measure density and surface tension, the maximum bubble pressure method was used. This method was selected because of the simultaneous measurements of both properties in one experiment and its ability to give accurate results at high temperatures.

The measuring device consisted of a resistance furnace fitted with an adjustable lid for fixing the position of the capillary, a thermocouple and a platinum wire, which served as an electrical contact for adjusting the exact touch of the capillary with the liquid surface.

A ZEPARIS controller was used to adjust the temperature of the furnace with an accuracy of ±2.5 °C using an additional control thermocouple. The PtRh6–PtRh18 thermocouple was used for exact temperature measurement, the voltage of which was measured using a THERM 3256-2 voltmeter with an accuracy of ±0.5 °C.

A capillary made of PtRh10 alloy was used. To ensure accurate results, the capillary tip was carefully machined. The orifice had to be as circular as possible, with a sharp conical edge. A precise inner diameter of the capillary is very important if accurate measurements are to be performed. A high-temperature LEITZ microscope was used to measure the diameter of the orifice at 1573 K.

A micrometry screw, fixed on the upper furnace lid, determined the position of the exact touch of the capillary with the liquid surface and indicating the desired immersion depth.

For pressure measurement the UMK micro-manometer with a moving arm was used. Nitrogen was used to form the bubbles and to maintain an inert atmosphere over the sample. The gas was slowly fed through the capillary during the experiment to avoid condensation in the upper part of capillary. The nitrogen flow was adjusted using a fine needle valve. The rate of bubble formation was approx. 3-6 bubbles per minute.

The surface tension was calculated according to the equation

$$\sigma = \frac{r}{2} (P_{\text{max}} - ghd)$$  \hspace{1cm} (1)

where \( r \) is the capillary radius, \( P_{\text{max}} \) is the maximum bubble pressure when the bubble is a hemisphere with the radius equal to the radius of the capillary, \( g \) is the gravitational constant, \( h \) is the depth of immersion of the capillary, and \( d \) is the density of the melt.

The density of the melt was calculated from the pressure difference at two depths of immersion according to the equation

$$\rho = \frac{P_{\text{max},2} - P_{\text{max},1}}{g (h_2 - h_1)}$$  \hspace{1cm} (2)

where \( g \) is the gravitational constant.

The measurement was performed after the melt reached chemical equilibrium, which required approx. 2-4 hours of isothermal heating at the desired temperature. The density
and surface tension of each sample was measured at 3-5 different depths of immersion. The pressure in the capillary at one depth of immersion was measured more than 10 times and the average value was used for the calculation. After the measurement a sample of the melt was taken for chemical analysis using the platinum rod. Then the chemical composition of the melt was changed and the measurement was repeated again after 2 hours of heating.

Magnesium oxide even in small amounts increases substantially the fusibility of the system CaO-FeO-Fe$_2$O$_3$-MgO, which required that the measurement of the properties of these melts had to be performed at the higher temperature of 1623 K. The lower number of measured compositions is due to the narrow interval of the homogenous liquid phase at this temperature. The composition of the investigated samples of the system CaO–FeO-Fe$_2$O$_3$-MgO varied in the following concentration range 41-56 mole % CaO, 0-27 mole % FeO, 24-43 mole % Fe$_2$O$_3$, and 1-10 mole % MgO.

In the system CaO-FeO-Fe$_2$O$_3$-ZnO the composition of individual oxides varied in the range: 32-60 mole % CaO, 1-30 mole % FeO, 19-58 mole % Fe$_2$O$_3$, and 0-34 mole % ZnO.

Finally, in the system CaO-Fe$_2$O$_3$-Cu$_2$O the composition varied in the range 5-58 mole % CaO, 0-63 mole % Fe$_2$O$_3$, and 0-95 mole % Cu$_2$O. The measurement in the last two systems was carried out at 1573 K.

The total amount of Fe, Ca, Al, and Si in the samples was determined using atomic absorption spectroscopy. In order to distinguish Fe(II) and Fe(III), the samples were dissolved under an inert atmosphere and the content of Fe(II) was determined by titration with KMnO$_4$ according to Reinhard and Zimmerman.

In the density and surface tension measurements using the maximum bubble pressure method several sources of error may occur. As mentioned above, the exact machining of the capillary orifice is important. A deviation from a circular orifice caused an error of ±0.5 %. The determination of the immersion depth with an accuracy of ±0.01 mm introduced an error of ±0.3 %. The accuracy of ±3 Pa in the pressure measurement caused an additional error of ±1.2 %. Test measurements of the density and surface tension of distilled water, methanol and mercury were used to check the experimental set up. The relative error in the surface tension measurement was approx. ±3.7 %, while in the density measurement the error attained ±1.8 %.

The values of the density and surface tension, as well as of the molar volumes of the investigated samples for the investigated CaO-FeO-Fe$_2$O$_3$-MgO melts are given in Table 1, those of the CaO-FeO-Fe$_2$O$_3$-ZnO melts in Table 2, and those of the system CaO-Fe$_2$O$_3$-Cu$_2$O in Table 3.

3 Results and discussion

According to earlier literature reports for the investigated slags the following species of the individual oxides may be present. Fe$_2$O$_3$ may form the anions FeO$^+$ [6, 7], FeO$_2^-$ [8], FeO$_4^{5-}$ [7, 9], Fe$_2$O$_9^{4-}$ [7, 9, 10], Fe$_2$O$_6^{6-}$ [9], and Fe$_2$O$_7^{5-}$ [9]. The coordination of Fe atoms may be either 4, and/or or 6. Copper(I) oxide in slags is basic in character and acts as the
modifier of the network structure. Together with Fe$_2$O$_3$ it may form stable clusters of the compound delafosite, CuFeO$_2$, which, depending on the oxygen partial pressure, can exist also in the melt up to 1456 K [11, 12]. Basic oxides CaO, MgO, FeO, and ZnO are donors of free oxygen anions, which may participate on the formation of complex anions.

To get some information on the structure of melts in the investigated systems the dependence of the given property on composition was described by the general Redlich-Kister function

$$Y = \sum_{i=1}^{4} A_i x_i + \sum_{i,j=1}^{4} \sum_{b=0}^{k} B_{bij} x_j^b + \sum_{i,j,k=1}^{4} \sum_{c=0}^{l} C_{cijk} x_i x_j x_k^c$$

In eqn (3) $A_i$'s are the properties of pure components and $x_i$'s are their mole fractions in the mixture. Coefficients $e$, $f$, $g$, $h$, are integers in the range 0-2. The first term represents the ideal behavior, the second term gives the interactions of the binary systems, the third one relates the interactions in ternary subsystems, and the fourth term represents the interaction of all four components.

With respect to the density, the dependence of the molar volume on the composition was followed. However, for the surface tension it is very important to define the course of surface tension in “ideal solutions”. The general approach used for the variation of surface tension with composition was given by Guggenheim [13], who stated, that the surface tension of ideal solutions should follow the simple additivity formula with a good approximation. The thermodynamic derivation of the additivity of surface tension for ideal solutions was given also by Dáňek and Proks [14]. When the “ideal” behavior is given, the excess surface tension in the investigated ternary and quaternary systems can be described by the Redlich-Kister excess function.

However, because of the prevailing basic nature in the concentration range of this study, the melts are simple in structure and no higher than third order interactions could be found. Therefore eqn (3) has been reduced into the simpler form

$$Y = \sum_{i=1}^{4} A_i x_i + \sum_{i,j=1}^{4} B_{ij} x_i x_j + \sum_{i,j,k=1}^{4} C_{ijk} x_i x_j x_k$$

The first term in eqn (4) represents the ideal behavior while the second and third terms represent the excess function, i.e. the deviation from ideal behavior, which is caused by chemical interaction of the components. The calculation of the coefficients $A_i$, $B_{ij}$, and $C_{ijk}$ was performed using multiple linear regression analysis, omitting the statistically non-important terms on the 0.99 confidence level. It should be expected that the excess terms would become numerically smaller in order.
3.1 System CaO-FeO-Fe$_2$O$_3$-MgO

The dependence of the molar volume of the melt on the content of calcium and ferrous oxides is shown in Fig. 1. The molar volume increases linearly with the content of both oxides. The dispersion of the experimental data is caused by the difference in the content of the other three oxides, since it was not possible to change the concentration of one component and keeping the concentrations of the other three at a constant value.

**Fig. 1** Dependence of the molar volume of melts of the system CaO-FeO-Fe$_2$O$_3$-MgO on the content of CaO and FeO at the temperature of 1623 K.

The influence of MgO to the basic system CaO-FeO-Fe$_2$O$_3$ can be explained in the following way. Magnesium oxide decreases the density of the system up to the concentration of 8 mole %. In this concentration range the molar volume increases, however the changes of the molar volume are minimal. As it can be seen from Fig. 2, magnesium oxide increases the surface tension of the calcium-ferritic melts up to approximately 10 mole %. Higher concentrations MgO do not change the surface tension of the melt. MgO, like CaO, behaves in the calcium-ferritic melts as the strong donor of oxygen, which supports the formation of the simple ferritic anions. However, after surpassing a certain concentration, MgO becomes more and more network-forming in character and starts to participate in the formation of complex anions together with anions of Fe(III). On the basis of the obtained results of the density and surface tension measurements it may be supposed that besides the cations Ca$^{2+}$, Mg$^{2+}$ and Fe$^{2+}$ only simple complex anions FeO$_4^{5-}$, FeO$_6^{6-}$, Fe$_2$O$_5^{4-}$, etc. may be present in the melts of the CaO-FeO-Fe$_2$O$_3$-MgO system.
Fig. 2 Dependence of the surface tension of melts of the system CaO–FeO–Fe$_2$O$_3$–MgO on the content of MgO at the temperature of 1623 K.

For the concentration dependence of the molar volume of the system CaO–FeO–Fe$_2$O$_3$–MgO the following final equation was obtained

$$V = A_1x_{CaO} + A_3x_{FeO} + A_4x_{Fe_2O_3} + A_2x_{MgO} +$$
$$+B_{14}x_{CaO}x_{Fe_2O_3} + C_{124}x_{CaO}x_{Fe_2O_3}x_{MgO}$$  \(5\)

while for the surface tension of this system the final equation has the form

$$\sigma = A_1x_{CaO} + A_3x_{FeO} + A_4x_{Fe_2O_3} + A_2x_{MgO} +$$
$$+C_{124}x_{CaO}x_{Fe_2O_3}x_{MgO} + C_{234}x_{FeO}x_{Fe_2O_3}x_{MgO}$$  \(6\)

The values of the coefficients $A_i$, $B_{ij}$, $C_{ijk}$, and the standard deviations of approximation in the system CaO(1)-FeO(2)-Fe$_2$O$_3$(3)-MgO(4) at the temperature of 1623 K are given in Table 4.

The chemical interpretation of interactions represented by individual interaction coefficients in the system CaO-FeO-Fe$_2$O$_3$-MgO is in agreement with the general structure of these basic melts. Due to the low concentration of network-forming ferric oxide, it is most probably the FeO$_4^{5-}$ tetrahedrons that are formed. This corresponds to the binary interaction coefficient $B_{14}$ and also to the ternary coefficients $C_{124}$ and $C_{234}$, when the donor of oxygen atoms is either CaO or both CaO+MgO, or MgO+FeO, respectively.
3.2 System CaO-FeO-Fe$_2$O$_3$-ZnO

The dependence of the molar volume of the melt on the content of FeO is shown in Fig. 3 for demonstration. The molar volume increases linearly with the increasing content of FeO. Again, the dispersion of experimental data is caused by the difference in the content of the other three oxides.

![Figure 3](image)

**Fig. 3** Dependence of the molar volume of melts of the system CaO-FeO-Fe$_2$O$_3$-ZnO on the content of FeO at the temperature of 1573 K.

In the system CaO-FeO-Fe$_2$O$_3$-ZnO, the increasing content of ZnO decreases the molar volume and increases the surface tension (see Fig. 4) of the melts. This influence is minimal when substituting CaO, but substantial when substituting Fe$_2$O$_3$. Thus it can be assumed that in the calcium-ferritic melt it behaves similarly as CaO and acts as the donor of oxygen atoms participating in the formation of complex ferritic anions. The substitution of CaO by ZnO is accompanied by an increase in the surface tension of the melt. In the substitution of Fe$_2$O$_3$, similar behavior can be observed by ZnO.

The zinc oxide in the melts of the system CaO-FeO-Fe$_2$O$_3$-ZnO acts as the modifier of the anionic structure, causing a decrease in the molar volume and an increase in the surface tension. The free oxygen anions donated by ZnO participate in the change in the coordination of the complex ferritic anions. On the basis of the obtained results, it may be assumed that besides Ca$^{2+}$, Fe$^{2+}$, and Zn$^{2+}$ only very simple ferritic anions like FeO$_2^-$, FeO$_{5}^{5-}$, and Fe$_2$O$_{5}^{5-}$ could be present in the melts of the CaO-FeO-Fe$_2$O$_3$-ZnO system.

For the concentration dependence of the molar volume of the system CaO-FeO-Fe$_2$O$_3$-ZnO, the following final equation was obtained
Fig. 4 Dependence of the surface tension of melts of the system CaO–FeO-Fe$_2$O$_3$-ZnO on the content of ZnO at the temperature of 1573 K.

\[ V = A_1x_{CaO} + A_2x_{FeO} + A_4x_{Fe_2O_3} + A_3x_{ZnO} \] (7)

while for the surface tension of this system, the final equation has the form

\[ \sigma = A_1x_{CaO} + A_2x_{FeO} + A_4x_{Fe_2O_3} + A_3x_{ZnO} + B_{12}x_{CaO}x_{FeO} + B_{24}x_{FeO}x_{Fe_2O_3} \] (8)

The values of the coefficients $A_i$, $B_{ij}$, $C_{ijk}$, and the standard deviations of approximation in the system CaO(1)-FeO(2)-Fe$_2$O$_3$(3)-ZnO(4) at the temperature of 1573 K are given in Table 5.

It was found that from the point of view of the volume properties the system CaO-FeO-Fe$_2$O$_3$-ZnO behaves ideally within the experimental error of measurement. From the surface tension measurements only two binary interaction coefficients were found. The binary interaction coefficient $B_{12}$ can be attributed to the formation of ionic pairs CaO-FeO and the coefficient $B_{24}$ for the formation of the complex anion FeO$_5^{4-}$. Thus, the melts of this system are very simple in structure. Besides the Ca$^{2+}$, Fe$^{2+}$, Zn$^{2+}$ cations and O$^{2-}$ anions, only FeO$_5^{4-}$ complex anions are present.
3.3 System CaO-Fe$_2$O$_3$-Cu$_2$O

The increasing content of Cu$_2$O in the CaO-Fe$_2$O$_3$-Cu$_2$O melts causes an increase in the density due to the substantially higher density of Cu$_2$O compared with that of CaO and FeO. From the obtained results, it follows that the molar volume of the system CaO-Fe$_2$O$_3$-Cu$_2$O is mostly influenced by the content of Fe$_2$O$_3$ (see Fig. 5). The substitution of Fe$_2$O$_3$ by Cu$_2$O causes a decrease in the molar volume of the melt.

![Fig. 5](image)

**Fig. 5** Dependence of the molar volume of melts of the system CaO−Fe$_2$O$_3$-Cu$_2$O on the content of Fe$_2$O$_3$ at the temperature of 1573 K.

The addition of Cu$_2$O to the system CaO-Fe$_2$O$_3$ causes a decrease in surface tension of the melt (see Fig. 6). At an approximate ratio of $n$(CaO)/$n$(Cu$_2$O) = 4 this dependence passes through a minimum. Further additions of Cu$_2$O would lead to an increase in the surface tension. This behavior can be explained by the change in the anionic structure. Cu$_2$O behaves in the ferritic melt in a similar fashion to CaO, i.e. as an oxygen donor, which participates in the change of structure of the present ferritic anions, e.g. according to the reaction scheme

$$FeO^2^- + 2Cu_2O = FeO_5^{4-} + 4Cu^+$$

The oxidation-reduction process involving cuprous and ferric ions was not considered due to the lack of relevant analytical data.

It may be therefore supposed that besides the cations Ca$^{2+}$ and Cu$^+$ only simple ferrite complexes, most probably FeO$_2^-$, FeO$_4^{3-}$, and/or Fe$_2$O$_5^{3-}$ would be present in the melts of the system CaO-Fe$_2$O$_3$-Cu$_2$O. The presence of individual complexes depends obviously on the content of Fe$_2$O$_3$. 
Fig. 6 Dependence of the surface tension of melts of the system CaO-Fe$_2$O$_3$-Cu$_2$O on the content of Cu$_2$O at the temperature of 1573 K.

For the concentration dependence of the molar volume of the system CaO-Fe$_2$O$_3$-Cu$_2$O the following final equation was obtained

$$V = A_1 x_{CaO} + A_2 x_{Fe_2O_3} + A_3 x_{Cu_2O} +$$
$$+ B_{23} x_{Fe_2O_3} x_{Cu_2O} + C_{123} x_{CaO} x_{Fe_2O_3} x_{Cu_2O}$$

(9)

and a similar equation was also obtained for the surface tension

$$\sigma = A_1 x_{CaO} + A_2 x_{Fe_2O_3} + A_3 x_{Cu_2O} +$$
$$+ B_{23} x_{Fe_2O_3} x_{Cu_2O} + C_{123} x_{CaO} x_{Fe_2O_3} x_{Cu_2O}$$

(10)

The values of the coefficients $A_i$, $B_{ij}$, $C_{ijk}$, and the standard deviations of approximation in the system CaO(1)-Fe$_2$O$_3$(2)-Cu$_2$O(3) at the temperature of 1573 K are given in Table 6.

In the system CaO-Fe$_2$O$_3$-Cu$_2$O only two interaction coefficients were found from the density measurements as well as from the surface tension measurements. The binary and ternary interaction coefficients, $B_{23}$ and $C_{123}$, represent the formation of the complex anion FeO$_5^{5-}$. It may be therefore concluded that in this system besides the Ca$^{2+}$ and Cu$^+$ cations and O$^{2-}$ anions only FeO$_5^{5-}$ complex anions are present.

In Table 7 the values of the molar volumes of the essentially pure oxides CaO, FeO, and Fe$_2$O$_3$, obtained from calculations of the molar volume of individual systems, are given together with the results for the systems CaO-FeO-Fe$_2$O$_3$-SiO$_2$ and CaO-FeO-Fe$_2$O$_3$-Al$_2$O$_3$. 
obtained in [5]. The agreement of values obtained from the measurement in independent systems is surprisingly excellent. The literature data coincide fairly with the calculated values. For illustration, Ličko and Daněk [15] published a similar value for the molar volume of CaO at 1873 K, $V_o^{\text{(CaO)}} = 18.28 \text{ cm}^3\text{.mol}^{-1}$, and Bottinga and Weill [16] published the following values of molar volumes of the oxides: $V_o^{\text{(CaO)}} = 16.5 \text{ cm}^3\text{.mol}^{-1}$, $V_o^{\text{(FeO)}} = 12.8 \text{ cm}^3\text{.mol}^{-1}$, and $V_o^{\text{(Fe}_2\text{O}_3)} = 52 \text{ cm}^3\text{.mol}^{-1}$, all at the temperature of 1723 K. The differences in the values may be a reflection of the different temperatures since the molar volume is rather sensitive to temperature.

The calculated values of surface tension of pure oxides are given in Table 8. Again, surprisingly excellent agreement can be observed. For the surface tension of pure oxides the following values could be found in the literature for comparison: Daněk and Ličko [17], based on the measurement in the system CaO–MgO–SiO$_2$, published for CaO at 1800 K the value $\sigma^{\text{(CaO)}} = 726 \text{ mN.m}^{-1}$, Daněk at all. [18] calculated from the measurements in the system CaO–FeO–Fe$_2$O$_3$–SiO$_2$ for CaO, FeO, and Fe$_2$O$_3$ at 1723 K the values $\sigma^{\text{(CaO)}} = 689 \text{ mN.m}^{-1}$, $\sigma^{\text{(FeO)}} = 502 \text{ mN.m}^{-1}$, and $\sigma^{\text{(Fe}_2\text{O}_3)} = 467 \text{ mN.m}^{-1}$, respectively. For FeO the value $\sigma^{\text{(FeO)}} = 585 \text{ mN.m}^{-1}$ is reported by Richardson [19].

4 Conclusions

The coincidence of the interaction coefficients with the appearance of the complex species, indicates that the application of the Redlich-Kister formalism is suitable for multi-component oxide systems. The obtained density and surface tension data, as well as the interpretation of the interactions found in the individual systems, leads to the suggestion that the cations Ca$^{2+}$, Fe$^{3+}$, Zn$^{2+}$, Cu$^+$, and the complex anions FeO$_5^{2−}$ may be present in all the investigated CaO-FeO-Fe$_2$O$_3$-X ($X = \text{MgO}, \text{ZnO}, \text{Cu}_2\text{O}$) melts, where the content depends on the concentration of Fe$_2$O$_3$ in the melt.

The results obtained in the present paper can be used in choosing the optimum composition for slags used in the technology of continuous copper production. From a metallurgical point of view it is important to know how the individual oxides influence the basic calcium-ferritic slag. The surface tension of these slags is apparently higher than that of the common silicate slags which also results in higher interfacial tension between individual phases in the melt. Higher values in surface tension and the chemistry of the calcium-ferritic slags may inhibit the chemical corrosion of the periclase grains in the basic refractory lining [20–23]. The viscosity of the calcium-ferritic slags is more than one order lower than the viscosity of the silicate slags [24, 25]. A lower viscosity, higher interfacial tension, and as high as possible difference in the density of the calcium-ferritic slag enhance’s the coalescence of metallic droplets. These may have a positive effect on the efficiency of the process by lowering the mechanical loss of metal in the slag.
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### Table 1

Experimentally determined values of the density, molar volume and surface tension of the investigated melts of the system CaO-FeO-Fe$_2$O$_3$-MgO at the temperature of 1623 K.

| $x_{\text{CaO}}$ | $x_{\text{FeO}}$ | $x_{\text{Fe}_2\text{O}_3}$ | $x_{\text{MgO}}$ | $\rho_{\text{exp}}$ | $V_{\text{exp}}$ | $V_{\text{calc}}$ | $\sigma_{\text{exp}}$ | $\sigma_{\text{calc}}$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|---------------|-----------------|-----------------|
| 0.5163          | 0.0000          | 0.4140          | 0.0695          | 3.52            | 27.65         | 27.59         | 599             | 599             |
| 0.5206          | 0.0000          | 0.4048          | 0.0743          | 3.49            | 27.45         | 27.39         | 603             | 604             |
| 0.5016          | 0.0000          | 0.4111          | 0.0872          | 3.54            | 27.35         | 27.57         | 610             | 612             |
| 0.4835          | 0.0000          | 0.4029          | 0.0976          | 3.57            | 26.96         | 27.08         | 607             | 607             |
| 0.4851          | 0.0000          | 0.4036          | 0.0986          | 3.55            | 27.20         | 27.16         | 614             | 611             |
| 0.4952          | 0.0000          | 0.3932          | 0.1000          | 3.53            | 27.00         | 26.94         | 606             | 615             |
| 0.5607          | 0.0000          | 0.4219          | 0.0172          | 3.65            | 27.11         | 27.61         | 564             | 554             |
| 0.5528          | 0.0000          | 0.4160          | 0.0310          | 3.58            | 27.38         | 27.52         | 557             | 567             |
| 0.5233          | 0.0000          | 0.4281          | 0.0484          | 3.59            | 27.58         | 27.86         | 568             | 579             |
| 0.5191          | 0.0000          | 0.4196          | 0.0612          | 3.54            | 27.66         | 27.70         | 597             | 591             |
| 0.4957          | 0.0000          | 0.4263          | 0.0779          | 3.55            | 27.72         | 27.90         | 612             | 601             |
| 0.4912          | 0.0000          | 0.4297          | 0.0789          | 3.55            | 27.85         | 27.98         | 595             | 601             |
| 0.4136          | 0.2682          | 0.2459          | 0.0625          | 3.67            | 23.12         | 22.82         | 673             | 699             |
| 0.4471          | 0.1588          | 0.3107          | 0.0727          | 3.66            | 24.51         | 24.55         | 707             | 689             |
| 0.4286          | 0.0751          | 0.3573          | 0.0828          | 3.56            | 26.16         | 25.86         | 694             | 660             |
| 0.4904          | 0.0403          | 0.4008          | 0.0683          | 3.53            | 27.41         | 27.16         | 611             | 624             |
| 0.4850          | 0.0199          | 0.4231          | 0.0717          | 3.53            | 27.98         | 27.75         | 611             | 611             |

### Table 2

Experimentally determined values of the density, molar volume and surface tension of the investigated melts of the system CaO-FeO-Fe$_2$O$_3$-ZnO at the temperature of 1573 K.

| $x_{\text{CaO}}$ | $x_{\text{FeO}}$ | $x_{\text{Fe}_2\text{O}_3}$ | $x_{\text{ZnO}}$ | $\rho_{\text{exp}}$ | $V_{\text{exp}}$ | $V_{\text{calc}}$ | $\sigma_{\text{exp}}$ | $\sigma_{\text{calc}}$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|---------------|-----------------|-----------------|
| 0.4568          | 0.2308          | 0.3121          | 0               | 3.83            | 23.24         | 23.36         | 433             | 483             |
| 0.5289          | 0.0180          | 0.4524          | 0               | 4.03            | 25.62         | 26.22         | 454             | 501             |
| 0.4119          | 0.2979          | 0.2802          | 0               | 3.98            | 22.53         | 22.57         | 525             | 474             |
| 0.5109          | 0.0132          | 0.4758          | 0               | 4.01            | 26.32         | 26.74         | 470             | 497             |
| 0.4361          | 0.1708          | 0.3931          | 0               | 3.99            | 24.99         | 25.07         | 527             | 519             |
| 0.6030          | 0.0160          | 0.3810          | 0               | 3.88            | 24.73         | 24.69         | 550             | 515             |
| 0.5282          | 0.0779          | 0.3939          | 0               | 3.63            | 27.06         | 25.02         | 534             | 502             |
| 0.5419          | 0.0389          | 0.4192          | 0               | 3.98            | 25.16         | 25.53         | 522             | 505             |
| 0.5188          | 0.0130          | 0.4682          | 0               | 4.05            | 25.90         | 26.57         | 460             | 499             |
| 0.4368          | 0.2554          | 0.3078          | 0               | 3.87            | 23.77         | 23.29         | 451             | 486             |
| 0.4787          | 0.0733          | 0.4480          | 0               | 4.40            | 23.52         | 26.18         | 499             | 507             |
|
|---|---|---|---|---|---|---|---|
| $x_{\text{CaO}}$ | $x_{\text{FeO}}$ | $x_{\text{Fe}_2\text{O}_3}$ | $x_{\text{ZnO}}$ | $\rho_{\text{exp}}$ g·cm$^{-3}$ | $V_{\text{exp}}$ cm$^3$·mol$^{-1}$ | $V_{\text{calc}}$ cm$^3$·mol$^{-1}$ | $\sigma_{\text{exp}}$ mN·m$^{-1}$ | $\sigma_{\text{calc}}$ mN·m$^{-1}$ |
| 0.4529 | 0.0684 | 0.4472 | 0.0314 | 3.95 | 26.43 | 26.22 | 525 | 515 |
| 0.4345 | 0.0775 | 0.4480 | 0.0400 | 3.94 | 25.51 | 26.27 | 530 | 520 |
| 0.3464 | 0.1181 | 0.5355 | 0 | 4.08 | 27.79 | 28.11 | 527 | 547 |
| 0.3423 | 0.0611 | 0.5804 | 0.0162 | 4.08 | 28.81 | 29.07 | 533 | 513 |
| 0.3353 | 0.0829 | 0.5621 | 0.0196 | 4.09 | 28.41 | 28.70 | 528 | 530 |
| 0.3758 | 0.0442 | 0.5487 | 0.0318 | 3.98 | 28.77 | 28.41 | 521 | 506 |
| 0.3497 | 0.0902 | 0.5134 | 0.0467 | 4.01 | 27.90 | 27.70 | 533 | 537 |
| 0.3756 | 0.0673 | 0.5072 | 0.0498 | 3.91 | 28.19 | 27.56 | 543 | 523 |
| 0.3863 | 0.1283 | 0.4140 | 0.0714 | 3.82 | 26.87 | 25.63 | 549 | 543 |
| 0.4134 | 0.1002 | 0.4020 | 0.0843 | 3.97 | 25.76 | 25.38 | 540 | 534 |
| 0.4402 | 0.0865 | 0.3806 | 0.0926 | 3.91 | 25.41 | 24.92 | 542 | 530 |
| 0.4079 | 0.0805 | 0.3958 | 0.1157 | 3.99 | 25.43 | 25.29 | 548 | 538 |
| 0.4141 | 0.0552 | 0.3897 | 0.1409 | 4.02 | 25.13 | 25.19 | 540 | 539 |
| 0.4185 | 0.0481 | 0.3726 | 0.1607 | 3.96 | 25.13 | 24.85 | 546 | 543 |
| 0.3776 | 0.0844 | 0.3617 | 0.1762 | 3.96 | 25.13 | 24.68 | 550 | 553 |
| 0.3761 | 0.0524 | 0.3617 | 0.2098 | 4.03 | 24.71 | 24.72 | 547 | 556 |
| 0.3732 | 0.0418 | 0.3606 | 0.2244 | 3.97 | 25.14 | 24.72 | 554 | 558 |
| 0.4039 | 0.0365 | 0.3265 | 0.2330 | 4.07 | 23.68 | 23.99 | 556 | 561 |
| 0.3756 | 0.1803 | 0.2627 | 0.1814 | 3.91 | 23.21 | 22.62 | 580 | 541 |
| 0.3311 | 0.3093 | 0.1975 | 0.1621 | 4.03 | 21.19 | 21.27 | 535 | 510 |
| 0.4258 | 0.0710 | 0.3310 | 0.1722 | 3.90 | 24.54 | 24.00 | 546 | 547 |
| 0.3873 | 0.0763 | 0.3218 | 0.2145 | 4.03 | 23.82 | 23.88 | 551 | 559 |
| 0.4014 | 0.0464 | 0.3364 | 0.2158 | 4.02 | 24.17 | 24.18 | 561 | 557 |
| 0.3452 | 0.0794 | 0.3375 | 0.2379 | 4.05 | 24.26 | 24.27 | 557 | 568 |
| 0.3308 | 0.0763 | 0.3444 | 0.2485 | 4.05 | 24.48 | 24.44 | 561 | 571 |
| 0.3644 | 0.0545 | 0.3240 | 0.2571 | 3.99 | 24.32 | 24.00 | 573 | 568 |
| 0.3677 | 0.0268 | 0.3337 | 0.2718 | 4.16 | 23.52 | 24.22 | 561 | 568 |
| 0.3542 | 0.0265 | 0.3422 | 0.2770 | 4.21 | 23.60 | 24.41 | 565 | 568 |
| 0.3364 | 0.0224 | 0.3442 | 0.2970 | 4.15 | 23.99 | 24.49 | 578 | 571 |
| 0.3264 | 0.0271 | 0.3782 | 0.2683 | 4.14 | 24.75 | 25.17 | 574 | 562 |
| 0.3523 | 0.0176 | 0.3785 | 0.2516 | 4.10 | 24.87 | 25.14 | 556 | 557 |
| 0.3593 | 0.0187 | 0.3631 | 0.2588 | 4.02 | 25.03 | 24.82 | 552 | 561 |
| 0.3360 | 0.0249 | 0.3544 | 0.2846 | 4.07 | 24.63 | 24.69 | 574 | 568 |
| 0.3238 | 0.0243 | 0.3117 | 0.3402 | 4.04 | 24.13 | 23.88 | 576 | 584 |

Table 2 (continue) Experimentally determined values of the density, molar volume and surface tension of the investigated melts of the system CaO-FeO-Fe$_2$O$_3$-ZnO at the temperature of 1573 K.
| $x_{\text{CaO}}$ | $x_{\text{Fe}_2\text{O}_3}$ | $x_{\text{Cu}_2\text{O}}$ | $\rho_{\text{exp}}$ g cm$^{-3}$ | $V_{\text{exp}}$ cm$^3$ mol$^{-1}$ | $V_{\text{calc}}$ cm$^3$ mol$^{-1}$ | $V_{\text{exp}}$ mN m$^{-1}$ | $V_{\text{calc}}$ mN m$^{-1}$ |
|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|
| 0.3253          | 0.4928          | 0.1818          | 4.20           | 29.27          | 28.23          | 524            | 546            |
| 0.3654          | 0.5954          | 0.0391          | 4.08           | 29.74          | 30.38          | 502            | 498            |
| 0.3379          | 0.6102          | 0.0518          | 4.10           | 30.22          | 30.67          | 494            | 501            |
| 0.3310          | 0.6273          | 0.0417          | 4.06           | 30.73          | 31.02          | 492            | 498            |
| 0.3338          | 0.5627          | 0.1035          | 4.19           | 29.45          | 29.68          | 490            | 519            |
| 0.3251          | 0.5407          | 0.1342          | 4.16           | 29.80          | 29.19          | 496            | 532            |
| 0.3436          | 0.5257          | 0.1307          | 4.11           | 29.67          | 29.00          | 496            | 522            |
| 0.3404          | 0.5343          | 0.1253          | 4.12           | 29.73          | 29.15          | 498            | 522            |
| 0.3654          | 0.5215          | 0.1131          | 4.11           | 29.18          | 28.99          | 484            | 509            |
| 0.3641          | 0.5494          | 0.0865          | 4.08           | 29.52          | 29.50          | 483            | 506            |
| 0.3675          | 0.4831          | 0.1494          | 4.14           | 28.77          | 28.30          | 510            | 513            |
| 0.3247          | 0.5541          | 0.1212          | 4.14           | 29.95          | 29.46          | 494            | 528            |
| 0.3775          | 0.4357          | 0.1867          | 4.24           | 27.98          | 27.51          | 516            | 511            |
| 0.4080          | 0.4459          | 0.1461          | 4.13           | 27.84          | 27.74          | 489            | 495            |
| 0.4006          | 0.5739          | 0.0254          | 3.96           | 29.94          | 29.89          | 528            | 501            |
| 0.3759          | 0.5249          | 0.0992          | 4.09           | 29.09          | 29.07          | 472            | 504            |
| 0.4164          | 0.4846          | 0.0990          | 4.02           | 28.06          | 28.36          | 474            | 495            |
| 0.4105          | 0.5090          | 0.0805          | 4.08           | 28.38          | 28.77          | 482            | 498            |
| 0.4029          | 0.4635          | 0.1336          | 4.23           | 27.99          | 28.02          | 489            | 497            |
| 0.4206          | 0.5793          | 0.0000          | 3.93           | 29.95          | 29.86          | 560            | 509            |
| 0.4180          | 0.3510          | 0.2310          | 4.20           | 26.79          | 26.22          | 523            | 491            |
| 0.4316          | 0.4302          | 0.1381          | 4.10           | 27.46          | 27.47          | 487            | 488            |
| 0.4692          | 0.4204          | 0.1104          | 4.02           | 27.15          | 27.22          | 496            | 486            |
| 0.4569          | 0.4467          | 0.0964          | 4.00           | 27.67          | 27.65          | 494            | 490            |
| 0.4522          | 0.4539          | 0.0940          | 4.07           | 27.37          | 27.78          | 490            | 491            |
| 0.4342          | 0.4728          | 0.0930          | 4.05           | 27.94          | 28.13          | 490            | 493            |
| 0.4413          | 0.4718          | 0.0869          | 4.02           | 27.98          | 28.09          | 502            | 494            |
| 0.4422          | 0.4744          | 0.0838          | 4.04           | 27.88          | 28.13          | 504            | 494            |
| 0.4467          | 0.4158          | 0.1375          | 4.11           | 27.01          | 27.22          | 486            | 485            |
| 0.4554          | 0.3574          | 0.1872          | 4.15           | 26.15          | 26.32          | 485            | 478            |
| 0.4488          | 0.3327          | 0.2185          | 4.18           | 26.12          | 25.95          | 495            | 479            |
| 0.4594          | 0.4685          | 0.0721          | 4.01           | 27.69          | 27.95          | 503            | 496            |
| 0.4325          | 0.4763          | 0.0912          | 4.05           | 28.02          | 28.19          | 486            | 494            |
| 0.4314          | 0.4913          | 0.0773          | 4.04           | 28.15          | 28.42          | 492            | 496            |
| 0.4311          | 0.4749          | 0.0940          | 4.10           | 27.66          | 28.17          | 500            | 494            |
| 0.4251          | 0.4638          | 0.1111          | 4.06           | 28.05          | 28.01          | 486            | 492            |
| 0.4500          | 0.5500          | 0.0000          | 3.97           | 29.48          | 29.19          | 580            | 518            |
| 0.4320          | 0.3740          | 0.1940          | 4.11           | 27.19          | 26.60          | 487            | 485            |
| 0.4290          | 0.3301          | 0.2409          | 4.21           | 26.42          | 25.91          | 480            | 486            |

**Table 3** Experimentally determined values of the density, molar volume and surface tension of the investigated melts of the system CaO-Fe$_2$O$_3$-Cu$_2$O at the temperature of 1573 K.
| $x_{\text{CaO}}$ | $x_{\text{Fe}_2\text{O}_3}$ | $x_{\text{Cu}_2\text{O}}$ | $\rho_{\text{exp}}$ g cm$^{-3}$ | $V_{\text{exp}}$ cm$^3$ mol$^{-1}$ | $V_{\text{calc}}$ cm$^3$ mol$^{-1}$ | $\sigma_{\text{exp}}$ mN m$^{-1}$ | $\sigma_{\text{calc}}$ mN m$^{-1}$ |
|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|
| 0.4757          | 0.3957          | 0.1286          | 4.07           | 26.57          | 26.83          | 486            | 481            |
| 0.4785          | 0.3981          | 0.1234          | 4.07           | 26.55          | 26.86          | 485            | 482            |
| 0.4843          | 0.3971          | 0.1185          | 4.03           | 26.68          | 26.81          | 485            | 483            |
| 0.4895          | 0.4373          | 0.0732          | 3.92           | 27.48          | 27.33          | 523            | 497            |
| 0.4970          | 0.4279          | 0.0750          | 3.97           | 26.97          | 27.15          | 518            | 496            |
| 0.5179          | 0.2898          | 0.1923          | 4.13           | 24.88          | 25.13          | 470            | 469            |
| 0.4996          | 0.5004          | 0.0000          | 3.87           | 28.44          | 28.04          | 595            | 533            |
| 0.4646          | 0.3826          | 0.1528          | 4.12           | 26.48          | 26.68          | 495            | 479            |
| 0.4540          | 0.3805          | 0.1655          | 4.10           | 26.81          | 26.68          | 502            | 480            |
| 0.4569          | 0.3593          | 0.1838          | 4.13           | 26.45          | 26.35          | 492            | 478            |
| 0.4546          | 0.3230          | 0.2224          | 4.15           | 26.24          | 25.80          | 485            | 477            |
| 0.4859          | 0.3007          | 0.2134          | 4.15           | 25.50          | 25.40          | 483            | 470            |
| 0.4531          | 0.2820          | 0.2648          | 4.28           | 25.30          | 25.16          | 496            | 479            |
| 0.4989          | 0.2582          | 0.2428          | 4.12           | 25.05          | 24.71          | 486            | 469            |
| 0.5500          | 0.2026          | 0.2474          | 4.08           | 24.20          | 23.64          | 486            | 474            |
| 0.5219          | 0.1978          | 0.2803          | 4.30           | 23.48          | 23.67          | 470            | 475            |
| 0.5827          | 0.1686          | 0.2486          | 4.10           | 23.22          | 22.89          | 472            | 485            |
| 0.5749          | 0.1634          | 0.2617          | 4.18           | 22.94          | 22.85          | 471            | 485            |
| 0.5161          | 0.1529          | 0.3309          | 4.30           | 23.42          | 22.93          | 465            | 488            |
| 0.5757          | 0.1309          | 0.2934          | 4.40           | 21.32          | 22.27          | 461            | 497            |
| 0.0507          | 0.0000          | 0.9493          | 5.80           | 23.91          | 23.51          | 492            | 473            |
| 0.0909          | 0.0000          | 0.9091          | 5.75           | 23.51          | 23.22          | 468            | 482            |
| 0.1844          | 0.0000          | 0.8156          | 5.43           | 23.38          | 22.52          | 471            | 503            |
| 0.2451          | 0.0000          | 0.7549          | 5.25           | 23.19          | 22.07          | 468            | 517            |
| 0.3450          | 0.1004          | 0.5546          | 5.13           | 21.24          | 22.43          | 693            | 551            |
| 0.3767          | 0.1486          | 0.4746          | 4.56           | 24.75          | 23.05          | 474            | 535            |
| 0.4308          | 0.1332          | 0.4360          | 4.55           | 23.70          | 22.81          | 484            | 514            |
| 0.3489          | 0.1261          | 0.5250          | 5.56           | 20.63          | 22.74          | 544            | 551            |
| 0.3679          | 0.1916          | 0.4405          | 4.99           | 22.93          | 23.65          | 557            | 538            |
| 0.3607          | 0.2121          | 0.4272          | 5.10           | 22.60          | 23.91          | 623            | 542            |
| 0.3144          | 0.2461          | 0.4395          | 5.05           | 23.73          | 24.14          | 595            | 587            |
| 0.2647          | 0.2712          | 0.4476          | 5.00           | 24.64          | 23.72          | 742            | 642            |

Table 3 (continue) Experimentally determined values of the density, molar volume and surface tension of the investigated melts of the system CaO-Fe$_2$O$_3$-Cu$_2$O at the temperature of 1573 K.
Table 4 Coefficients $A_i$, $B_{ij}$, $C_{ijk}$, and the standard deviations of approximation of the fit in the system CaO-FeO-Fe$_2$O$_3$-MgO at the temperature of 1623 K.

| Coefficient | $V$ (cm$^3$/mol) | $\sigma$ (mN/m) |
|-------------|------------------|------------------|
| $A_1$       | 16.50±0.14       | 656.7±11.8       |
| $A_2$       | 17.01±0.15       | 582.8±12.7       |
| $A_3$       | 39.01±0.34       | 374.4±7.9        |
| $A_4$       | 16.00±0.14       | 619.9±7.5        |
| $B_{13}$    | 6.34±1.12        | —                |
| $C_{124}$   | 30.81±12.32      | 4128±463         |
| $C_{234}$   | —                | 27870±2720       |
| $sd$        | 0.21             | 24.4             |

Table 5 Coefficients $A_i$, $B_{ij}$, and the standard deviations of approximation of the fit in the system CaO-FeO-Fe$_2$O$_3$-ZnO at the temperature of 1573 K.

| Coefficient | $V$ (cm$^3$/mol) | $\sigma$ (mN/m) |
|-------------|------------------|------------------|
| $A_1$       | 16.44±0.38       | 617.5±16.7       |
| $A_2$       | 17.22±0.42       | 589.4±25.4       |
| $A_3$       | 38.06±0.45       | 363.3±14.8       |
| $A_4$       | 18.44±0.41       | 747.5±21.2       |
| $B_{12}$    | —                | -2162±320        |
| $B_{23}$    | —                | 2484±429         |
| $sd$        | 0.64             | 23.2             |

Table 6 Coefficients $A_i$, $B_{ij}$, $C_{ijk}$, and the standard deviations of approximation of the fit in the system CaO-Fe$_2$O$_3$-Cu$_2$O at the temperature of 1573 K.

| Coefficient | $V$ (cm$^3$/mol) | $\sigma$ (mN/m) |
|-------------|------------------|------------------|
| $A_1$       | 16.42±0.35       | 686.9±25.7       |
| $A_2$       | 39.29±0.36       | 379.5±15.7       |
| $A_3$       | 23.97±0.27       | 461.9±13.8       |
| $B_{23}$    | -45.65±7.58      | 4146±433         |
| $C_{123}$   | 111.9±19.8       | -10983±1175      |
| $sd$        | 0.62             | 28.6             |


Table 7 Molar volumes of pure oxides calculated from individual independent systems.

| System                                                   | \( V_{\text{CaO}}^O \) cm\(^3\)·mol\(^{-1}\) | \( V_{\text{FeO}}^O \) cm\(^3\)·mol\(^{-1}\) | \( V_{\text{Fe}_2\text{O}_3}^O \) cm\(^3\)·mol\(^{-1}\) |
|----------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------------------------------------|
| CaO-FeO-Fe\(_2\)O\(_3\)-SiO\(_2\) (1573 K) \[5\]        | 16.41±0.26                                   | 17.03±0.28                                   | 38.79±0.48                                               |
| CaO-FeO-Fe\(_2\)O\(_3\)-Al\(_2\)O\(_3\) (1573 K) \[5\]  | 16.31±0.60                                   | 17.00±0.63                                   | 38.11±1.37                                               |
| CaO-FeO-Fe\(_2\)O\(_3\)-MgO (1623 K)                     | 16.50±0.14                                   | 17.01±0.15                                   | 39.01±0.34                                               |
| CaO-FeO-Fe\(_2\)O\(_3\)-ZnO (1573 K)                     | 16.44±0.38                                   | 17.22±0.42                                   | 38.06±0.45                                               |
| CaO-Fe\(_2\)O\(_3\)-Cu\(_2\)O (1573 K)                   | 16.42±0.35                                   | --                                           | 39.29±0.36                                               |
| Average                                                  | 16.42±0.35                                   | 17.07±0.37                                   | 38.65±0.60                                               |

Table 8 Surface tension of pure oxides calculated from individual independent systems.

| System                                                   | \( \sigma_{\text{CaO}} \) cm\(^3\)·mol\(^{-1}\) | \( \sigma_{\text{FeO}} \) cm\(^3\)·mol\(^{-1}\) | \( \sigma_{\text{Fe}_2\text{O}_3} \) cm\(^3\)·mol\(^{-1}\) |
|----------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------------------------------------|
| CaO-FeO-Fe\(_2\)O\(_3\)-SiO\(_2\) (1573 K) \[5\]        | 657.6±12.8                                   | 588.6±11.3                                   | 376.2±7.3                                                 |
| CaO-FeO-Fe\(_2\)O\(_3\)-Al\(_2\)O\(_3\) (1573 K) \[5\]  | 661.6±7.8                                    | 585.1±7.0                                    | 375.0±4.5                                                 |
| CaO-FeO-Fe\(_2\)O\(_3\)-MgO (1623 K)                     | 656.7±11.8                                   | 582.8±12.7                                   | 374.4±7.9                                                 |
| CaO-FeO-Fe\(_2\)O\(_3\)-ZnO (1573 K)                     | 617.5±16.7                                   | 589.4±25.4                                   | 363.3±14.8                                               |
| CaO-Fe\(_2\)O\(_3\)-Cu\(_2\)O (1573 K)                   | 686.9±25.7                                   | --                                           | 379.5±15.7                                               |
| Average                                                  | 656.06±15.0                                  | 586.48±14.1                                  | 373.68±10.0                                               |